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Astrobiology

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Uncover the origins of life on Earth

Understand the biology of life

Discover the search for life in the universe

Conor Nixon, PhD

Planetary Scientist and Astrobiologist

Astrobiology For Dummies®

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Table of Contents

- Cover
- Table of Contents
- Title Page
- Copyright
- Introduction
  - About This Book
  - Foolish Assumptions
  - Icons Used in This Book
  - Beyond the Book
  - Where to Go from Here
- Part 1: Getting Started with Astrobiology
  - Chapter 1: Astrobiology in a Nutshell
    - Asking the Big Questions
    - The Scope of Astrobiology
    - Origins of Life on Earth
    - Searching for Life in Our Solar System
    - Life beyond Our Solar System
    - Astrobiology and Culture
  - Chapter 2: Origins of Astrobiology

Watching the Night Sky
Wondering about the Origins of Life
Evolving Astrobiology

Chapter 3: Modern Astrobiology

From Exobiology to Astrobiology
Giant Telescopes
Space Missions
Lab Experiments
Earth and Analog Fieldwork
Computer Simulations

Part 2: Origins of Life on Earth

Chapter 4: Defining Life

Characteristics of Life
Determining What Is Alive
Classifying Life

Chapter 5: History of Life on Earth

Finding Clues in Ancient Rocks
Ordering the Earth's Rock Records
The Earliest Times: The Hadean
The Rise of Life: The Archean
Getting Some Oxygen: The Proterozoic
Life's Full Richness: The Phanerozoic

Chapter 6: From Chemicals to Cells

Setting the Stage for Life
Building Complex Molecules
Stepping into the RNA World
Forming Protocells
DNA and Information Encoding
Who Ate Whom?

Chapter 7: Multicellular Life

Working as a Team: Unicellular Cooperatives
Advantages of Multicellularity

Becoming Multicellular
Living the Multicellular Life
Is Evolution Still Occurring?

Chapter 8: Recreating the Origins of Life

Cooking Up a Chemical Soup
Oró's Experiments Brew Up Adenine
Mimicking Deep-Sea Vents
Testing Self-Replicating DNA
Minimal DNA Cells
Computer Simulations

Chapter 9: Life in the Extremes

Introducing the Extremophiles
Some Like It Hot: Thermophiles
Life in the Freezer: Psychrophiles
Passing the Acid Test: Acidophiles
Back to Basics: Alkaliphiles
Getting Salty: Halophiles

Part 3: Searching for Life in Our Solar System

Chapter 10: Comets

Comets in History
Comet Appearance and Composition
Comet Origins and Populations
Comets and Life
Comet Missions

Chapter 11: Impacts and Origins: Meteorites

Order from Chaos: The Early Solar System
Meteorite Falls and Finds
Meteorite Types and Origins
Bringing Home the Bounty

Chapter 12: Mars

Romancing the Red Planet
The Space Age Arrives

The History of Mars
Habitability of Mars Today
Future Missions

Chapter 13: Ocean Worlds

Missions of Discovery
Galileo's Moons
Europa
Enceladus
Titan
Other Moons and Dwarf Planets

Chapter 14: Life in the Clouds

Surfin' the Breeze: Aeroplankton
Venus
Floating, Sinking, and Hunting on Jupiter

Part 4: Life beyond Our Solar System

Chapter 15: Astrochemistry

Building Atoms with Nucleosynthesis
Obscured by Clouds
Decoding the Rainbow with Spectroscopy
Next-Generation Radio Observatories

Chapter 16: Habitable Exoplanets

Dreaming of Many Worlds
Spinning Disks into New Worlds
Detecting Exoplanets
Getting Comfy in the Habitable Zone
Exoplanet Atmospheres

Chapter 17: Extra-Terrestrial Intelligence and Technosignatures

Hunting for Aliens
Grappling with Fermi's Paradox
Little Green Men, WOW!
Scaling Up with Present Day SETI

Reaching Out with Active SETI
Other Technosignatures
Interplanetary Missions
Part 5: Astrobiology and Culture
Chapter 18: Hoaxes and Conspiracies
Ancient Aliens
The Flying Saucer Craze of 1947
The Roswell Incident
Area 51
Alien Abductions
Interstellar Spacecraft
Crop Circles
Chapter 19: Astrobiology in Arts and Culture
Cells and Spores from Space
Decoding Alien Broadcasts
Alien Languages
Alien Invasions
Unleashing Aliens
Exotic Planets
Extraterrestrial Anatomy
Alien Civilizations
Alien Technology
Part 6: The Part of Tens
Chapter 20: Ten Questions in Astrobiology
How Did Life Start on Earth?
When Did Life Arise on Earth?
Did Life Come to Earth from Elsewhere?
Where Did Our Water Come From?
Did Life Ever Start on Mars?
Is There Life in Ocean Worlds?
Must Life Be Based on DNA?
Is There Sentient Life Elsewhere?

Is Anyone Trying to Contact Us?
Fermi's Paradox
Chapter 21: Ten Future Astrobiology Missions
Cloudy with a Chance of Life: The DAVINCI Mission to Venus
Sampling Mars: ExoMars and MSR
Visiting and Landing on Europa
Sampling an Icy Wanderer
Jetting to Enceladus
Three Titanic Missions
Index
About the Author
Dedication
Author's Acknowledgments
Connect with Dummies
End User License Agreement

List of Tables

Chapter 9
TABLE 9-1 Extremophile Types and Environments
Chapter 13
TABLE 13-1 Missions to the Outer Planets
Chapter 18
TABLE 18-1 Disputed Evidence for Ancient Aliens

List of Illustrations

Chapter 2
FIGURE 2-1: (a) Portrait of Galileo Galilei. (b) Galileo's writings and diagram...

FIGURE 2-2: The electromagnetic (EM) spectrum. Numbers attached to the visible ...

FIGURE 2-3: An exquisite drawing from 1699 by Antonie van Leeuwenhoek of a fema...

Chapter 3

FIGURE 3-1: Graphical depiction of the three key themes of astrobiology.

FIGURE 3-2: Modern Earth-based telescopes: (a) the Jansky VLA; (b) ALMA; (c) NA...

FIGURE 3-3: Space telescopes (a) Hubble Space Telescope; (b) Spitzer Space Tele...

FIGURE 3-4: Examples of different types of space missions to the planets: (a) a...

FIGURE 3-5: Astrobiology field work: (a) collecting meteorites in Antarctica; (...

Chapter 4

FIGURE 4-1: Seven characteristics of life according to a broad modern definitio...

FIGURE 4-2: Comparison of various possible forms of life.

FIGURE 4-3: The continuum of life.

FIGURE 4-4: The ladder or path of life detection.

FIGURE 4-5: The CoLD scale.

FIGURE 4-6: The tree of life after revisions by Woese in 1990. LUCA = last univ...

Chapter 5

FIGURE 5-1: Earth’s geological timeline.

FIGURE 5-2: The Earth during the Hadean eon undergoing the Late Heavy Bombardme...

FIGURE 5-3: (a) Aerial view of the Jack Hills, Western Australia. (b) 4.4 billi...

FIGURE 5-4: (a) Stromatolites at Shark Bay, Western Australia, present day. (b)...

FIGURE 5-5: Proposed supercontinents on Earth.

FIGURE 5-6: Lifeforms that originated in the Proterozoic: (a) algae; (b) worms;...

FIGURE 5-7: (a) A fossilized trilobite. (b) A horseshoe crab today.

FIGURE 5-8: Reconstructed skeleton of a Tyrannosaurus Rex dubbed “Sue” at the F...

Chapter 6

FIGURE 6-1: From simple to more complex carbon (organic) molecules.

FIGURE 6-2: Ingredients and processes that could have come together to allow li...

FIGURE 6-3: Comparison between the DNA and RNA structures.

FIGURE 6-4: Various forms of RNA working together to build proteins.

FIGURE 6-5: The RNA world hypothesis.

FIGURE 6-6: Lipid structures.

FIGURE 6-7: Details of some cell membrane structures.

FIGURE 6-8: Information flow in biology.

Chapter 7

FIGURE 7-1: Biofilm examples: (a) slimy biofilm in a streambed, MT, USA; (b) to...

FIGURE 7-2: (a) *Flavoparmelia caperata,* a foliose lichen. (b) *Letharia vulpina*,...

FIGURE 7-3: (a) and (b) Creatures whose extinction was caused or hastened by hu...

Chapter 8

FIGURE 8-1: (a) Stanley Miller beside his famous experiment. (b) Diagram of the...

FIGURE 8-2: (a) Haze in Titan’s atmosphere as seen by the Voyager 1 spacecraft ...

FIGURE 8-3: (a) Deep sea “black smoker” vents. (b) Laboratory re-creation of bl...

Chapter 9

FIGURE 9-1: Grand Prismatic Spring, Yellowstone National Park.

FIGURE 9-2: Sully Vent in the Main Endeavour Vent Field of the northeastern Pac...

FIGURE 9-3: Two cold-loving species, (a) the “sunburst lichen” *Rusavskia elegan*...

FIGURE 9-4: A ledge on the side of chimney in the Lost City Hydrothermal Field ...

FIGURE 9-5: Left — Lake Vostok seen from space extending 160 miles (250 km) in ...

FIGURE 9-6: The International Space Station, showing the locations on the exter...

FIGURE 9-7: Tardigrades or “water bears” are the toughest extreme animals.

Chapter 10

FIGURE 10-1: The bright comet Hale-Bopp photographed in 1997.

FIGURE 10-2: The depiction of a comet appearing to soldiers in the Bayeux Tapes...

FIGURE 10-3: Sketches of the appearance of the Great Comet of 1577 in the noteb...

FIGURE 10-4: Appearance of a bright comet.

FIGURE 10-5: Photograph of the dramatic Perseid meteor shower.

FIGURE 10-6: Diagram of the solar system showing location of the Oort cloud, th...

FIGURE 10-7: ‘Oumuamua.

FIGURE 10-8: Illustration of panspermia.

FIGURE 10-9: (a) The European *Giotto* spacecraft; (b) close-up image of Comet Ha...

FIGURE 10-10: The *Stardust* mission: (a) artistic image of the spacecraft in fli...

FIGURE 10-11: The *Rosetta* mission: (a) artistic image of the *Rosetta* spacecraft...

Chapter 11

FIGURE 11-1: Stages in solar-system formation.

FIGURE 11-2: Diagram of the Moon-forming impact scenario.

FIGURE 11-3: Witnessed meteorite falls: (a) flattened trees at Tunguska, 1908. ...

FIGURE 11-4: (a) The 2520-lb Murnpeowie iron meteorite found in the Australian ...

FIGURE 11-5: Carbonaceous meteorites: (a) Orgueil. (b) Allende section, showing...

FIGURE 11-6: Lunar and Martian meteorites. (a) The first known lunar meteorite,...

FIGURE 11-7: Asteroid sample return missions and targets: (a) *Hayabusa*; (b) Ito...

Chapter 12

FIGURE 12-1: Schiaparelli’s 1877 map of Mars where many terrains received their...

FIGURE 12-2: (a) Percival Lowell (March 13, 1855 — November 12, 1916), an influ...

FIGURE 12-3: The NASA *Mariner 4* spacecraft that took the first photographs of M...

FIGURE 12-4: Image of Mars from *Mariner 4* showing cratered landscape, taken fro...

FIGURE 12-5: Distant view of Mars from *Mariner 7*, showing polar caps.

FIGURE 12-6: (a) *Mariner 9* being prepared for launch. (b) Three volcanoes of th...

FIGURE 12-7: Global picture of Mars assembled from images from the *Viking 1* orb...

FIGURE 12-8: (a) Mars exploration rover *Spirit*. (b) Mars *Phoenix*. (c) Mars Scie...

FIGURE 12-9: Bright water ice showing up near to the *Phoenix* lander when the su...

FIGURE 12-10: The “leopard spots” at Chevaya Falls, a sedimentary deposit of mu...

FIGURE 12-11: Gaseous composition of Mars vs Earth air (percentages by volume)....

Chapter 13

FIGURE 13-1: Artists’ renditions of (a) *Pioneer 10* and *11*; (b) *Voyager 1* and *2*;...

FIGURE 13-2: The Grand Tour of the outer solar system, undertaken by the *Voyage*...

FIGURE 13-3: Galilean moons of Jupiter (to scale).

FIGURE 13-4: Schematic diagram of tidal forces between the Earth and Moon.

FIGURE 13-5: Interiors of “ocean worlds” in our solar system.

FIGURE 13-6: Close up of the surface of Jupiter’s moon Europa showing geologica...

FIGURE 13-7: Plumes of water seen erupting from the south pole of Enceladus int...

FIGURE 13-8: (a) Artist’s impression of the *Huygens* probe on Titan’s surface. (...

FIGURE 13-9: Titan azotosomes proposed by Cornell University, composed of nitro...

FIGURE 13-10: Moons of Saturn: (a) Mimas; (b) Tethys; (c) Dione.

FIGURE 13-11: (a) Neptune's moon Triton photographed by *Voyager 2* in 1989. (b) ...

Chapter 14

FIGURE 14-1: Atmospheric temperature profiles of Venus, Earth, and Mars compare...

FIGURE 14-2: (a) Appearance of Venus in the ultraviolet (UV) seen by the *Akatsu*...

FIGURE 14-3: Artistic visualization showing the inhabitants of the Jovian ecosy...

Chapter 15

FIGURE 15-1: The periodic table of elements, with added information about their...

FIGURE 15-2: The history of the universe.

FIGURE 15-3: Life cycles of stars.

FIGURE 15-4: The Taurus Molecular Cloud (TMC-1) imaged by the Herschel space te...

FIGURE 15-5: Examples of complex molecules found in space.

FIGURE 15-6: Creation of absorption and emission lines in space.

FIGURE 15-7: Radio spectrum from the molecular cloud Sgr-B2(N) showing emission...

FIGURE 15-8: (a) The Atacama Large Millimeter-submillimeter Array (ALMA). (b) D...

Chapter 16

FIGURE 16-1: Images of different protoplanetary disks taken with the SPHERE ins...

FIGURE 16-2: Image of the PDS 70 system from ALMA telescope of the ESO.

FIGURE 16-3: Radial velocity (or Doppler) method of exoplanet detection.

FIGURE 16-4: Transit (or eclipse) method of exoplanet detection.

FIGURE 16-5: (a) Artist's impression of the Kepler Space Telescope. (b) The pat...

FIGURE 16-6: Scatter diagram of detected exoplanets.

FIGURE 16-7: The habitable zone.

FIGURE 16-8: Comparison of the TRAPPIST 1 system to our solar system.

FIGURE 16-9: Spectrum of exoplanet K2-18b showing dips in the light due to the ...

Chapter 17

FIGURE 17-1: (a) The Robert C. Byrd Green Bank Telescope (GBT) at the National ...

FIGURE 17-2: (a) The Interplanetary Scintillation Array at Cambridge, used to d...

FIGURE 17-3: The printer chart used by Jocelyn Bell to note repeating radio bur...

FIGURE 17-4: The WOW! signal detected by the Big Ear telescope at Ohio State Un...

FIGURE 17-5: The 64 m (210 ft) Parkes radio telescope in New South Wales, Austr...

FIGURE 17-6: (a) The Pioneer Plaque. (b) The Voyager Golden Record.

Chapter 18

FIGURE 18-1: (a) Nazca geoglyphs known as “the Spider”; (b) the Great Pyramid o...

FIGURE 18-3: A crop circle seen near Lausanne, Switzerland in 2007.

FIGURE 18-2: (a) CIA map of Area 51. (b) U-2 high altitude reconnaissance aircr...

Chapter 20

FIGURE 20-1: Ten of the key open questions in astrobiology today.

Chapter 21

FIGURE 21-1: (a) The *DAVINCI* probe descending through the Venusian atmosphere. ...

FIGURE 21-2: (a) The *Europa Clipper* mission. (b) Concept of future *Europa Lande*...

FIGURE 21-3: (a) The *Dragonfly* Titan aerorover. (b) Proposed Titan sea explorat...



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Introduction

When you first heard the term *astrobiology*, it may have conjured up visions of green aliens in flying saucers — and, let's be clear, that would certainly fall within the scope of the subject. However, astrobiology is a wide and deep scientific field and covers everything from microbial life to the formation of the planets.

The term *astrobiology* only began to be used widely from the late 1990s, when NASA was searching for a way to describe a new program to understand the origin and prevalence of life in the universe. However, astrobiology is really a very old field: a modern way to ask questions that have occupied humans for eons.

- Where did life come from?
- Is there life elsewhere in the universe, not on Earth?
- Are there other technological civilizations out there, trying to communicate or even visit with us?

Astrobiology is therefore a big melting pot with all the fun subjects from grade school thrown in: from the fate of the dinosaurs to space travel, from boiling hot springs to freezing polar ice caps, from green slime molds to green-skinned aliens landing their UFOs. No kidding: astrobiology is *seriously* fun! (But *ssh*, don't tell everyone.)

So, what's the day-to-day life of an astrobiologist? We're not quite at the point of chatting with aliens on Tau Ceti b yet, but some of us are out there looking. Although some astrobiologists are staring through telescopes on mountaintops, trying to figure out what other planets are made of, others are in the lab zapping bacteria with radiation to see whether they could survive a space journey to Mars. Yet others are out collecting meteorites in the Arabian desert while their office mate is back home writing computer programs to figure out how stars explode. It's a pretty fun gig, as jobs go.

One practice that almost all astrobiologists love to engage in is communicating their work to others. This isn't just an exercise of necessity, trying to drum up federal funding dollars for their latest idea. It's a genuine passion to convey their enthusiasm and knowledge to others. Often, they don't have to try hard to get a willing audience. There's always someone at a dinner party wanting to know if the government *really* has alien bodies stashed in the Nevada desert, or what's going on with that new comet that's been in the news a lot recently? The questions come thick and fast.

This book is therefore my attempt to answer a lot of these questions for a lot of people at once.

About This Book

In this book, you'll be coming along on a pretty wild roller-coaster ride through a ton of fun topics. For starters, you'll get to know what prompted night-owl astronomers and bug-hunting biologists to team up to try to solve the biggest mysteries of the universe, creating the new field of astrobiology. You'll see how the big questions of astrobiology have been kicked around for ages, causing thinkers from Aristotle to Einstein to scratch their heads.

From the biology perspective, you'll get a crash course in life, from the smallest to the largest creatures, and see how these developed over time from evidence in fossils. You'll learn how a cell works, and why some cells may have decided to team up together to make the larger multicelled entities, including us. You'll even see how some experiments are trying to recreate the origin of life in a test tube.

Next, you'll journey out into space, starting with our local planets. You'll visit Mars, Venus, and the moons of Jupiter and Saturn, learning why and where scientists are probing around in the dust, soil, and water for life. You'll get to know some of the most famous spacecraft sent by NASA and other countries to find out if other worlds may be habitable.

And then onwards to interstellar clouds, exoplanets hot and cold, and the possibilities of alien civilizations building spheres around their Suns to

capture energy. Are they trying to communicate with us? And would we understand them if they did? Finally, you'll see how astrobiology has permeated our culture and arts deeply, from that alien on the hamburger box at the fast-food restaurant to the games on your smartphone.

But I'm getting ahead. The cool thing is that how you use this book is up to you. You can read each chapter in any order you like, so start now and flick ahead to your favorite topic, or just curl on the couch and dig in at chapter 1, and let the book unfurl from the beginning. It's time to choose your own adventure.

Foolish Assumptions

I'm assuming that you have picked up this book because something about the title of *Astrobiology For Dummies* piqued your attention. Maybe it was the picture of a perky rover on the front cover. Maybe you've already heard of astrobiology and want to know more. Or maybe you haven't heard of astrobiology at all, and wonder what in the world it could be about? Whichever it is, I'm assuming that you are curious enough at this point to know more, and so I'm going to make it easy and fun for you to find out.

I'm *not* assuming that you know anything about astrobiology at all (although if you do, you may already be one of my colleagues, in which case, Hi!) Everything in the book is therefore explained in the easiest terms possible, although there may be some things that are just a bit more complicated than others, which are clearly labeled.

If you have an interest in finding out about astrobiology and you can read pretty well, you'll be able to understand everything in this book. (If not, give it another read after a good night's sleep.)

Icons Used in This Book

Throughout this book, helpful icons highlight particularly useful information — even if they just tell you to not sweat the tough stuff. Here's what each symbol means:



REMEMBER The string-tied-on-a-finger icon points out information you should file away for future reference.



TECHNICAL STUFF This nerd symbol appears beside discussions you can skip if you just want to know the most important stuff and not the nitty-gritty details. Skip over and come back to these parts later if you decide to dig deeper into a topic.



TIP This lightbulb tells you a fun or interesting fact that you can bring up to amaze others.



WARNING This sign lets you know when some of the science is unclear or uncertain, so we can't be too sure about it. Sometimes it flags when something went wrong in the past or something we should be careful about in the future (like touching any space bugs we find with our bare hands).

Beyond the Book

In addition to what you're reading right now, this product comes with a free access-anywhere Cheat Sheet that provides lists of fun astrobiology-related activities and events. To get this Cheat Sheet, simply go to www.dummies.com and type *Astrobiology For Dummies Cheat Sheet* in the Search box.

Where to Go from Here

You're now ready to start diving into the book anywhere you want. As you go along, you may be craving additional info or to see more pictures related to a topic, so the Internet will be your friend here.

I suspect that some of you are budding grade school or college undergraduates who really want to get involved in astrobiology research yourselves, in graduate education or beyond. In that case, I suggest you comb through news articles and even scientific papers on Google Scholar to see which scientists are publishing on what topics and then reach out to them by email. You'll be surprised how often you get a response, since researchers love to hear from enthusiastic students. NASA's astrobiology program at https://science.nasa.gov/astrobiology also has a ton of useful information and links.

Astrobiology is an adventure, so don't be afraid to jump in and get your metaphorical feet wet (just watch out for metaphorical sharks). In astrobiology, there are no wrong questions, and nothing too crazy to ask. Sometimes the craziest questions lead to the biggest breakthroughs.

Have fun and stay curious. And if you see ET, say hi from me.

Part 1

Getting Started with Astrobiology

IN THIS PART …

Discover the scope of astrobiology and take a brief tour through the whole field to get your bearings.

Find out the history and origins of astrobiology, from ancient thinkers through the scientific revolution to the modern era.

Learn how astrobiology is conducted today, from laboratory and field experiments on Earth, to astronomy and space probes.

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Chapter 1

Astrobiology in a Nutshell

IN THIS CHAPTER

- **Knowing the "big questions" that astrobiology seeks to answer**
- **Learning the range of topics covered in astrobiology**
- **Getting a glimpse of what's in store later in this book**

On a clear summer night perhaps you've gone outside, looked up at the thousands of glittering stars in the sky, and wondered what and who is out there in the universe. You may even have asked yourself if there are any intelligent lifeforms on a planet circling one of those stars who, right now, are perhaps looking back up toward *you* and wondering if you exist!

Or maybe you've pondered a photograph of a bizarre deep-sea creature or a weird-looking microorganism under a microscope and wondered why it looks that way, and whether it could have ended up appearing differently. You may even have wondered how long humans have been around on Earth to ask these questions!

If you've thought about any of these conundrums, then congratulations, you're in good company. These mysteries have kept human thinkers and philosophers awake at night for millennia, from Aristotle to Einstein, along with most of the rest of us at some point in our life. But wait, can we really answer these questions? If they've been around for so long, what hope do we have to answer them now?

The good news for curious minded among us is that in recent decades we have made enormous progress toward finally unraveling some of these mysteries. Although we don't know everything yet, we now have reason to believe that these questions are indeed solvable, and that the answers may even be just over the horizon. The new field of scientific

study that has emerged to probe these questions is *astrobiology*, the subject of this book.

Asking the Big Questions

Because you've picked up this book, I already know something about you — that you're extremely curious about two big questions:

- How did life start on Earth?
- Is there life elsewhere?



REMEMBER Finding the answers to those questions is the ultimate goal of *astrobiology*, which could be stated as the field devoted to "*understanding life in the universe.*" Think *astro* = stars, plus *biology* = life. That wasn't so bad, was it?

Well, yes and no. It turns out that asking the questions is the easy part! Answering those questions is considerably harder, and has been vexing philosophers, theologians and scientists for millennia. In Chapter 2, I explain some of the historical thinking and theories that laid the groundwork for present day astrobiology.

Sometimes astrobiology is defined to include these questions:

- What environments are habitable?
- What is the future of life in the cosmos?



TIP Note that we make a distinction between *habitable* (somewhere that life *could* exist) and *inhabited* (somewhere that life *does* exist). Through the course of the book, I explain which environments we think are habitable as part of the wider search for life.

Regarding the future of life, this is quite an open-ended subject, and one that's not much constrained by our current scientific knowledge. However, you'll learn some ideas on this topic when I discuss advanced extraterrestrial civilizations (see Chapter 17), and the close relation between astrobiology and science fiction (see Chapter 19).

The Scope of Astrobiology

The scope of the present-day field of astrobiology encompasses both the origins of life on Earth, and the search for life elsewhere. Tools and techniques used by modern astrobiologists include:

- Giant telescopes on the Earth and in space.
- Space missions to explore environments in our solar system.
- Cutting-edge laboratory experiments to analyze samples from the Earth and space, and to probe the workings of biology.
- Expeditions to collect samples from extreme locations on Earth — such as polar regions, high deserts, volcanoes and the deep sea — and from space.
- Computer simulations of life's origins and evolution, and of cosmic environments.

Origins of Life on Earth

One of the two key questions of astrobiology tackled in this book is to understand the origins of life on Earth — where do we come from?

Defining life

A precursor even to finding life's origin is to define "life" — after all, we can't search for something if we don't know exactly what we're looking for. This perhaps seems simple at the outset, but turns out to be trickier than it looks.



TIP NASA has formulated a concise definition: "Life is a self-sustaining chemical system capable of Darwinian evolution." This works well in most circumstances, but isn't perfect. For example, it excludes the possibility that a computer-based intelligence could ever be considered alive.

Although it's proven difficult to arrive at a universally acceptable and robust definition of life, the process of searching for a definition may have been as useful as the (elusive) result itself. By trying to define life, we explore the boundaries in a productive way that enlarges our understanding.

Classifying life

After we've decided for the most part what is "in" and "out," an important process is to sort and categorize the various types of life we observe — a subdiscipline known as *taxonomy*. This was a key undertaking during the scientific revolution that helped to define the modern field of biology.



REMEMBER Besides helping us to organize our butterfly collections, the process of taxonomy led to the realization that various forms of life are more or less closely related to each other, and resulted in the "tree of life" — an organizational diagram that continues to be refined today.



TIP The tree of life encompasses not only present-day specimens, but also evidence of earlier animals and plants in the fossil record, leading to a linking of the fields of geology, paleontology, and biology.

This tree of life and the idea that diversification progressed over time, albeit in fits and starts, led to the concept of evolution (the branching of the tree), and even the idea of a "last universal common ancestor" (LUCA) — a hypothetical single-celled organism from which all other life subsequently evolved — the "trunk" of the entire tree of life.

Understanding the earliest life

The idea of a simple, universal common ancestor takes us to the heart of question 1: the origin of life on Earth. Today, paleobiologists and astrobiologists seek to understand how life made the leap from non-biological ingredients to the simplest self-replicating organisms.

They want to know how the first cells formed, and subsequently diversified. I explain ideas about this in Chapter 6, which although not yet definitive, are certainly progressing. I also describe the key distinction in the tree of life between two types of organisms: eukaryotes and prokaryotes — cells with and without a distinct nucleus.



REMEMBER Eukaryotes are the entry point to the study of multi-cellular life, since all multicellular lifeforms (including us) belong to the gang of eukaryotes. In Chapter 7 I explain the advantages of multi-cellularity, such as allowing cells to cooperate and specialize to perform different tasks like workers in a factory. This gives us some neat evolutionary advantages over our unicellular cousins, often allowing us to survive in a wider range of environments.

Since sadly we don't yet have a time machine that would take us back to Earth's past to observe the earliest stages of evolution in action, scientists instead try to replicate some of these processes in the lab. A famous example is the Miller-Urey experiment, which showed that complex ingredients can be formed from simpler ones relatively easily under the right conditions.



TIP Other fascinating experiments include the creation of minimal organisms and artificial life forms, and even life simulations *in silico* — inside the memory of a computer.

Probing life's limits

I mentioned that astrobiologists are interested in the limits of life on Earth, since that informs us about where we can search for life in space. This leads to the study of *extremophiles*, life forms that can survive the most challenging environments known on Earth.

These range from frigid polar terrains, to boiling hot springs, and from high-pressure, deep-undersea locations to the vacuum of space. Some extremophiles love salty plains, whereas others prefer acidic baths, alkaline springs or arid deserts. Extremophiles include many single-celled creatures, but some larger ones as well, such as the hardy little tardigrades, sometimes called "water bears."

Searching for Life in Our Solar System

The second part of astrobiology focuses on the search for life in space. This takes us out into the solar system, including the study of materials in comets and asteroids, to the characteristics of other planets and moons.

Comets and meteorites

Comets were once-feared omens and harbingers of disaster that are now known to be not messengers of the gods, but giant dirty snowballs. Comets are among the most pristinely preserved precursors of our modern solar system, leftovers from the giant celestial baking experiment that produced our planets and moons.



TIP Comets are of intense interest to astronomers, as they provide clues not only to the simpler materials that comprise the solar system worlds, but also to our oceans and even the origins of life itself.

Another class of primitive bodies are meteorites and their parent bodies, which are (mostly) asteroids. Some meteorites are remnants from the earliest eras of solar system formation and even before, including grains from earlier stars and solar systems than our own.

Meteorites were somewhat belatedly identified to arrive from space in the 1800s and today are classified as either *falls* (witnessed falls from space) or *finds* (meteorites found without a witnessed fall). I'll explain what has been learned from the collection and study of meteorites, as well as from asteroid samples directly collected at the source and returned to Earth.

Planets and moons

The planet Mars has been a perpetual fixture in astrobiology for hundreds of years, giving us visions of canal-building farmers and fearsome invaders. However, since our first landings on the red planet in the 1970s our understanding of Mars has changed profoundly, to a vision of an uninhabited and dusty barren desert. Yet Mars has not yielded up all its secrets yet, and scientists continue to delve for clues of extinct or even extant life beneath the soil, with today's rovers and future sample return missions.

In the past several decades, significant astrobiological focus has shifted toward the moons of the outer known solar system, now known to include many "water worlds" within vast oceans inside. These include Jupiter's cracked-up moon Europa, and Saturn's active satellite Enceladus. You'll learn what evidence exists for watery oceans inside these worlds, and our current best understanding of their habitability and potential for life. I also describe current deep space missions, as well as

future missions we hope to send to learn more about worlds such as Titan and Triton.

Finally, some scientists are pursuing ideas of exotic life in the clouds of Venus, Jupiter, and other gas planets. Despite being perhaps fanciful and remote possibilities, these ideas help to push the boundaries of potentially habitable environments, making sure that no stone (or cloud droplet) is unturned in our search for life, which may well surprise us by differing greatly from life on Earth. One lesson we have learned from extremophiles is not to be too conservative in where we look.

Life beyond Our Solar System

Whereas our solar system includes many fascinating and yet-unexplored possible habitats for life, these pale into insignificance when compared to vast expanse of space, including the other stars and their planetary systems in our galaxy, and beyond to innumerable other galaxies.

Astrochemistry is the field that seeks to identify complex chemicals in space. I describe the tools of the trade, especially the workhorse radio telescope, and show how far and fast astronomers are expanding our inventory of space substances, from carbon *buckyballs* to space sugars.

Today many astrobiologists are focused on exoplanets — planets orbiting other stars in our galaxy, which already vastly outnumber the eight planets in our own solar system by a factor now approaching a thousand to one! You'll learn in this book how exoplanets were first discovered and what are the closest, hottest, largest and most Earthlike examples yet known. Be aware though, the subject matter is literally changing every day, so always be sure to check online for the latest news and results.

The search for extraterrestrial intelligence (SETI), is what many people first think of when life in space is mentioned. SETI is guided by the Drake Equation, a simple formula which seeks to place a value on the number of extraterrestrial civilizations that we could communicate with today. I'll explain some of the false starts and dead ends that have historically given SETI a bad rep over the years, but also how modern

SETI is seeking to put the search for aliens on a more robust and scientific footing.

Astrobiology and Culture

Later in the book I discuss some fun cultural topics around astrobiology, including hoaxes and conspiracies (see Chapter 18) and astrobiology in the arts (see Chapter 19). From the "ancient aliens" and pyramid builders of pseudo-factual conspiracy books and TV documentaries to the outright engaging fictions of sci-fi novels, games, TV series, and movies, you'll see how far the human imagination stretches when it comes to imagining aliens.



REMEMBER These fictions do however often serve a useful purpose to advance science and technology, by challenging our ideas of what is possible in astrobiology, and inspiring and motivating budding sci-fi fans to go into serious science in later life.

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Chapter 2

Origins of Astrobiology

IN THIS CHAPTER

- **Learning about humanity's quest to understand the universe with astronomy**
- **Understanding how the field of biology grew to explain life on Earth**
- **Finding out how astronomy and biology came together to form astrobiology**

Where does the field we call *astrobiology* come from? Can we trace the roots of scientific thinking about the origins of life, from the earliest recorded history to the present? And how have our questions changed over time as we've acquired more knowledge about the nature of life?



TIP In this chapter, you begin your journey of discovery into astrobiology by seeing how the field started — with the questions of ancient peoples and a multitude of ideas. You learn how, over time, theories were proposed and tested, and science moved from primarily philosophy to experimentation during the scientific revolution. By the end of the chapter, you'll be ready to delve into the questions and techniques of modern astrobiology in Chapter 3.

The field of astrobiology draws from many other scientific fields: chemistry, physics, geology, and others. But at its heart, it is the fusion of two disciplines in particular: *astronomy* — the study of the universe, and *biology* — the study of life. So, to understand where astrobiology comes from, you need to appreciate the intertwined origins of these two fields.

Watching the Night Sky

Astronomy — the study of the night sky, the stars, planets, and all objects off Earth — has evolved over time as technologies improved, especially after the invention of the telescope. For the very first astronomers, the naked eye was all there was to use, yet careful observation still enabled them to ask very deep questions.

Ancient observers

Imagine you're a member of a clan of ancient hunter-gatherer people, huddled around a campfire on a cool autumn night. The sky is clear and full of twinkling points of light, and a dim, pale band of whiteness arcs from horizon to horizon like the stroke of paintbrush. Early peoples likened this to spilled milk, calling it the *milky way*.

The points of light would become known as stars, and every people on Earth would become fascinated with them, incorporating them into many aspects of their cultures. Why were some brighter than others? Why did some appear to be grouped together while others were solitary? Star gazers would see patterns in their arrangements, giving these *constellations* (star groupings) names such as the Plough, the Great Bear, the Hunter, and more.



TIP Check out *Stargazing For Dummies* by Steve Owens or *Astronomy For Dummies* by Stephen P. Maran and Richard Tresch Fienberg (both Wiley) to learn more about making your own observations and recognizing constellations.

Although the heavens might appear quite still and static at first glance, careful observers noticed changes over time. Some of the brighter points of light moved! These five remarkable objects would become the *wandering stars* and acquired the highest cultural significance, often being associated with major deities. In the English-speaking world today, these are the *planets*: Mercury, Venus, Mars, Jupiter, and Saturn. You revisit them in more detail later in the book.

Planets weren't the only things in motion. A patient sky watcher would eventually be rewarded with the sight of *shooting* or *falling stars*. Good grief! Some of the stars were literally falling out of the sky, tracing a brief trail and then vanishing forever. Seeing a shooting star was often associated with a change of luck, but today we know them as *meteors*, and if one survives intact to reach the ground, a *meteorite.* If you're impatient to learn about meteorites, skip ahead to Chapter 11.

Even rarer were *comets*, new stars that appeared in the sky for sometimes months on end, moving slowly onwards and growing vast tails like a serpent or dragon. These terrifying visitors often became associated with major upheavals in society: revolutions, wars, and the like — although the comets themselves — innocent balls of gas and dust tracing a cosmic display — knew nothing of these associations. You learn more about comets in Chapter 10.

Finally, let's not forget the grandest points of light of them all — the Sun and Moon.

The Sun was often imagined as fiery chariot, the all-important giver of warmth, permitting the crops to grow and all life to exist, and frequently associated with fierce male deities. Ancient peoples noted carefully that the Sun rose higher and longer in the summer, and traversed lower and for less time in the winter, and based their entire lives on planting, harvesting, feasting, and celebrating around this annual cycle.

The Moon, cooler and more mysterious, was most often seen when the Sun was gone, but it had its own vital significances. The correspondence of its monthly (or "moon-thly") pattern of waxing and waning with the monthly cycle of a woman's fertility could not be overlooked, and hence the Moon was most often associated with female deities. She was also often associated with romantic love, for reasons that nighttime couples seeking solitude after workday duties and away from prying eyes will understand intuitively.

The importance of celestial motions — both for practical purposes such as planting and calendar keeping, and for their imagined influence on human affairs — gave rise to two prominent and important professions.

Astronomers were primarily methodical observers and record keepers, whereas *astrologers* concerned themselves with interpretation of heavenly changes, predicting future human fates and fortunes based on the configuration of the stars at important times in human lives such as birth, marriage, and maternity.



TIP *Astrology For Dummies* by Rae Orion (Wiley) is a great starting point to learn more about this belief system.

Philosophers of the universe

As primitive cultures morphed into more complex civilizations and systems of writing and mathematics were developed, philosophy began to emerge as a separate and distinct tradition from religion. Not surprisingly, many philosophers thought long and hard about the origin of life, the relation of the Earth to the heavens (cosmology), and even the possibility of other intelligent lifeforms that we had not yet made contact with.

A great many thinkers contributed to this area of knowledge over time, too many to list here, but a few of the most important figures in the early development of western cosmology were:

- **Anaximander** (c. 610–546 BC), who suggested that the Earth was a disk free-floating in space, ingeniously allowing the Moon, Sun, and stars to pass underneath when they were out of sight. He placed the stars, Sun, and Moon on vast distant wheels circling the Earth, but placed them in the wrong order, with the stars closer than the Sun and Moon.
- **Pythagoras** (c. 570–495 BC) was a philosopher and teacher of mathematics who acquired a cult following (Pythagoreans) based around his mystical reverence for numbers and their effects on all aspects of life. In cosmology, he is associated with the origin of the idea of a spherical Earth, and that the heavenly bodies moved on

perfect geometric solids and produced music inaudible to the human ear.

- **Anaxagoras** (c. 500–428 BC) was a prolific thinker who proposed many novel and important ideas far ahead of his time. These included descriptions of the Sun as a ball of red-hot metal, the stars as hot stones, and the Moon as composed of earthly material, complete with mountains and inhabitants, shining with reflected light from the Sun. He recorded and attempted to predict the fall of meteorites, and was one of the first to write about *panspermia*, the notion that life is prevalent in space.
- **Aristotle** (c. 384–322 BC) built on early ideas of Anaximander and others, developing a highly refined model of the heavens as a series of concentric crystal spheres. So-called "terrestrial spheres" of water, earth, air, and then fire were enclosed within the heavenly spheres carrying the planets, Moon, and most distant stars, eternal and incorruptible. Aristotle's *geocentric* universe (that is, placing Earth at the center of the cosmos), with later refinements by Ptolemy, survived as the dominant cosmological model in western civilization for two thousand years.
- **Aristarchus** (c. 310– 230 BC) proposed the first known heliocentric model of the universe, with the Sun at the center rather than the Earth. The Earth revolved around the Sun once a year and rotated once per day on its own axis. However, in the absence of evidence, the Ptolemaic model of the universe had too strong a hold on thinking and continued right up to the Copernican revolution.
- **Claudius Ptolemy** (c. 100–160 or 170 AD) is noted for his prolific scientific writings, and in particular for his detailed (and incorrect) geocentric model of the universe, with all the planets and the Sun revolving around the Earth. To make the calculations work accurately, he devised a highly detailed model of epicycles ("circles within circles") that became the standard astronomical model for over 1,000 years.
- **Nicolaus Copernicus** (1473–1543 AD) proposed (or re-proposed) the heliocentric model of the universe, reviving the suggestion of

Aristarchus 1,800 years earlier. His book on the topic ushered in a new era of astronomy (the Copernican Revolution) and contributed to the wider Scientific Revolution that soon got underway.

- **Giordano Bruno** (1548–1600 AD) was an Italian philosopher who expanded on the ideas of Copernicus. Bruno proposed that the distant stars were themselves suns and surrounded by their own planetary systems — anticipating the discovery of exoplanets some 400 years later. You'll get to hear more about Bruno in Chapter 16.

The telescope arrives

Human civilizations up to the start of the Renaissance period in the 14th century AD (using the Western calendar) would not have clearly distinguished between nascent scientific studies such as astronomy and mathematics, and belief systems including astrology and religion.

A major turning point was the invention of the telescope (and its counterpart, the microscope — see next section), which enabled more accurate tracking of stellar movements, and the ability to see the surfaces of the Moon and planets much more closely. A huge shock came when Galileo Galilei (1564–1642 AD) first turned his telescope to examine the planets Jupiter and Saturn in 1610 (see Figure 2-1).



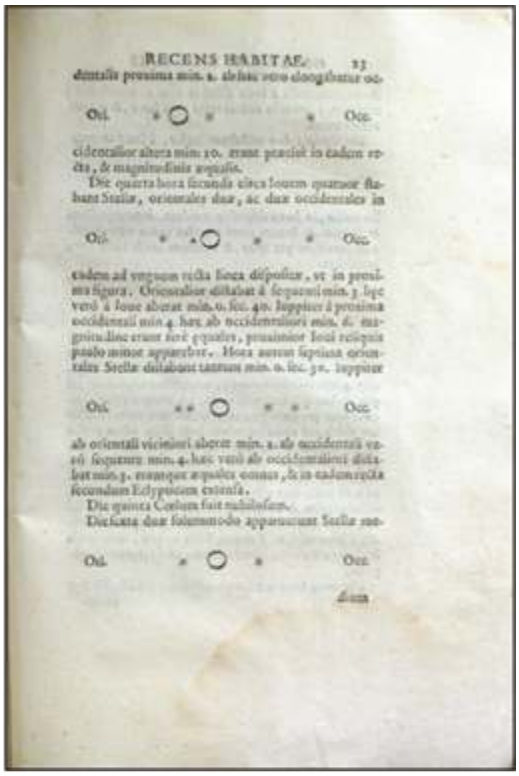
REMEMBER To Galileo's amazement, Jupiter was clearly accompanied by a retinue of *four moons*, a discovery whose importance cannot be overstated. Up until this point, the position of the Earth as the center of the Universe was clearly established and widely believed — the heretical ideas of Copernicus in the 16th century placing the Sun at the center instead notwithstanding.

Although Copernicus's mathematical genius in simplifying the calculation of planetary motions by placing the Sun at the center of the solar system had been recognized, most astronomers and philosophers considered this to be a mathematical trick only, not a true reflection of the actual cosmic situation. However, Galileo had now shown that other

planets could have moons just like the Earth, indeed *even more moons*, demoting the status of Earth from the center of the Universe to just one of a number of planets in the Sun's retinue.



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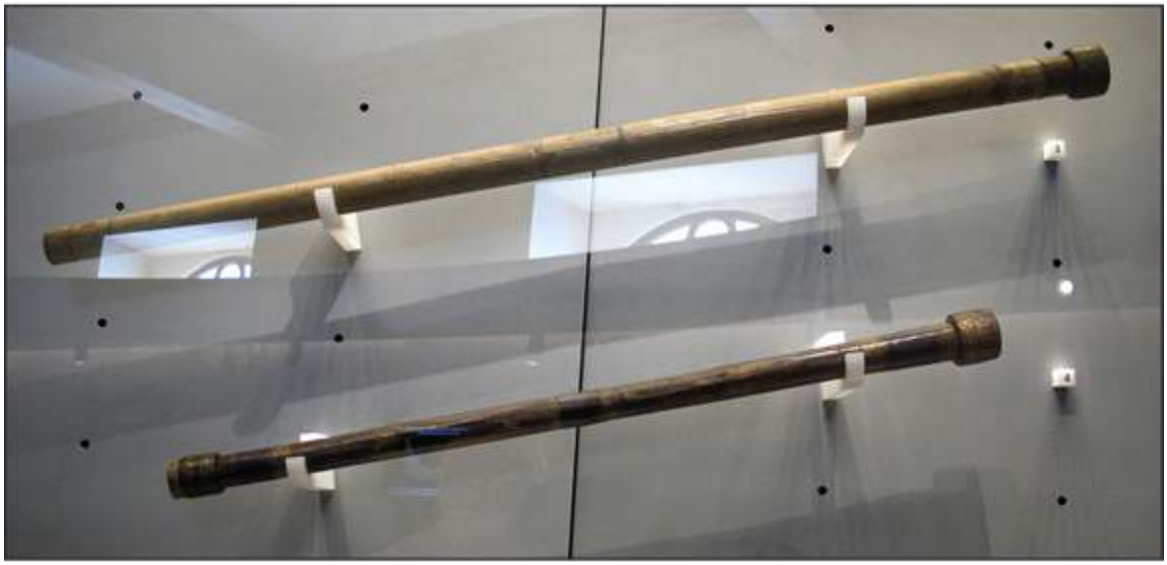
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min. 3. eramque æquales omnes, & in eadem recta
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Die sexta duæ solummodo apparuerunt Stellæ me-

Occ. * ○ * Occ.

(b)



(c)

(a) Justus Sustermans/Wikimedia Commons/Public domain (b) Sailko/Wikimedia Commons/CC BY-SA 3.0 (c) Galileo Galilei/Wikimedia Commons/Public domain

FIGURE 2-1: (a) Portrait of Galileo Galilei. (b) Galileo's writings and diagrams showing the large moons in movement around Jupiter. (c) Telescopes suspected to have been used by Galileo.



TIP Soon after Galileo's discoveries, other astronomers rushed to take up the use of telescopes, and the field of astronomy was irrevocably transformed. You meet many other astronomers and their discoveries in Parts 3 and 4 of this book, and you can check out *Astronomy For Dummies* by Stephen P. Maran and Richard Tresch Fienberg (Wiley) for even more information.

Another important scientist from this period was Christiaan Huygens (1629-1695 AD), a Dutch polymath whose work ranged widely across many areas of physical sciences and engineering, including the discovery of Saturn's moon Titan (see Chapter 13). In his very last writings, he speculated on the existence of extraterrestrial life, proposing that dark markings on Mars and Jupiter could be evidence for water, and suggested that where there was water life could be found — presaging some important ideas of present-day astrobiology.



TIP From the Renaissance period onwards, the separation of astronomers and astrologers accelerated, as astronomers focused on observable and repeatable experiments and testing falsifiable hypotheses, while astrologers focused on adding further layers and complications to a sophisticated but unprovable system of beliefs and mysticism.

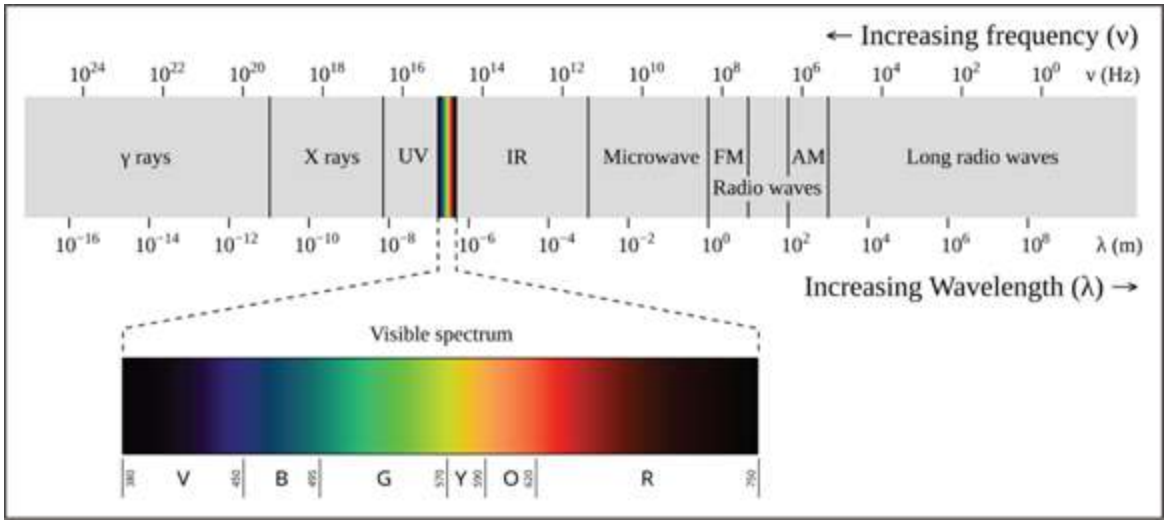
Beyond the visible

Astronomy initially focused (no pun intended) on using telescopes that amplified the capabilities of the human eye, which in fact is only sensitive to certain types of light called the *visible spectrum.* Over time,

scientists discovered that there are many other types of light (aka *electromagnetic radiation*) — for more on this, see *Physics For Dummies* by Cynthia Phillips and Shana Priwer (Wiley).



TECHNICAL STUFF Light (or EM radiation) can be thought of as a wave of energy, and like an ocean wave, waves can be long and broad, or closely spaced. The distance between crests is called the *wavelength.* Visible light has a medium wavelength, whereas light with longer wavelengths becomes invisible infrared (IR), microwave, or radio waves. At the shorter end of the scale, or spectrum, light with wavelengths too short for the human eye to see become ultraviolet (UV), X-rays, and gamma rays (see Figure 2-2).



Philip Ronan/https://commons.wikimedia.org/wiki/File:Electromagnetic_radiation_spectrum_-_en.svg/CC BY-SA 2.5/last accessed Oct. 10, 2026.

FIGURE 2-2: The electromagnetic (EM) spectrum. Numbers attached to the visible spectrum are wavelengths in nanometers.



TIP Many of these waves are blocked by molecules in the Earth's atmosphere, excepting mostly the longer radio waves and

microwaves. After World War II, the science of *radio astronomy* began to explore the use of radio waves to learn about the large-scale structure of the universe, and to listen for alien radio broadcasts (fast-forward to Chapter 17 if you're anxious to learn more about that topic).



TIP However, in space, all types of EM waves are emitted by planets, stars, and galaxies, so we can find out valuable information about them if we can detect all their emissions as IR, UV, X-rays, and gamma rays. As the space age progressed from the 1960s, spacecraft began to be launched that could tune in to these exciting and often energetic waves. See *Astrophysics For Dummies* by Cynthia Phillips and Shana Priwer (Wiley) for more details.

Now that you've had a background in the development of astronomy, let's turn our focus to biology.

Wondering about the Origins of Life

Although astronomers were concerned with the very large, other scientists (and sometimes even the same scientists) became interested in the very small. Ideas and discoveries about the atoms and elements were important to developing the field of chemistry, which later became the underpinning of modern biology.

Atoms and elements



REMEMBER The idea that matter cannot be divided infinitely — that eventually there is a "smallest piece" — is called *atomism* and is traceable back to the Greek philosophers Leucippus and his pupil, Democritus (460–370 BC). Democritus wrote extensively on atoms, postulating that:

- There are many different kinds of atoms (he envisaged them as smooth and rough, concave and convex, some with hooks and some with holes).
- There is only matter and void (nothingness). All atoms have always existed.
- Atoms are constantly in motion, colliding with others and sticking together. Everything that is not void is therefore a combination of different types of atoms combined in different ways.
- We experience different kinds of atoms using our senses. Although we can't see the very tiny individual atoms, we can experience their properties through senses like taste and smell.

Although *wrong* in details, we now know that Leucippus and Democritus were *correct* in the broad sense (check a periodic table of the elements if you need reminding).



TIP Unfortunately, chemical thinking soon took a wrong turn. Democritus' contemporary Plato (c. 425-348 BC), and later Aristotle (see earlier) became enamored of a simpler, more idealized view of the four elements: air, fire, water, and earth, which was to hold sway for over two thousand years.

Atomism was gradually revived in fits and starts through the Age of Enlightenment, and Scientific Revolution. But it finally became mainstream thinking in the early 1800s, when Englishman John Dalton conceived his Law of Definite Proportions. Using careful measurement, he showed that substances such hydrogen and oxygen always combine in simple proportions to each other, such as $2H + 1O = H_2O$ (water).



REMEMBER The 19th century saw incredible advances in chemistry, including the ordering of elements into the periodic table in 1871 by Russian Dmitri Mendeleev. Finally, in the early 20th century, the nature of elements became clear when the structure of the atom was unraveled and the nucleus discovered.

Theories on the origins of life

Many of the same philosophers who speculated on the origins of inanimate matter extended their theories to also include animate matter — life.



REMEMBER A key debate for millennia concerned *spontaneous generation*, the idea that the living could spring directly from the nonliving. In this way, mice could spring from an unattended bag of grain, for example, or maggots from meat.

Let's look at the development of some key ideas:

- **Anaximander** (c. 610–546 BC) believed that living matter came from the elemental matter of the universe. In this he may have been right, as scientists now pursue the details of *abiogenesis* (the idea that life first originated from inorganic substances; see Chapter 8). However, in the details he was wrong, suggesting, for example, that fish were produced by the action of sunlight on water. (He missed a few steps.)
- **Anaximenes** (c. 586–526 BC), and later **Anaxagoras** (c. 500–426) believed that life came from a primordial slime — in some senses quite correct. However, the lack of chemical knowledge at the time led Anaximenes to propose a much-simplified version of what we now understand abiogenesis to be, with the element air imparting life into inanimate combinations of earth and rock through its vital motion.

- **Aristotle** (c. 384–322 BC) believed in both sexual reproduction as well as the spontaneous generation of life. He proposed that males provided a structure and plan for the child through their seed, whereas the female provided the materials to construct the organism through her menstrual blood. However, in his writings he also left room for some animals and plants to be generated entirely from the earth, aided by the Sun.

As with the existence of atoms, the question of spontaneous generation was to remain open for more than two millennia, proving difficult to solve one way or the other by philosophy alone. It was only through diligent experimentation that the problem was finally put to rest in the 19th century by Louis Pasteur, whom you'll meet in the next section.

Investigating the very small

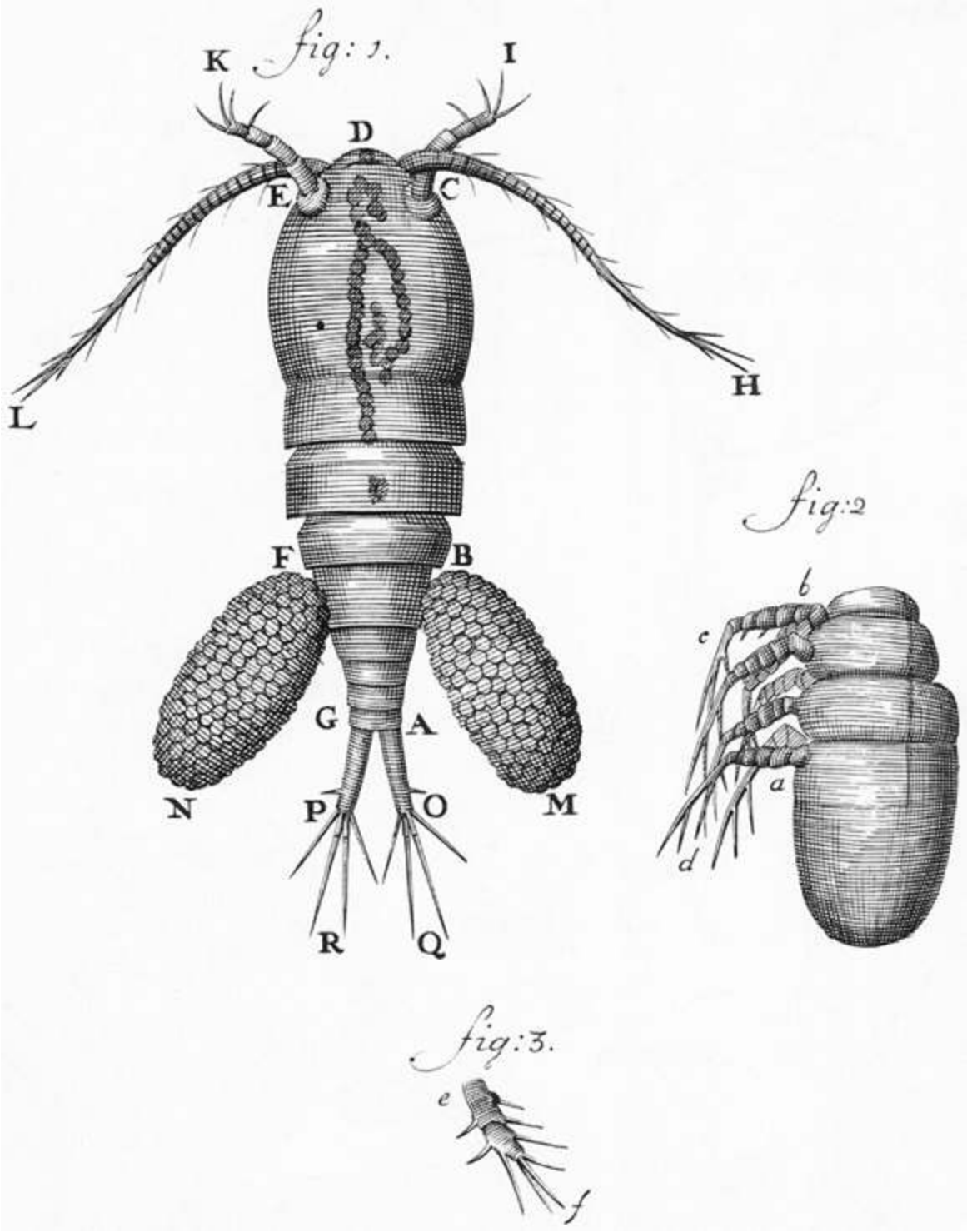
The invention of microscope was just as transformational for biology as the telescope was for astronomy and occurred around the same time.

Dutch draper and inventor Antonie van Leeuwenhoek (1632-1723) is credited as the father of microbiology. Although magnifying glasses were by then in common use, van Leeuwenhoek perfected methods of making much higher magnifications (mainly through heating and then drawing rods of glass to make high powered lenses).

With his new optical devices, van Leeuwenhoek went on to make extensive studies and drawings of previously unseen microscopic creatures and objects, including red blood cells, human spermatozoa, muscle fibers, single-celled organisms (protists) such as amoebae, and much more. For his discoveries and extensive writings and drawings (see Figure 2-3), Van Leeuwenhoek was elected to the Royal Society of London in February 1680.

French chemist and biologist Louis Pasteur (1822-1895) is credited with finally debunking the notion of spontaneous generation. While investigating winemaking at the behest of a friend, he was able to finally prove that alcohol was generated not through decomposition of purely dead plant matter, but through the fermenting action of yeast. If there was no yeast, there was no fermentation.

His demonstration that spoilage is due to living bacteria was seminal in the development of biology. By taking two identical flasks of soup, boiling both to sterilize the contents, and leaving one open to bacteria and one sealed, he was able to show that without fresh air (and fresh bacterial invaders) the flask did not spoil. This paved the way for subsequent breakthroughs in understanding diseases and gave birth to the modern *germ theory of disease*.



Antoni van Leeuwenhoek/Wikimedia Commons/Public domain

FIGURE 2-3: An exquisite drawing from 1699 by Antonie van Leeuwenhoek of a female cyclops, a tiny freshwater crustacean.

We now come to three of the most fundamental underpinnings of modern biology — the Theory of Evolution by Natural Selection, its associated Mendelian Heredity and finally the explanation of heredity by genes and DNA.

Evolution by natural selection

The *theory of evolution by natural selection* was conceived by two British biologists in the mid-19th century: Charles Darwin (1809-1882), and Alfred Russell Wallace (1823-1913). At the time, species of animals and plants were widely thought to have existed forever, with beginnings from the biblical story of creation. However, mounting fossil evidence — that some species that had once lived were now extinct and had become replaced by newer species — began to pressurize that notion.



REMEMBER Darwin and Wallace, through extensive personal voyages of natural exploration around the world, had both noticed that different species appear adapted to their particular environment, and wondered what could cause that to happen. Eventually they independently hit upon the notion of natural selection, which works as follows:

- In every species, children are born with slightly different characteristics to their parents.
- The slight variations from individual to individual give some a competitive advantage in the quest for survival: a longer or shorter nose, a wider wingspan, thicker fur.
- Fitter individuals survive and compete better, passing their traits to their offspring, whereas less fit individuals die out more easily, and are less likely to pass along their traits.
- Over time, the species evolves to assume all the best-fitting traits for that particular environment. And crucially, species differentiate from each other over time, giving rise to diversity.



REMEMBER These ideas explained the remarkable fitness of each species to its habitats and food: long beaks for hummingbirds to drink nectar, thick fur for bears to survive winter hibernation in mountainous caves. They explained how some species have persisted whereas others appear only in the fossil record.

Many objected to the new theory. Some defended an older idea, Lamarckism, which proposed that species could inherit acquired traits from parents. For example, the children of a man who learned to be a strong swimmer or a great tennis player would acquire these traits from him. Others preferred to go back to creationism, the idea that an intelligent deity had designed each species, objecting that complex biological traits like the human eye could not have evolved piecemeal, since the more primitive forms would likely be useless.



TIP However, over time a gradual accumulation of evidence for natural selection caused the theory to be increasingly accepted.

Heredity and genes

Despite the success of Darwin and Russell's theory, major pieces of the puzzles remained. How were traits inherited?



REMEMBER At around the same time that Darwin was writing his great book *On The Origin of Species,* a Czech monk named Gregor Mendel (1822-1884) was experimenting with growing peas in the garden of his monastery. Mendel made careful notes about how parent peas passed on traits to their offspring, and arrived at an understanding of the mechanism of sexual reproduction:

- Traits come in discrete forms, rather than a continuum of variations. Therefore, one plant may be tall and another short.
- Traits are inherited from both parents, so a child inherits two types, called *alleles*.
- One allele may be dominant over the other, so that only the dominant one is expressed in the child.
- If the parent has two different alleles of a trait, the type passed on to its children is randomly selected.



REMEMBER These ideas now provided a concrete foundation for natural selection by explaining the mechanism of variation and heredity.



TECHNICAL STUFF The final piece of the puzzle was to explain how the traits and alleles were encoded and combined biochemically. This turned out to be the job of a molecule — *DNA*, or *deoxyribonucleic acid*. DNA acts like a chain of blocks that come in four types, known as nucleobases. The order of the four types acts like a computer code, spelling out and encoding the structure of life — how to grow, live, and repair an organism. The entire code for the individual is contained in every one of its cells.



TIP Although the role and chemistry of DNA as the carrier of genetic information was worked out over many decades by many people, two are often highlighted in the popular imagination: Francis Crick (1916-2004) and James Watson (1928-2025). Although Crick and Watson did not "discover" DNA, they are credited with uncovering its "double spiral helix" structure and

proposing the mechanism by which it splits apart and replicates. You revisit this important topic in Chapter 6.

Evolving Astrobiology



REMEMBER In this brief and rapid tour through astronomy and biology, you've seen how ideas developed over thousands of years of human history — mutating, merging, and evolving just as much as the species that biology sought to explain. Some ideas (atomism, heliocentrism) were proposed and then abandoned for thousands of years before being successfully revised and ultimately vindicated.



TIP One theme that emerges is eventual success of the scientific method over pure philosophy and reasoning, which failed to provide definite answers through thought and debate alone. Rather, it was the conducting of experiments and careful collection of evidence that enabled science to discriminate between competing theories and thereby to make advances.

From philosophy to sci-fi to science

Astrobiology itself began as speculation about life on other worlds. Over time it was refined and expanded, often through creative ideas in science fiction (see Chapter 19). And eventually the modern science of astrobiology branched from astronomy during the 1950s and 1960s, when scientists finally had tools and techniques to search for life in space via radio astronomy and space missions (see Part 4).

Exobiology becomes astrobiology



TIP Before we dive into modern astrobiology in the next chapter, a brief note about terminology. In its first incarnation, what was later to become astrobiology was known as *exobiology* — the search for life in space.

However, in 1995, the term astrobiology was adopted by NASA to more accurately describe the related and intertwined tasks of understanding prebiotic chemistry in space, the origins of life on Earth, the quest to find life in space, and the desire to communicate with other intelligent life.



TIP In the next chapter, you'll see how all these diverse parts come together in modern field of astrobiology.

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Chapter 3

Modern Astrobiology

IN THIS CHAPTER

- **Learn about the tools and techniques of modern astrobiology**
- **Find out how giant telescopes are used to research the cosmos**
- **Uncover how laboratory and field work helps to unravel the origins of life**

In the last chapter, I briefly summarize the thousands of years of philosophy and scientific inquiry that laid the foundations for modern astrobiology. It's clear from the historical record that thinkers down the ages were repeatedly asking the right questions, but, for many centuries, they didn't have the right tools to get any closer to the answers.

Today is different. Especially since the "space age," beginning in the 1950s, we have been able to venture into space — at least to our solar neighborhood — and search directly for life on other worlds. At the same time, back here on Earth, we have the tools and understanding of modern physics, chemistry, and biology that enable us to probe the biochemical workings of cells and the history of life's evolutionary tree, enabling us to see how and from where we evolved in the writing of DNA.



REMEMBER In short — astrobiology can now be pursued as an investigative science, not merely a branch of philosophy. So, let's dive right in and see how modern astrobiology is pursued.

From Exobiology to Astrobiology

The term *astrobiology* was first proposed by Russian astronomer Gavriil Tikhov in 1953, but the term did not immediately enter widespread usage.



TECHNICAL STUFF NASA established its *exobiology* program in 1960 at the behest of Nobel Prize-winning biologist Joshua Lederberg, to search for life on other worlds. The program followed an arc of hope as the first missions were sent out to Mars, leading later to despondency in the 1970s as the *Viking* missions discovered no traces of life on the dusty red planet (more on that in Chapter 12).

In contrast, at the same time back on Earth, new forms of life *were* being discovered. The 1977 finding of abundant life on the deep seabed near hydrothermal vents — previously imagined to be mostly barren — opened up the new study of *extremophiles* (see Chapter 9). This discovery widened the scope of possible habitats where life might exist off-Earth.



REMEMBER It was the 1996 announcement of possible microbial life in a Martian meteorite found on Earth (see Chapter 11) that led to the vigorous revival of exobiology, and the birth of NASA's new astrobiology program in 1998.

Three overarching themes were identified in 2003 (see Figure 3-1), which guide NASA's astrobiology research today:

- How does life begin and evolve?
- Does life exist elsewhere in the universe?
- What is the future of life on Earth and beyond?

In this chapter, I discuss the tools astrobiologists use to attempt to answer these questions.



Credit: Generated with AI using OpenAI

FIGURE 3-1: Graphical depiction of the three key themes of astrobiology.

Giant Telescopes

Because *astrobiology* is the melding of *astronomy* and *biology*, clearly a key goal is to search for life in space — which in turn can perhaps also inform us as to how life got underway on Earth.

Astronomy using telescopes, which has been established for hundreds of years, has led to many breakthroughs and played a key role in the development of astrobiology (see Chapter 2), including such key moments as:

- Galileo's discovery of the four large moons of Jupiter, telling us that not everything is in orbit around the Sun, and (unknown to him) giving us fruitful places to search for life in *ocean worlds* (see Chapter 13).
- Schiaparelli's investigation of *canali* (channels) on Mars, giving rise to the mistaken idea of "canals" by Lowell, and subsequent dreams of planetwide Martian agrarian civilizations (see Chapter 12).
- The first searches for alien radio broadcasts in the 1960s, leading to excitement over the imagined detection of "Little Green Men" (see

Chapter 17), that nevertheless led to the modern-day search for extraterrestrial intelligence (SETI) and civilizations.

- The first detections of an exoplanet around a main-sequence star by Mayor and Queloz (see Chapter 16), opening the door to the burgeoning field of exoplanet science.



TIP Today, astrobiologists take advantage of the full range of radio, optical, and infrared telescopes to search for life of all types in space. Let's take a look at some cutting-edge observatories (see Figure 3-2).

Earth-based behemoths

Modern telescopes on Earth range across the entire spectrum of light, from the long wavelengths of radio waves, through to infrared and visible light (see Chapter 2). Some of the largest telescopes used today at different wavelengths include:

- **The Jansky Very Large Array (VLA):** One of the most productive radio telescopes on Earth, the VLA consists of a Y-shaped array of twenty-seven 25 m (82 ft)–wide radio "dishes" located near the town of Socorro, New Mexico. Commissioned in the 1970s, the VLA became famous for playing a key role in the movie *Contact* (1997), where alien radio signals are decoded by a human astronomer, played by Jodie Foster (see Chapter 19). In reality, the VLA has played a prominent role in the hunt for alien radio broadcasts (see Chapter 17), as well as groundbreaking astronomical discoveries encompassing planets, stars, and galaxies.
- **The Atacama Large Millimeter/sub-millimeter Array (ALMA):** ALMA is also an array, like the VLA; however, it works at shorter wavelengths. Built on the high *altiplano* desert of northern Chile, ALMA is at a remote and dry location, where there is little water vapor in the atmosphere to interfere with microwave observations of space. The 66 "dish" antennas of ALMA (ranging from 7 to 12 m in

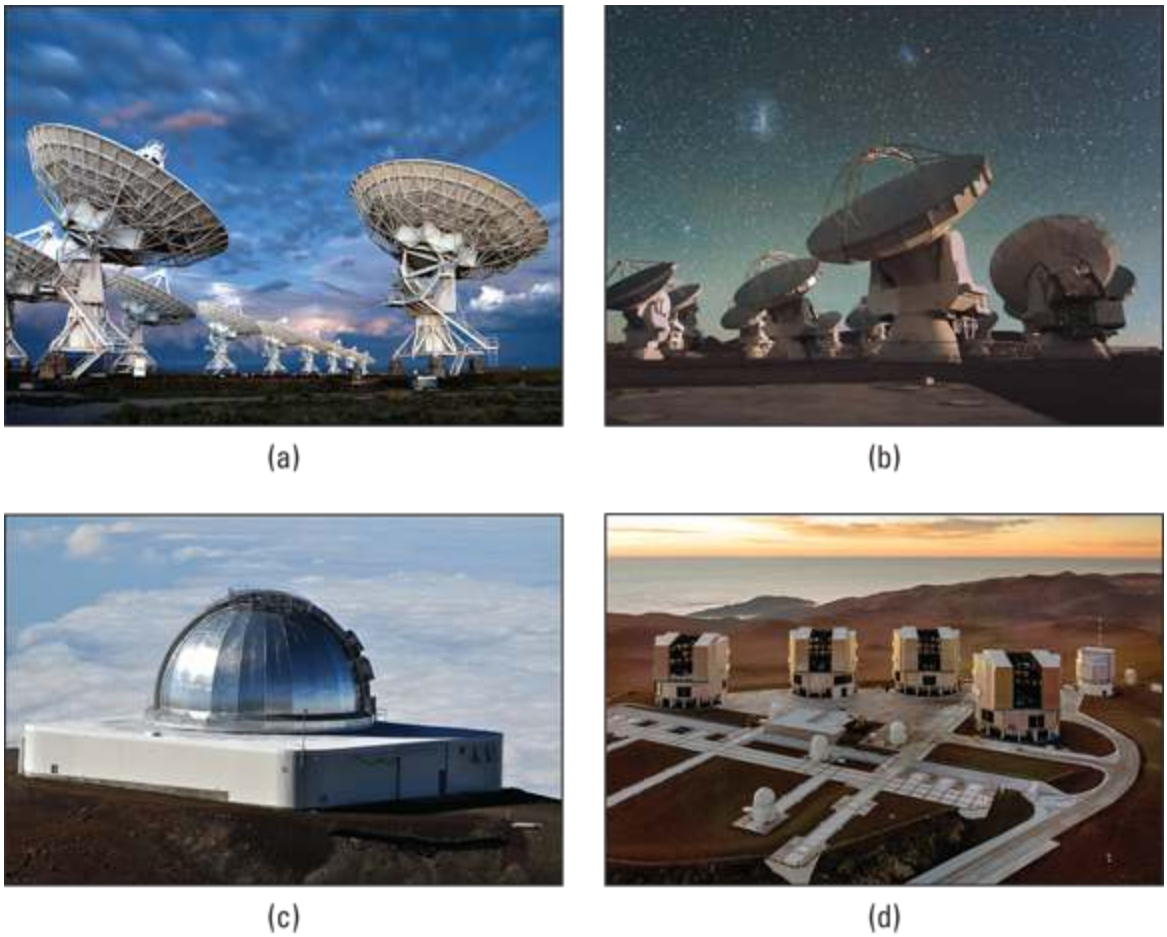
diameter, or 23-40 ft), commissioned in the early 2010s, work together as a team, forming the equivalent of a much larger telescope, spanning anywhere from 1 to 16 km (0.6 to 10 miles) in width.

- **The NASA Infrared Telescope Facility (IRTF):** On the summit of Maunakea, Hawaii, the IRTF consists of a single 3.2 m (10 ft) telescope that saw "first light" in 1979. IRTF continues today to be a workhorse for observations of the solar system at infrared wavelengths, including of planets, asteroids, and comets, seeing particular use in high-resolution *spectroscopy* (splitting light into different colors), which enables different constituents in planetary and stellar atmospheres to be distinguished.
- **The Very Large Telescope (VLT):** The VLT is another observatory in Chile, consisting of four 8.2 m (27 ft)–diameter telescopes in fixed positions, as well as four smaller 1.8 m (6 ft) movable "outrigger" telescopes. Together these form a network able to work at short (visible) wavelengths, taking very high-resolution images of stars, nebula, and star-forming disks.



TIP All these modern ground-based observatories use a number of "tricks" to obtain the clearest possible view of the sky: They're located in dry places on Earth such as deserts and volcanoes; they concentrate on wavelengths not absorbed by the Earth's atmosphere; and they even use fancy "adaptive optics" to compensate for the twinkling induced by the atmosphere.

However, for some types of astronomy, there is no getting around the limitations of the Earth's atmosphere, which absorbs light across the shortest wavelengths, as well as portions of the infrared and microwave spectrum. To observe these types of light and to get the clearest view overall, we need telescopes outside the atmosphere entirely — in space.



Credit: (a) National Radio Astronomy Observatory/CC BY 4.0 (b) ESO/C. Malin/CC BY 4.0 (c) Afshin Taylor Darian/Flickr/CC BY 2.0 (d) ESO/G.Hüdepohl/CC BY 4.0

FIGURE 3-2: Modern Earth-based telescopes: (a) the Jansky VLA; (b) ALMA; (c) NASA's IRTF; (d) the VLT.

Eyes in the sky

Since the advent of the space age, astronomers have had the ability to take their telescopes outside the Earth's atmosphere and into space to get the clearest view of planets and stars over the widest range of wavelengths.

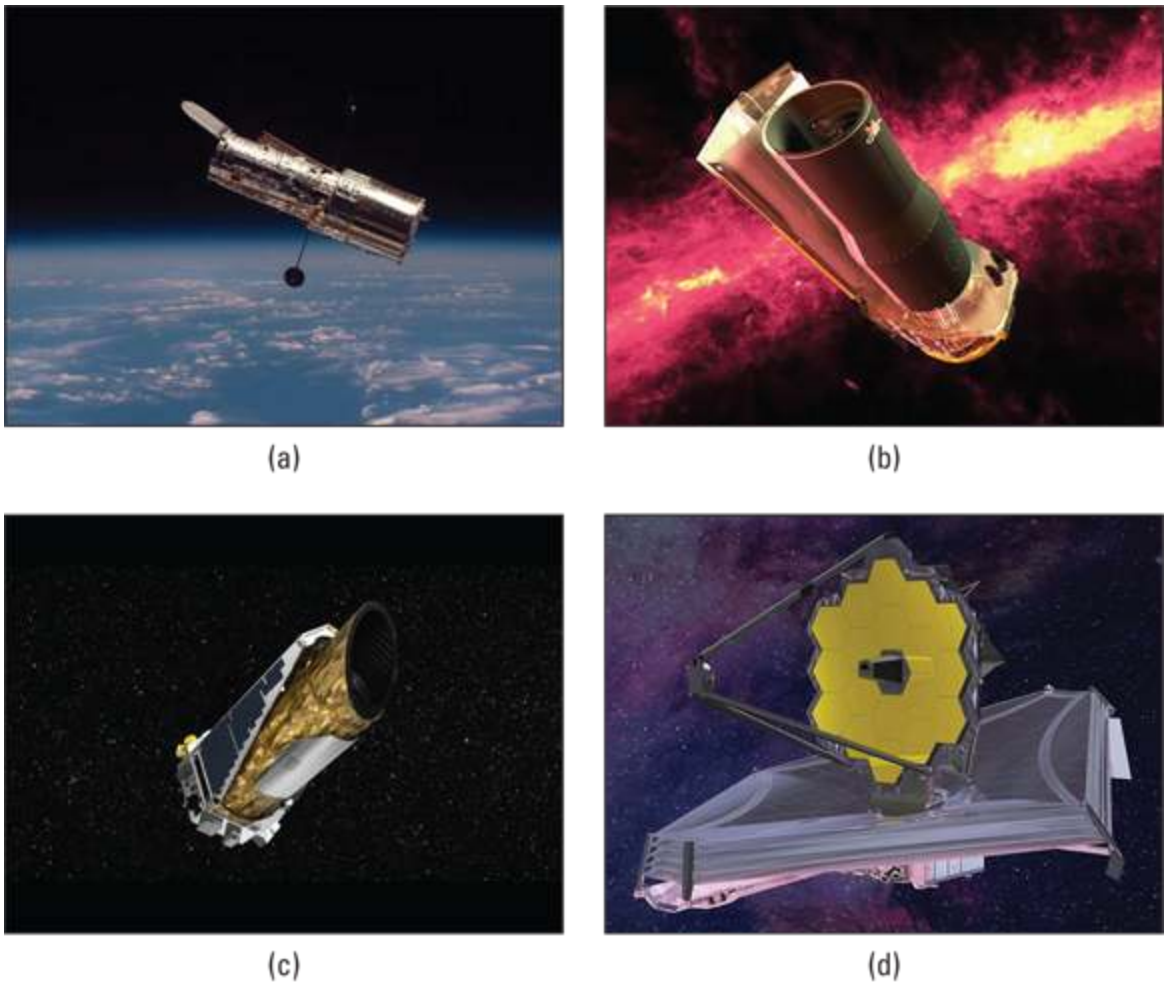
Here's a look at some of the space telescopes in the past half-century that have been important for astrobiology (see Figure 3-3):

- **The Hubble Space Telescope (HST):** Launched in 1990, the Hubble Space Telescope (HST, or just "Hubble") was named after American astronomer Edwin Hubble, who discovered the expansion

of the universe in the 1920s — confirmation of the "Big Bang" theory. Although Hubble was designed to do fundamental work in cosmology, it also provided unique and important views of our solar system, as well as iconic views of solar systems being born in nearby dark nebulae, such as the famous "pillars of creation" in the Eagle nebula. Following the discovery of exoplanets in the 1990s, Hubble has been used to make groundbreaking studies of exoplanet orbits and atmospheres as well. Now more than 40 years since launch, Hubble continues to be the most famous space telescope of all time.

- **The Spitzer Space Telescope:** Although a relatively small telescope (85 cm mirror) compared to Hubble (275 cm diameter), Spitzer, launched in 2003, turned out to be a workhorse for astronomy at infrared wavelengths. In 2016, Spitzer helped to confirm the existence of five of the seven exoplanets in the famous TRAPPIST-1 solar system and was used to measure their sizes and masses, greatly enhancing our knowledge of small exoplanets that may be close to the "habitable zone" (see Chapter 16 for more on this fascinating planetary system).
- **The Kepler Space Telescope:** Kepler, brainchild of NASA astronomer Bill Borucki, was a clever idea to gather as many new exoplanet discoveries as possible with a low-cost mission. Borucki's idea was to stare at a single patch of sky dense with stars (a portion of our Milky Way galaxy) to see which stars dimmed by the passage of a planet in front. Using sensitive detectors and a lot of patience, Kepler, launched in 2009, racked up close to 3,000 confirmed planetary discoveries during its main mission — almost half the total number of exoplanets discovered to date. These gave us the first robust knowledge for the number of planets around Sun-like stars — an important component of the Drake Equation (see Chapter 17). Due to its astounding success, a number of similar missions have since been conceived, such as the TESS and ARIEL missions.
- **The James Webb Space Telescope (JWST):** JWST (or "Webb") launched in 2022 has a primary mirror (6.5 m) more than double the diameter of Hubble's. Webb's overall technology is also much more complicated, being designed to look at infrared rather than visible

wavelengths. This required cooling of much of the telescope to eliminate heat emissions, which would far outshine the dim infrared rays from distant stars and galaxies. Following a more than 20-year development time, JWST has proved worth the wait, making revolutionary observations of exoplanets as well as planets and moons in our solar system.



Credit: (a) NASA/Public domain (b) NASA/JPL-Caltech/Wikimedia Commons/Public domain (c) NASA/ESA/CSA/STScI/Public domain (d) NASA/ESA/CSA/Northrop Grumman/Public domain

FIGURE 3-3: Space telescopes (a) Hubble Space Telescope; (b) Spitzer Space Telescope; (c) Kepler Space Telescope; (d) James Webb Space Telescope.

Although telescopes on the ground and in space can be tremendous tools for discovery: for asteroids, comets, planets, and moons in our solar system we have another, more direct means of investigation — to send a

spacecraft to visit the body and make direct measurements or even to return samples, as you see in the next section.

Space Missions

Missions to visit bodies in our solar system have transformed our understanding of the planets, as well as many small asteroids, moons, and comets. We have flown by or orbited some of these worlds, whereas for others we have landed, driven robotic or human rovers across the surface, flown balloons or helicopters, and even returned samples.

To orbit, land, or rove?

You encounter many different planetary missions during the course of this book that have been pivotal for astrobiology. Now let's take an introductory look at several of the key types of missions that have given us data for astrobiology (see Figure 3-4):

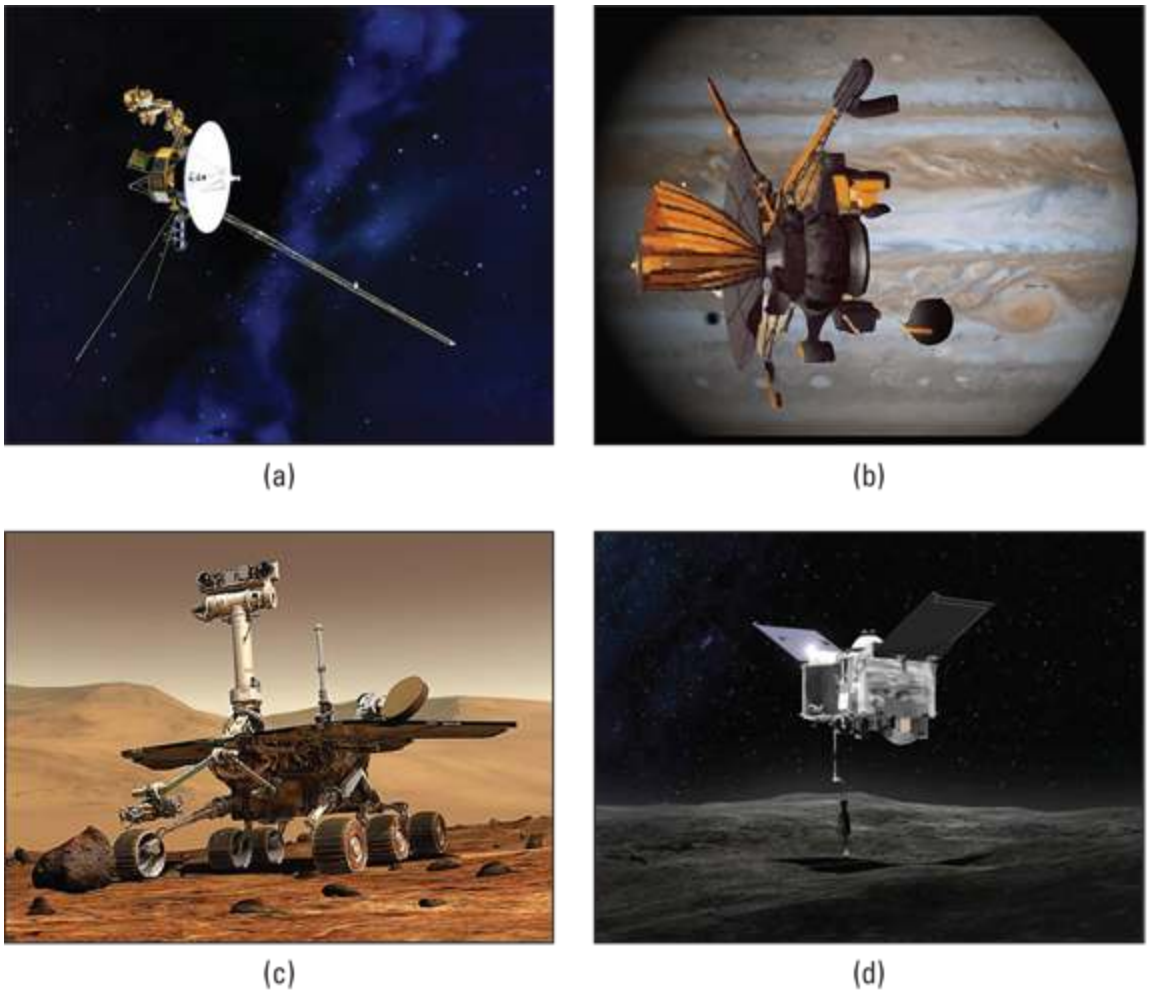
- **Flyby missions:** Flybys were the earliest interplanetary missions of the space age. Spacecraft reached the inner and outer planets for the first time, making close flyby passes to take photographs as reconnaissance for later orbiters and landed missions. Typical instruments carried included cameras, spectrometers, and magnetometers.
- **Orbiters:** Planets from Mercury to Saturn, as well as some smaller bodies, have also now been investigated by longer-duration orbiter missions. Orbiters typically seek to make more detailed mapping of the planetary surface, using cameras but also RADAR or LIDAR ranging for topographical mapping. Orbiters can watch over long periods as a planet's weather changes from season to season, and even investigate nearby moons in the same system (especially for Jupiter and Saturn).
- **Rovers:** After mapping the surface, typically the next step of planetary exploration is to send a probe to descend through the atmosphere and soft land on the surface. However, since probes are limited to investigating only a tiny fraction of the surface at the

landing site, a more desirable follow-on mission for solid surface planets is a rover. Currently, rovers have driven across the Moon and Mars, while a helicopter has flown on Mars, and a quadcopter will soon land and explore Titan.

- **Sample return missions:** If we successfully reach the surface, we may eventually wish to return samples for analysis back on Earth, where the instruments available are much more sophisticated than the ones we can send on a space probe. Currently, samples have been returned from several asteroids, one comet, and the Moon, and plans are underway for a more ambitious sample return from Mars (see Chapter 12).



TIP Currently, all planets in our solar system have been orbited except the most distant — Uranus and Neptune. NASA has announced plans for a Uranus Orbiter and Probe (UOP) to reach the planet in the late 2040s or 2050s.



Credit: (a) NASA/JPL-Caltech/Public domain (b) NASA/JPL/https://science.nasa.gov/photojournal/mars-reconnaissance-orbiter-front-view-artists-concept//Public domain/last accessed Oct. 11, 2026 (c) NASA/JPL/Cornell University/Maas Digital LLC/Wikimedia Commons/Public domain (d) NASA's Goddard Space Flight Center/Public domain

FIGURE 3-4: Examples of different types of space missions to the planets: (a) a flyby mission, *Voyager 2*; (b) the Mars Reconnaissance Orbiter; (c) the *Opportunity* Mars Rover; (d) the *OSIRIS-REx* sample return mission.

Instruments of the trade

A spacecraft in itself is useless for science without carrying onboard some instruments. These can range from the ubiquitous cameras to much more sophisticated and specialized instruments for astrobiology. Here are a few that you encounter throughout this book:

- **Cameras:** Camera and video technology has developed enormously during the space age, beginning with the monochromatic ("black and white") cameras sent on early Moon and Mars missions to later color cameras. Often, both wide-angle and narrow-angle cameras are sent on orbiters and flyby missions, whereas rovers now include fancy zoom lens systems as well as close-up ("macro") lens and even microscopes. Among the most useful for science are *filter imaging systems*, where a monochromatic camera is paired with a filter wheel to pass only one color of light. By photographing the same target in different filters (including visible colors as well as UV and IR), detailed scientific information can be gathered about the object's physical and chemical properties.
- **Spectrometers:** Spectrometers split light into different colors, like a prism, and then detect the intensity of each color, giving information about rock types, gas composition, and more. Many different designs of spectrometers are available, depending on the wavelengths to be examined, the science goals, and more practical considerations such as the mass, volume, and power available on the spacecraft, and the cost.
- **Particle and field detectors:** These are instruments designed to measure the fluxes (flows) of charged particles, such as protons and electrons, as well as electrical and magnetic fields. They can provide important information about the object's own (intrinsic) magnetic field, as well as its interactions with the solar wind. Such instruments can provide valuable insights into the aging (*weathering*) of surfaces on moons, as well as atmospheric loss (*ablation*) from bodies such as Mars and Titan.
- **Mass spectrometers:** Mass spectrometers are different from spectrometers of light. These measure the mass ("heaviness") of different molecules, helping to inform scientists about the chemical composition. They can be combined with other instruments such as *gas chromatographs* (essentially chemical separators) to provide more detailed multi-stage measurement techniques that can help to separate similar substances from each other. Note that mass spectrometers can only sample the nearby environment, a process

known as “in situ” measurement, unlike cameras and spectrometers, which can work across any distance.

- **Life detection experiments:** Some experiments aim to detect life directly. I discuss some of these carried on the Viking landers in Chapter 12, such as the famous “labeled release experiment” that attempted to detect metabolism of lifeforms on Mars. For now, suffice it to say that these are designed to provide simple yes/no answers when we don’t have a good idea of what possible types of life may exist.



TIP Modern spectrometers can be combined with cameras to become spectral imagers, able to do two jobs at once!

Lab Experiments

Laboratory investigations are a key cornerstone of modern research into the origins of life, encompassing diverse investigations such as:

- **Microbiology:** Investigations of the life cycles of extremophiles (see Chapter 9) and other simple organisms, extending our understanding of the tree of life and adaptions to extremes of habitable environments.
- **Biochemistry:** Work to understand the origins and working of life’s chemicals such as DNA and RNA, how they arose from simpler chemicals, their uses, and the broader chemistry that occurs inside and between cells. (More on this coming up in Chapter 6.)
- **Origins of life simulations:** Miller-Urey type experiments (see Chapter 8) attempting to re-create the origins of life’s most basic chemicals in a simulated environment.
- **Sample analysis:** Investigation of samples from space (such as meteorites) to detect complex chemicals and measure isotopic ratios. Also, analysis of samples from Earth — such as, for example,

searching for the earliest traces of life in ancient rocks (see Chapter 5).

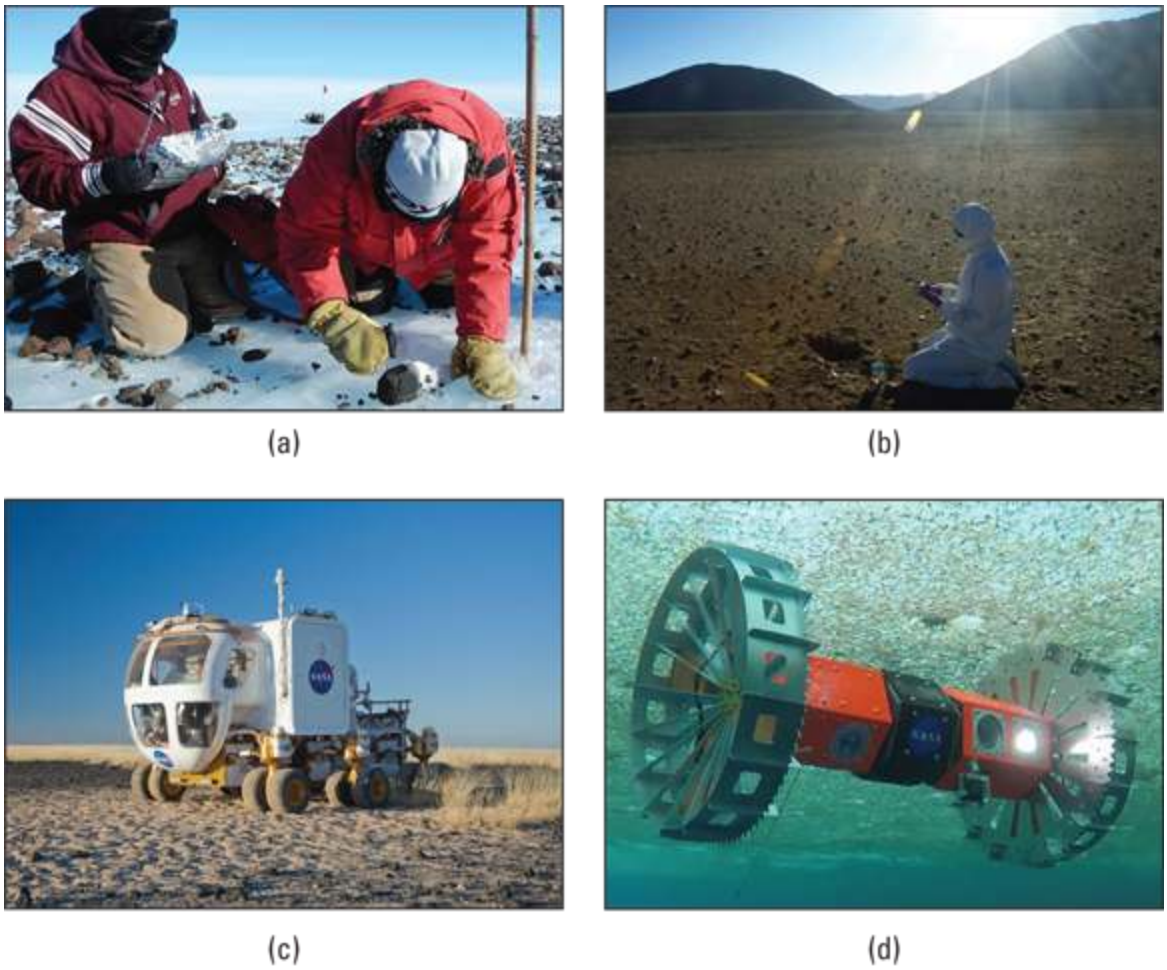
- **Space instrument design and test:** Testing the functioning and operations of instruments intended to fly in space in a laboratory environment. This makes sure that the instruments are well understood before flight; however, experiments using "flight spares" or "engineering test units" (essentially replicas of flown instruments) can be vital later on during the mission to help interpret ambiguous results.

Earth and Analog Fieldwork

Field work can be a fun and exciting part of astrobiologist's career — taking them to diverse (often extreme and challenging) locations to collect samples. (See Figure 3-5.) However, such field investigations are expensive and complex, not to mention occasionally dangerous, and must be carefully planned for both scientific and safety reasons.

Some examples include:

- **Meteorite collection:** Collection of both meteorite falls (witnessed falls to Earth from space) as well as finds (meteorites discovered on the ground long after falling) in locations ranging from Antarctica to deserts in Africa and Asia, and even rooftops in cities. (See Chapter 11.)
- **Extremophile investigations:** These include field work to remote areas of land such as deserts and tundras to collect hardy biological specimens and study their habitats (see Chapter 9), as well as voyages to the depths of the seas and oceans.
- **Instrument field testing:** Just as future space instruments are tested in the laboratory, they are often also field tested in outdoor environments. These include also mobility units such as rovers and undersea ROVs.



Credit: (a) NASA/Public domain (b) NASA/Public domain (c) NASA/Regan Geeseman/Wikimedia Commons/Public domain (d) NASA WITH NASA/Public domain

FIGURE 3-5: Astrobiology field work: (a) collecting meteorites in Antarctica; (b) searching for extremophile life in the Atacama; (c) testing a pressurized astronaut rover in Arizona; (d) an underwater rover crawls along the underside of sea ice in Alaska, sampling the biosphere.

Computer Simulations

Although all the many types of investigations mentioned already are important — astronomy, space missions, lab work, and field investigations — sometimes it's impossible to answer the question in any type of physical manner. In these cases, computer simulations are invaluable.

Examples where virtual astrobiology investigations are needed include:

- Simulations of solar system formation, planetary orbits, and atmospheric evolution
- Computations of chemistry in space, or deep inside cells
- Ecosystem evolution over time

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Part 2

Origins of Life on Earth

IN THIS PART …

Defining what life is, how it may have started on the early Earth, and how we could recognize life if we found it in space.

Exploring the history of life on Earth from chemicals to cells, and from single-celled organisms to multicellular plants and animals.

Finding out how scientists are attempting to recreate the origins of life in the laboratory, and probing the limits of life's survivability.

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Chapter 4

Defining Life

IN THIS CHAPTER

- **Getting to know the key traits of life**
- **Learning how scientists assess the importance of proposed biosignatures**
- **Understanding how life is classified**

If astrobiology is the search for life in the cosmos, along with the quest to understanding the origins of life on Earth, we must surely need to be able to define what life *is*.

This turns out to be harder than you might think, a bit like trying to define the boundary between the colors red and orange, or between asleep and awake. In fact, almost every definition of life is in some way subjective (like when you debate with your school teacher about whether you were awake or asleep in class).

Therefore, I'll start by giving away the punchline: There is no single "definition of life." However, we can make a definition for a particular purpose, so long as we're clear about its inherent biases and limitations.



TIP In this chapter, you learn about the whole topic of "defining life" — what the range of characteristics is that we may want to consider as part of our definition, and later, how life itself is not static or standing still, but is always changing and evolving. Therefore, our definition may need to be revised over time as well.

Characteristics of Life

NASA has a concise definition of life, which is useful for many purposes in astrobiology: "Life is a self-sustaining chemical system capable of Darwinian evolution." Note that this definition would exclude any type of artificial intelligence (AI) from being alive, since that would not be a "chemical system," but rather a system based on electronic data.



REMEMBER There are a handful of key traits associated with life that are often considered essential (see Figure 4-1):

- **Organization:** Being made of at least one structural unit, the cell.
- **Metabolism:** The ability to take in energy and transform it to sustain life.
- **Homeostasis:** The regulation of internal conditions to maintain a stable state.
- **Growth:** The capacity to increase in size and change over time.
- **Response to stimuli:** The ability to interact with and adapt to one's environment.
- **Reproduction:** The capability to produce new organisms.
- **Evolution:** The ability of populations to adapt and change over generations.

Let's look at each of these in more detail and consider not only how they are viewed on Earth, but how they might manifest in extraterrestrial environments as well.

Getting organized with cells

All known life is organized into cells, which serve as bounded compartments that separate an organism from its environment. The cellular boundary (usually a lipid membrane) is one of the most universal features of terrestrial life.



REMEMBER Cells perform several critical functions:

- They concentrate chemicals needed for life, which would otherwise be heavily diluted in the background environment.
- They maintain internal conditions (homeostasis).
- They contain a means of storing the code for the organism, the genetic information of DNA.
- They enable metabolism to occur, generating energy for movement, growth, and reproduction.
- They are units of reproduction.



Credit: Generated with AI using OpenAI

FIGURE 4-1: Seven characteristics of life according to a broad modern definition.

Life on Earth exists in two broad cellular forms:

- **Prokaryotes (bacteria and archaea):** Simple cells lacking a nucleus.
- **Eukaryotes:** More complex cells containing organelles such as nuclei and mitochondria.



TIP I look at these types in more detail in the next chapter.

For astrobiology, a key question is whether alien life must be cellular, although some form of boundary appears necessary for sustaining complex chemistry. For this reason, astrobiologists look for evidence of compartmentalization on other worlds — see the debate in Chapter 11 on the Martian meteorite ALH84001 to see how heated this discussion can get.



TECHNICAL STUFF On Saturn's moon Titan, which has lakes and seas of chilly liquid methane rather than water, a different type of cell membrane would be required. Scientists have therefore proposed a kind-of inside-out membrane known as an *azotosome*: See Chapter 13 for more on that topic.

Feeling energized with metabolism

If you've ever felt lethargic in the morning before going to school or work, you'll be aware that life requires *energy.*



TECHNICAL STUFF Organisms on Earth obtain energy through many pathways:

- **Photosynthesis** uses sunlight to convert carbon dioxide and water into organic molecules. This is the key energy-generating mechanism of plants, algae, and some types of bacteria (*cyanobacteria*).
- **Chemosynthesis** taps chemical energy rather than sunlight by exploiting energy differences between molecules that can be harnessed in chemical reactions. *Chemotrophs* include organisms living at hydrothermal vents on the sea floor (see Chapter 9), as well

as other types of extremophiles that consume methane (*methanotrophs*) or sulfur (*thiotrophs*).

- **Respiration** and **fermentation** break down organic molecules to release energy. This is the type of energy generation used by animals and many plants and microorganisms as well.

Metabolism is often considered one of the strongest *biosignatures*, or indicators of life. To detect metabolism, astrobiologists can design experiments to look for changes in gases around an investigated site, changes in types of atoms or chemical structures (isotopic or chiral ratios), and heat signatures, indicating that life is busy at work.



TIP In the past this has led to experiments on space missions to detect metabolism directly, with some ambiguous results — skip ahead to Chapter 12 and read about the *Viking* "labeled release experiment" for more insights on that.



TECHNICAL STUFF On other worlds and in space, organisms would have access to a wide range of energy sources, including sunlight, natural radioactivity, and chemical systems (sometimes called *redox gradients*). For example, the subsurface ocean of Europa may support life powered by chemical disequilibria generated at the ocean floor (see Chapter 13).

Homeostasis



TIP *Homeostasis* is another big, jargony word. However, it simply means the ability to maintain stable internal conditions despite changing external environments.



Homeostasis is necessary for life, otherwise the chemistry of the cell becomes unbalanced, reactions cease to proceed correctly, and the cell dies. Examples of homeostasis include:

- Regulation of body temperature
- Blood pH control
- Cellular ion balance
- Water regulation in plants

Even simple bacteria maintain homeostasis, including:

- Internal pH (acidity vs alkalinity)
- Salt concentrations, which in turn control osmotic pressure, the flow of water into or out of the cell

It seems clear, therefore, that homeostasis must also be a requirement for any type of extraterrestrial life, because that life must maintain the correct conditions for whatever types of reactions (metabolism and so on) it has evolved to use.



At a planetary scale, some researchers view the entire Earth itself as a self-regulating, homeostatic system — a theory known as the *Gaia hypothesis*. For example, feedback loops between animals and plants may have co-evolved to keep each other in balance. Although this concept is by no means universally accepted in the strong sense (the Earth as an "organism"), it's clear that some parts of this regulation are taking place.

For example, if the planet warms too much by emission of CO_2, life that uses respiration would naturally die out, reducing the amount of CO_2

going into the atmosphere, and/or promoting the growth of CO_2-consuming plants instead.



TIP The idea of planetary-scale homeostasis is an important one for astrobiologists studying exoplanets, who may look at a planet's atmosphere to see if there is an apparent chemical equilibrium or disequilibrium. An apparent imbalance may be a clue that life is providing the missing part of the equation.

Growth

Living systems grow by incorporating matter and energy from their environment, and growth often involves cell division, although it could also be growth of the cell itself. Growth includes both growth of the individual, such as a child becoming taller, as well as growth of a colony, as through bacterial cell division.

Growth is not merely accumulation. A crystal grows, but it blindly follows the laws of physics, replicating the same structure repeatedly. Biological growth, on the other hand, is more complex, following a set of rules (the genetic code) embedded in the cell. This may lead to the same cell replicating or giving rise to a different cell, such a red blood cell emanating from the cells of bone marrow.



TIP For astrobiology, growth may help to distinguish life from nonliving self-organizing systems, although care must be taken not to confuse the two. Missions to search for life can search for growth, but to determine whether the growth is truly life, they must also consider complexity, information storage within the growth unit, and possible differentiation over time.

One test may be to check whether individuals of the investigated system are different from each other, as happens in many living systems on Earth due to differences in genetic code and gene expression.

Reproduction

Reproduction is a key trait of life. Although individuals in the population do not have to reproduce (like worker bees), the overall population must be able to reproduce.



REMEMBER Reproduction occurs in two varieties:

- **Asexual reproduction** such as binary division in bacteria (*mitosis*) and budding in yeast.
- **Sexual reproduction** by *meiosis* (dividing of the genome into two halves) followed by recombination of a sperm and egg to form a new individual. This is the mechanism of reproduction used by most plants and animals.

Reproduction enables life to continue, to inherit characteristics from the progenitor population, and to evolve. Asexual reproduction (essentially cloning) tends to introduce few or no changes per generation, leading to slow evolution of the population. Sexual reproduction, on the other hand, implies that the child is a mixture of the genes of its parent, and so is a new unique individual. Sexual reproduction therefore often leads to more rapid evolution of the species.



TIP Researchers searching for life outside of the Earth may look for evidence of reproduction through growth, inheritance mechanisms and population evolution.

Response to the environment

Living systems sense and respond to external stimuli. Responses can range from very simple reactions to complex behaviors involving decision and choice, and may take place in milliseconds, or over centuries.

Examples include:

- Bacteria swimming toward nutrients
- Plants growing toward light
- Venus flytraps snapping shut
- Animals fleeing a predator
- A human driving a car



TECHNICAL STUFF Responsive behavior may be a powerful indicator of life in alien environments. Scientists could search for:

- **Directed movement**, toward/away from noise, light, or chemicals
- **Adaptation to a changed environment** such as cold or nightfall
- **Seasonal activity cycles**
- **Dynamic chemical responses** such as excreting defensive gases or liquids



TIP The challenge for astrobiology will be to distinguish biological responses from purely physical reactions, such as a crystal dissolving in hot water, versus a bacterial colony dying due to the changed temperature.

Evolution and adaption

This may be the most profound characteristic because it explains the diversity of life. Evolution on Earth over millions of years has led to complex plants and animals developing from single-celled organisms.



REMEMBER Evolution is necessary to avoid life from dying out completely when conditions change, most famously during mass extinction events (see Chapter 5) when species are driven to adapt more rapidly due to a changed environment.



TECHNICAL STUFF Evolution encompasses several different processes:

- **Mutation** occurs when a cell is copied with a change introduced accidentally into the genetic code. Some mutations are harmful, leading to death of the new cell or organism, whereas others may be harmless or even beneficial.
- **Selection** occurs when some individuals reproduce more successfully in their environment than others, passing on their genetic traits, whereas others die out.
- **Genetic drift** occurs when some alleles (traits) are passed on to child generations without selective pressure. This may occur due to chance, such as by a small portion of a population becoming isolated from the larger population, resulting in their alleles becoming enhanced.
- **Horizontal gene transfer** is a method by which genes may be exchanged or swapped, as between bacterial individuals, or between chromosomes prior to recombination.

Although it may be difficult to observe evolution taking place in real time in space, scientists can ask whether a putative living system shows adaption to its current environment.

Determining What Is Alive

Now that we've defined some key traits of life, we can return to our original question about where to draw the line between the living and the nonliving on Earth. This will help us in our quest to determine whether we have found life in space.

The continuum of life

We can start on Earth by comparing some different physical, chemical and biological systems versus our checklist of life traits (see Figure 4-2).

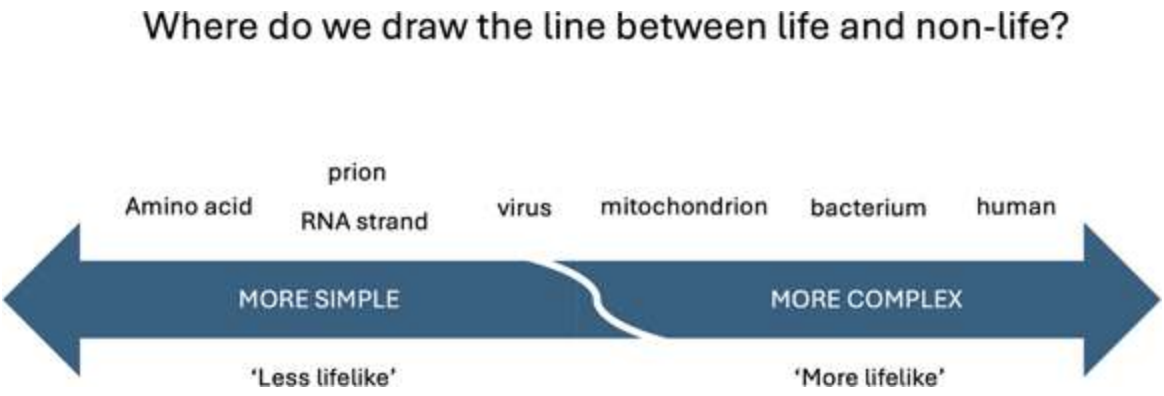


REMEMBER This comparison shows that some things check some of the traits, but not all. In addition, some check more of the traits than others. This leads us to the idea of a "continuum of life," where some things fall clearly on one side or the other, while others fall somewhere in the middle (see Figure 4-3).

Trait	Crystal	Prion	Virus	Bacterium	Tree	Human
Organization	Y	Y	Y	Y	Y	Y
Metabolism	N	N	N	Y	Y	Y
Homeostasis	N	N	N	Y	Y	Y
Growth	Y	N	N	Y	Y	Y
Stimulus response	N	N	N	Y	Y	Y
Reproduction	N	N	Y	Y	Y	Y
Evolution	N	N	Y	Y	Y	Y

Credit: author

FIGURE 4-2: Comparison of various possible forms of life.



Credit: author

FIGURE 4-3: The continuum of life.



TECHNICAL STUFF Viruses are a key point on the scale of complexity, having many but not all of the characteristics of life. They can be encapsulated, although they are not traditional cells; rather, they live within host cells. They certainly don't metabolize, although they reproduce and evolve. Most biologists classify viruses as nonliving, even though some of the language we use to describe them at times (as "invaders" of cells that "hijack the cell's machinery and multiply") tends to invoke living, even sentient creatures.

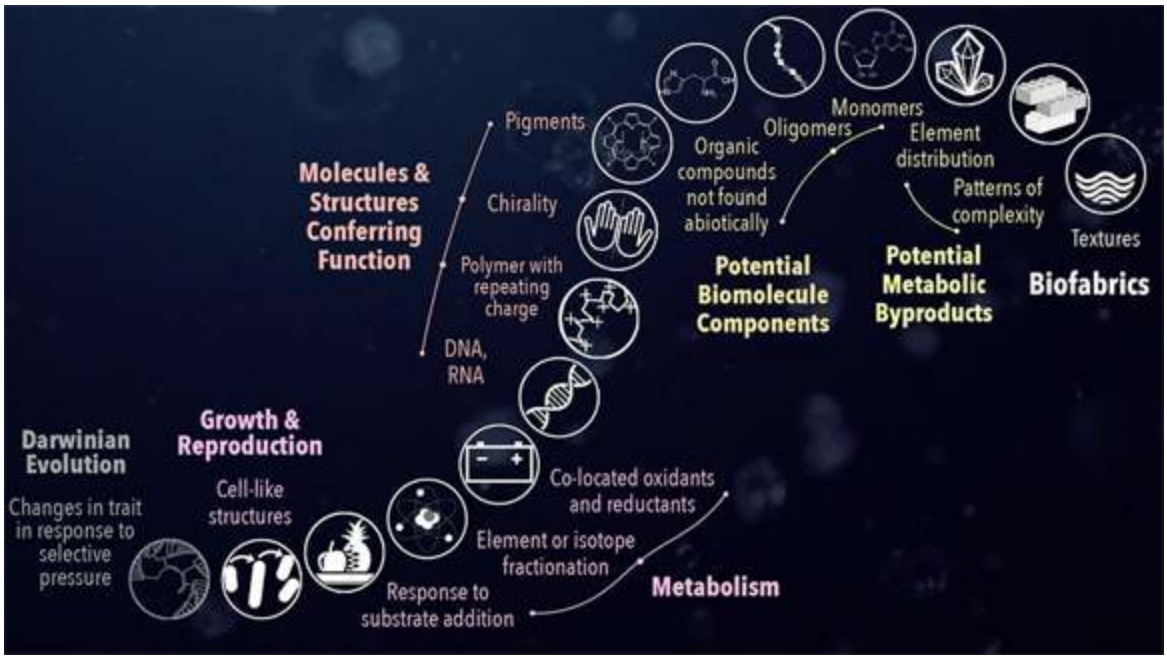


REMEMBER The concept of a continuum of life is important for astrobiology investigations: We may find something that falls somewhere along the continuum but that doesn't check all the boxes unambiguously. In that case, whether we have found life may become a matter of opinion.

Climbing NASA's ladder of life detection

In an attempt to guide astrobiology investigations to greater rigor, in 2018 NASA developed a "ladder of life detection." Similar to the continuum we just discussed, the ladder features a series of steps or rungs. When a potential biosignature (evidence for life) is discovered, it can be compared to the ladder to see how far along it advances. The further it advances, the more "lifelike" it is.

One depiction of the ladder (shown more like a pathway) is depicted in Figure 4-4. If a biosignature meets criteria further to the left the more likely it is to qualify for a true detection of life.



Credit: NASA/Marc Neveu/Public domain

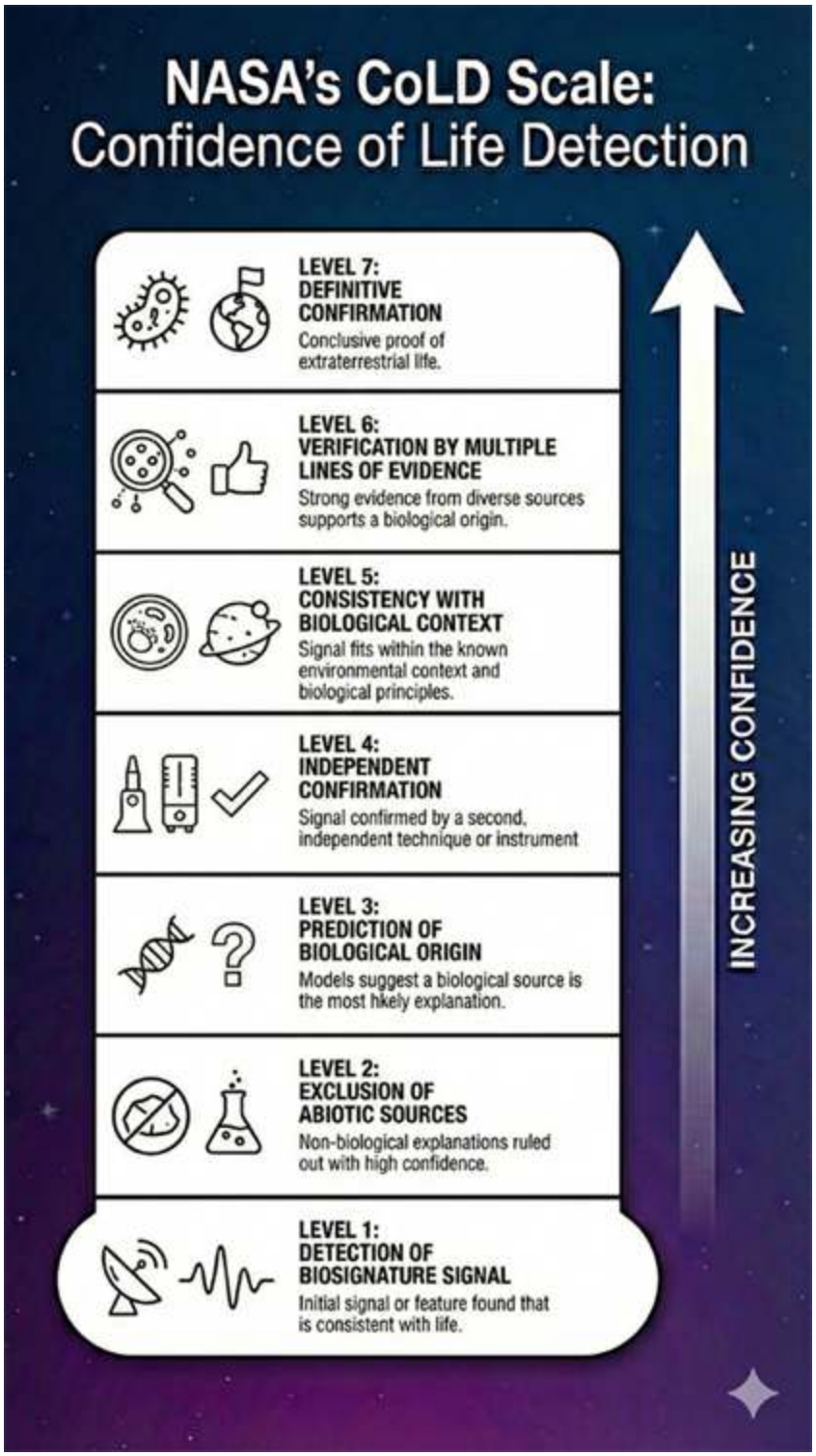
FIGURE 4-4: The ladder or path of life detection.

Wriggling up the CoLD scale

Following sensational (but not widely accepted) announcements by scientists of the detection of life on Venus (see Chapter 14), NASA wanted to go a step further than the ladder, and provide a framework for conveying the certainty of each potential biosignature to journalists and the public. This study led to the Confidence of Life Detection (CoLD) scale (see Figure 4-5).

TECHNICAL STUFF

The CoLD scale ranges from a score of 1 (tentative indication of life) to 7 (certainty of life), with intermediate steps being reached after the potential biosignature passes a series of tests. These include typical steps of scientific rigor, such as checking whether a non-biological source could give the same signal, independently verifying the biosignature with a second instrument or technique, and finding additional independent evidence supporting the original hypothesis.



Credit: NASA/Aaron Gronstal/Public domain

FIGURE 4-5: The CoLD scale.



REMEMBER To date, most scientists would agree that no potential biosignatures discovered so far have passed beyond Step 1 of the CoLD scale. Although this may sound disappointing, many scientists remain optimistic that life is out there in space, waiting to be discovered. A major reason for this is the abundance of exoplanets (see Chapter 16), combined with the Copernican principle that holds that Earth is most likely a typical, average planet and not an outlier.

Classifying Life

Having determined in general what life is and what it is not, scientists have further sought to classify life, building a branching tree that shows the relatedness of every possible living thing.

Linnaeus

Although there were some attempts through history to categorize plants and animals, the science of *biological taxonomy* (classification of life) did not truly begin until the pioneering work of Swedish biologist Carl Linnaeus in the 1750s.



TECHNICAL STUFF Linnaeus created a hierarchical system with five tiers:

- **Kingdom:** The top-level distinction between animals, plants, and minerals.
- **Class:** A high-level distinction. For animals, Linnaeus had classes of mammals, birds, fish, insects, and so on.
- **Order:** Mammals, for example, were divided into orders such as primates (humans, apes, monkeys), ferae (dogs, cats, weasels, and so on), cetae (whales, dolphins, and so on).

- **Genus:** For example: cats, dogs, bears.
- **Species:** For example: lion, tiger, brown bear, human.

The concept of *species* is important in biology: For species that reproduce sexually, it is the largest group of organisms that can mate with other members and produce fully functioning offspring. For asexual species, the definition becomes a little more difficult, because individual strains and colonies begin to diverge genetically, but some working definitions are possible.



REMEMBER Since Linnaeus's time, the tree of life has been reorganized and refined many times. In particular, the discoveries of evolution by natural selection in the 1800s, and the recognition of DNA and subsequent science of genomics have greatly enabled scientists to realize connections between branches of the tree that would otherwise have gone unrecognized on the basis of external appearance alone. In addition, whole new divisions of life have emerged.

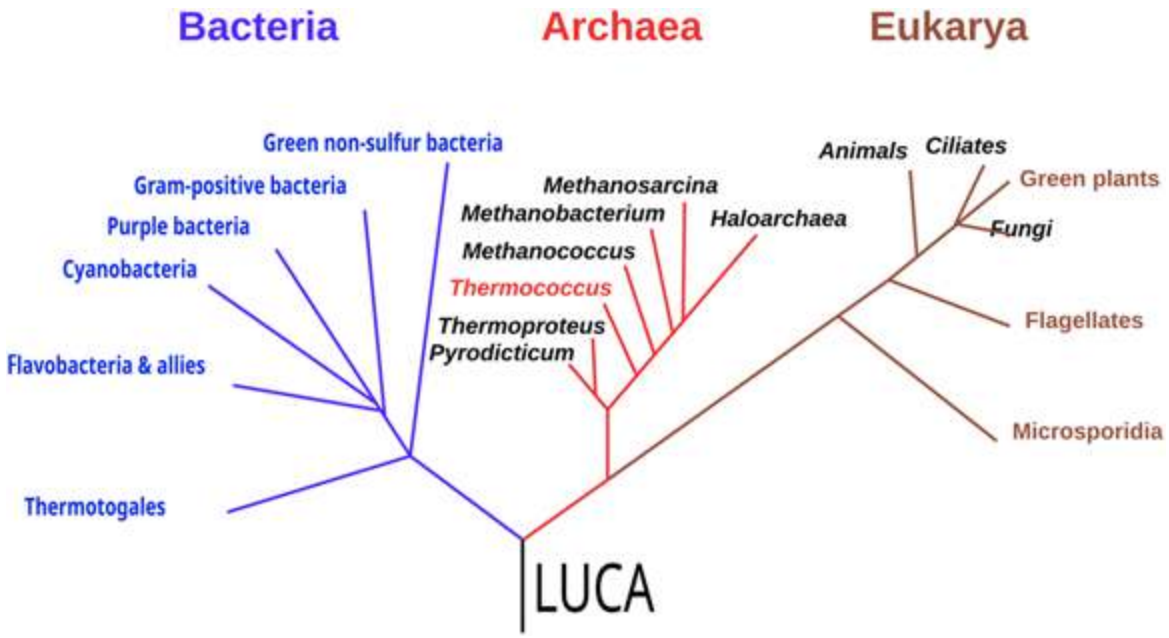


TECHNICAL STUFF Important revisions since Linnaeus include:

- **Addition of phylum and family:** In 1866, the German scientist Ernst Haeckel introduced the additional level of "phylum," sitting below "kingdom," but above "class." Also, in the mid-19th century the term "family" began to get widespread usage as a level of distinction between "order" and "genus."
- **Two empires:** In 1925, French biologist Eduard Chatton proposed a split above the animal/plant kingdom split of Linnaeus. At the level of "empire," organisms are divided into those with a cell nucleus (*eukaryotes*, including most animals and plants) and those without a

cell nucleus (*prokaryotes*, consisting of single-celled bacteria and their cousins, archaea).

- **Three domains:** Revolutionary work by Carl Woese and others in the 1980s led to an important understanding that not all single-celled organisms (prokaryotes) were alike. In fact, Woese argued that two separate types existed: bacteria and archaea, with archaea being more closely related to the eukaryotes (see Figure 4-6).



Credit: Chiswick Chap/https://commons.wikimedia.org/wiki/File:Phylogenetic_tree_of_life_LUCA.svg/CC BY-SA 4.0/last accessed Oct. 10, 2026.

FIGURE 4-6: The tree of life after revisions by Woese in 1990. LUCA = last universal common ancestor.

Since 1990, further divisions and revisions of the highest level of taxonomy have been proposed and continue to be contested as the DNA record is enlarged and investigated. Even today, there is no general agreement on biological taxonomy.

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Chapter 5

History of Life on Earth

IN THIS CHAPTER

- **Understanding how the fossil record was used to trace the rise of life**
- **Learning about the major eons of development of the Earth**
- **Finding out how mass extinction events led to dramatic changes for life on Earth**

When you think of life on Earth, you probably think mostly about *present day* life on Earth in all its rich diversity — forests of tall trees, flocks of birds, oceans full of fish, savannas teeming with herd animals, and more. However, life has existed on Earth for a very long time, and for most of that time it looked much simpler and different from life today. For scientists, the clues from past life helped advance our understanding of how life arose — a key question in astrobiology.



TIP In this chapter, I show you how geologists studying rocks first began to get curious about earlier forms of life, which led eventually to a questioning of life's entire history on Earth.

I give you a brief tour through 4.5 billion years of the Earth's geological history, focusing on the planet-wide characteristics that changed over this time that influenced the changing *habitability* of the Earth. You see how the changing environment affected life, as temperatures warmed and cooled, sea levels rose and fell, and different dynasties of life came and went.

Things started modestly — just some single-celled organisms hanging out in the ocean. Hundreds of millions of years passed quietly … but

then, changes began to come thick and fast. Fueled by a new availability of oxygen, life *exploded* in diversity. This eventually led to the rise of flowering plants, trees, birds — flora and fauna of all types — and eventually, you and me.

To begin the journey, let's see how the evidence for all these changes was accumulated: through painstaking work over centuries by geologists to build up the geologic and fossil record.

Finding Clues in Ancient Rocks

As the scientific enlightenment period got underway in Europe in the late 1600s, a more methodical approach began to be applied to collecting and categorizing rocks. This was especially true of rocks containing fossils — traces of once-living creatures in the form of imprints in the rock, or as preserved skeletons that had become *lithified* (replaced by minerals), such as dinosaur bones.



REMEMBER Over time (no pun intended), scientists realized that the layering of different rocks and fossils showed that they belonged to different time periods, which could be placed into order of occurrence. The resulting science of ordering rock layers and from it deriving a historical record of geological changes become known as *chronostratigraphy* — meaning "time ordering of layers."



TIP There are many twist and turns, false starts, and dead ends in this difficult undertaking — too many to relate in a book on Astrobiology, but if you're interested in learning more, check out *Geology For Dummies* by Alecia M. Spooner (Wiley). Eventually, however, a coherent picture began to emerge, which is still being actively refined today.

For our purposes — understanding the rise of life — I'll mention just a few of the pivotal players and their contributions to the field:

- **Niels Steensen (1638–1686) (also known by his Latinized name, Nicholas Steno)** was a Danish scientist and later bishop. In a 1669 treatise, he proposed four principles of stratigraphy (the study of rock layers), such as the *principle of cross-cutting relationships*: "If a body or discontinuity cuts across a stratum, it must have formed after that stratum." His principles are still actively used by stratigraphers today.
- **James Hutton (1726–1787),** a Scottish geologist and polymath sometimes hailed as the "father of modern geology," advanced the idea that the Earth's past history can be deduced from the geological record. He advocated for an ancient Earth, in contradiction to "young Earth" derived from a literal reading of the Bible, where the Earth's history begins with humanity. In his 1788 book, Hutton proposed the radical idea that much of currently observed land had once been seabed, implying that large geological changes over time took place.
- **William Smith (1769–1839)** was an English geologist and surveyor. Initially for practical purposes such as canal digging and mining, he produced the first detailed geological map of England, Wales, and parts of Scotland. In the process, he pioneered and popularized modern geological mapmaking techniques, such as the use of color to indicate different rock types, and even the 3D cutaway block diagram.
- **Charles Lyell (1797–1875),** another Scottish geologist, greatly extended and expanded on the work of Hutton, and is considered the father of "uniformitarianism" — the idea that the Earth continues to evolve slowly over time, and moreover has existed for an infinitely long period of time.



TIP These developments culminating in the late 1800s led to the formalization of the field of chronostratigraphy at the 2nd International Geological Congress in Bologna, Italy in 1881.

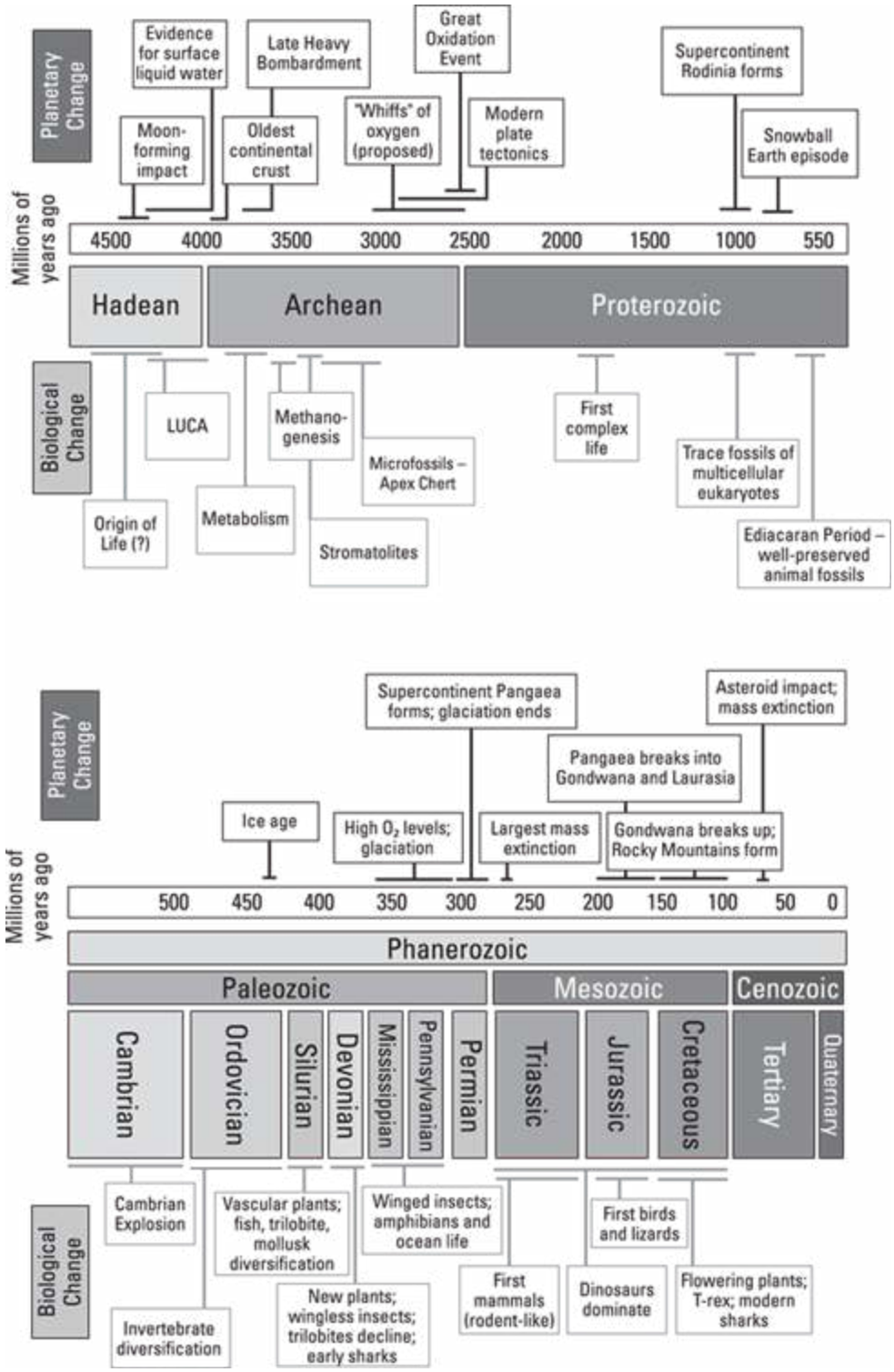
Ordering the Earth's Rock Records

This painstaking work to understand the geological record gradually resulted in the geological timeline used today.



REMEMBER Just as the tree of life is divided into large and small divisions: kingdom, phylum, order, class, family, genus, species — the geological record is also divided into large and small divisions. The largest time step is an *eon*, of which four are distinguished (see Figure 5-1):

- **Hadean:** The period of initial formation of the Earth and subsequent solidification, cooling and stabilization.
- **Archean:** The period that witnessed the origin of early life.
- **Proterozoic:** The period when the atmosphere changed and became oxygenated, allowing for life to harness respiration to generate energy.
- **Phanerozoic:** The most recent times, which began with the *Cambrian Explosion* when life rapidly diversified.



with permission of LabXchange

FIGURE 5-1: Earth's geological timeline.



TECHNICAL STUFF Smaller time divisions are the *era* (such as Paleozoic), which is divided into *periods* (such as Cambrian) and then into *epochs* and finally into *ages* (epochs and ages aren't shown in Figure 5-1). As we go further back in time, the geologic record is less well preserved, and so most of the smaller divisions are defined only for the most recent, *Phanerozoic* eon, where we have the most complete data. Collectively the three earlier eons are sometimes lumped together as the Precambrian *supereon*.



TIP Each of the major eons is associated with large changes in the development of life, and I now describe the conditions associated with each.

The Earliest Times: The Hadean

Back at the *very* start was the *Hadean* eon, named for the hellish conditions thought to have characterized this period (*Hades* being the underworld in the legends of ancient Greece), when the Earth was still hot from formation.



REMEMBER At around 4.6 billion years ago, the Earth had just coalesced from lumpy masses of dust and gas that formed in the debris disk around the nascent Sun. While our planet was still cooling and solidifying, it was pummeled for many more millennia by large impacts (see Figure 5-2) — including the large early impact that formed the Moon. The Hadean ended with a final drubbing of large impacts known as the Late Heavy Bombardment, around 4.0 billion years ago.



Credit: Generated with AI using OpenAI

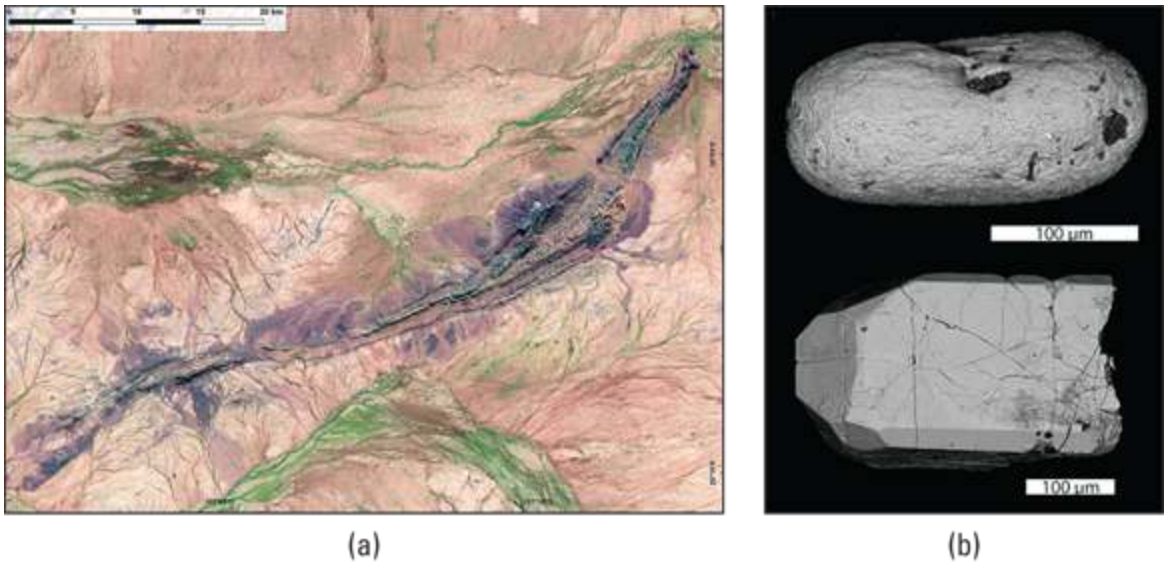
FIGURE 5-2: The Earth during the Hadean eon undergoing the Late Heavy Bombardment.

TIP See Chapter 11 for more details about the Earth's early formation process, and what we can learn about it today from study of meteorites.

Zircons: The oldest rocks

TECHNICAL STUFF The Hadean is the Earth's dimmest and most distant past — rocks from this period were mostly melted and remade many times over, and the geological record is consequently very sparse. The oldest crustal samples we have are *zircons* — tiny grains of

zirconium silicate ($ZrSiO_4$) that have survived through several different eras of rock formation. Zircons have been found with a range of ages from the Hadean eon. The oldest come from the Jack Hills in Western Australia (see Figure 5-3), and are dated at 4.4 billion years in age — almost as old as the Earth.



Credit: (a) Gretarsson/Wikimedia Commons/CC BY 4.0 (b) NASA/Public domain

FIGURE 5-3: (a) Aerial view of the Jack Hills, Western Australia. (b) 4.4 billion year old zircon crystals from the Jack Hills.

Life in the Hadean?

If you suspect that the Hadean eon was likely a tough period for life to take root, you'd be right. The earliest definitive evidence of life in the fossil record comes from much later, in the Archean eon at 3.5 billion years ago (see next section).

TECHNICAL STUFF

However, there is possible *indirect* evidence for life in the Hadean, in a 4.1 billion year old zircon from the Jack Hills. This single grain shows a peculiar ratio of two isotopes (atomic variants) of the element carbon — where the carbon-12 form is slightly enhanced relative to the heavier carbon-13 form. This is a known characteristic of living matter today, since life prefers to use the

slightly lighter isotope, which is easier to chemically manipulate. However, this is tenuous evidence at best, since many non-biological processes can also affect the isotopic ratios of chemical elements.

What sorts of life might have existed in the Hadean? A good candidate for the earliest lifeforms are hydrogen-guzzling bacteria known as *chemoautotrophs*, which are still found today living around deep-sea vents (see Chapter 9). These use available chemical energy rather than sunlight to generate food, a simpler mechanism that could have developed before later photosynthesis. These were likely followed by early *anoxygenic* photosynthesizers that consumed hydrogen sulfide (H_2S) and excreted sulfur, before the rise of modern *oxygenic* (oxygen-releasing) photosynthesizers, which I describe in the next section.



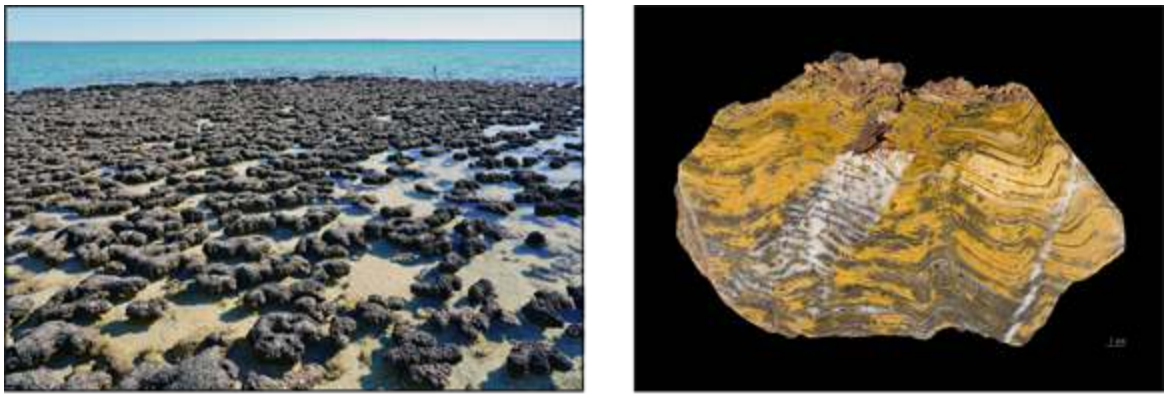
TIP It's important to also mention that during the Hadean — if life started at all — the first several starts may have been extinguished by giant, planet-sterilizing impacts. Therefore, life may have had to restart more than once.

The Rise of Life: The Archean

Conditions become significantly more pleasant in the Archean eon (4.0 to 2.5 billion years ago) — and this is when we begin to have solid evidence that life was firmly underway.



REMEMBER The most certain evidence in the fossil record for the earliest life are fossilized *stromatolites* dating from around 3.5 billion years ago. Stromatolites are layered mineral deposits created by microbial mats — sheets of photosynthesizing bacteria (cyanobacteria) that lived (and in some places, still live) in shallow water. See Figure 5-4.



(a) (b)

Credit: (a) eqroy/Adobe Stock Photos (b) Didier Descouens/Wikimedia Commons/CC BY-SA 4.0

FIGURE 5-4: (a) Stromatolites at Shark Bay, Western Australia, present day. (b) Fossilized stromatolite layers from the Pilbara Craton, Western Australia, dated at 3.6 to 3.2 billion years in age.

TECHNICAL STUFF

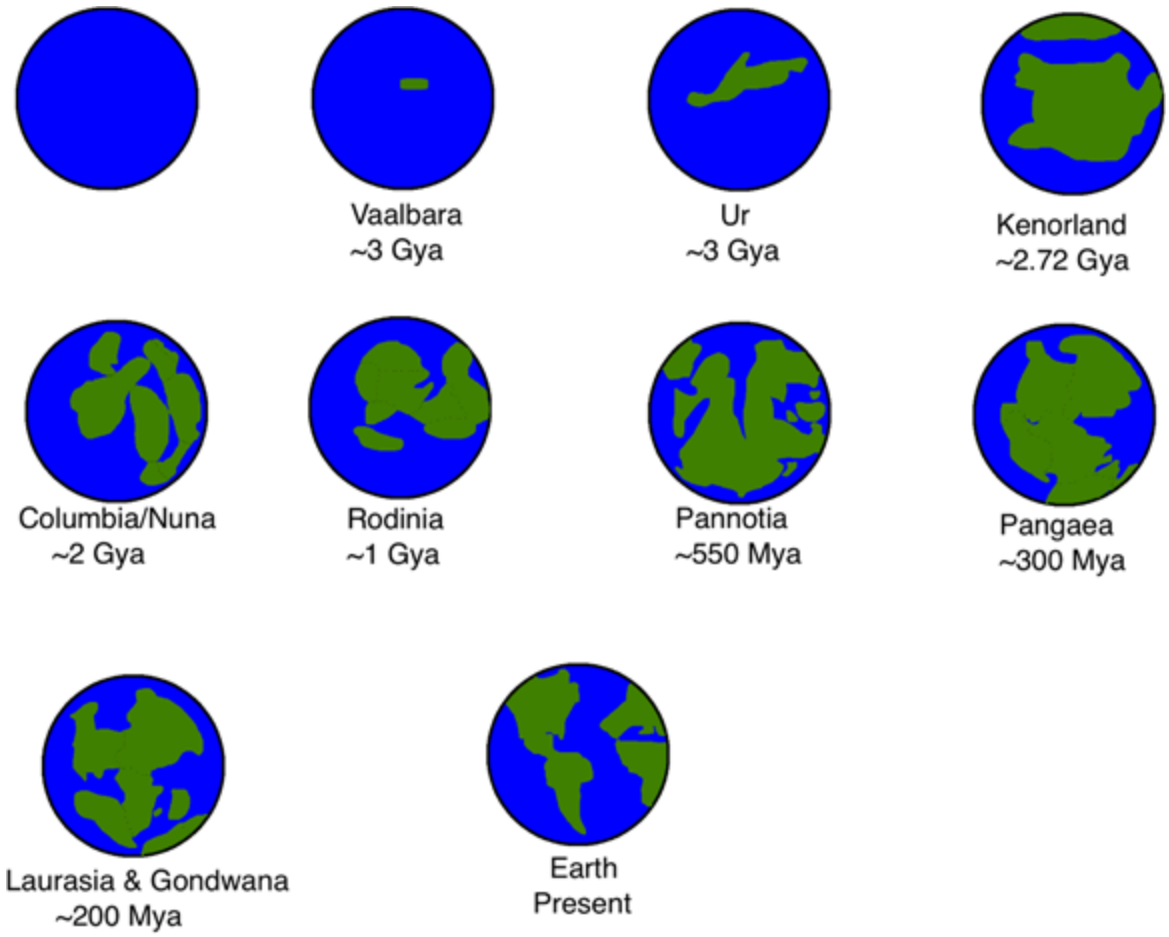
There is tentative evidence for even earlier life in the Archean, but like the Jack Hill zircons of the Hadean, this remains quite uncertain. Banded iron formations found in Greenland and dated to have formed 4.32 to 3.77 billion years ago may be even earlier evidence for microbial mats. Ancient graphite (a form of carbon) that *may* be remains of life has also been found in Greenland, dating to 3.7 billion years in age. Whatever the exact age, it seems likely that life did get underway in the Archean.

Getting Some Oxygen: The Proterozoic

The third eon of the Earth's history was also the longest: the Proterozoic, stretching from 2500 to 539 million years ago. The geologic record of this time period is much better preserved than in the Archean (let alone the Hadean), and many rocks are preserved that are minimally altered, or

even unaltered. This makes its study much easier and our knowledge more complete.

Proterozoic rocks retain the first definitive evidence of *supercontinent cycles:* waves of colliding giant landmasses, that came together and disintegrated time and time again (see Figure 5-5). This activity may have greatly affected the Earth's atmosphere through the release of gases.



Credit: SimplisticReps/Wikimedia Commons/CC BY-SA 4.0

FIGURE 5-5: Proposed supercontinents on Earth.

GOEing with Great Oxygenation Event

The start of the Proterozoic was marked by a rise in oxygen in the Earth's atmosphere: a key event in the Earth's history known as the *Great Oxygenation Event (GOE)*. The GOE was caused by the effect of the photosynthetic cyanobacteria that arose in the Archean, with

countless numbers of cells busy converting water (H_2O) and carbon dioxide (CO_2) to methane (CH_4) and releasing oxygen (O_2) in the process.



TECHNICAL STUFF From 2.3 to 1.9 billion years ago, iron was able to absorb some of the produced oxygen, slowing the increase in oxygen content. But oxygen continued to steadily accumulate in the atmosphere, allowing new types of life to proliferate and causing others to die out. For this reason, the GOE is also known as the *Oxygen Catastrophe*, due to the mass extinction it caused. Cyanobacteria continued to thrive for a while, reaching their peak at 1.25 billion years ago and then declining as a proportion of the Earth's biosphere.

The rise in oxygen also caused a simultaneous cooling of the planet, as oxygen reacted with methane (a strong greenhouse warming gas) to form weaker greenhouse gases water and carbon dioxide. The consequence was a global drop in temperature, and glaciers advanced across the planet from 2.5 to 2.2 billion years ago in an event known as the *Huronian Glaciation*.

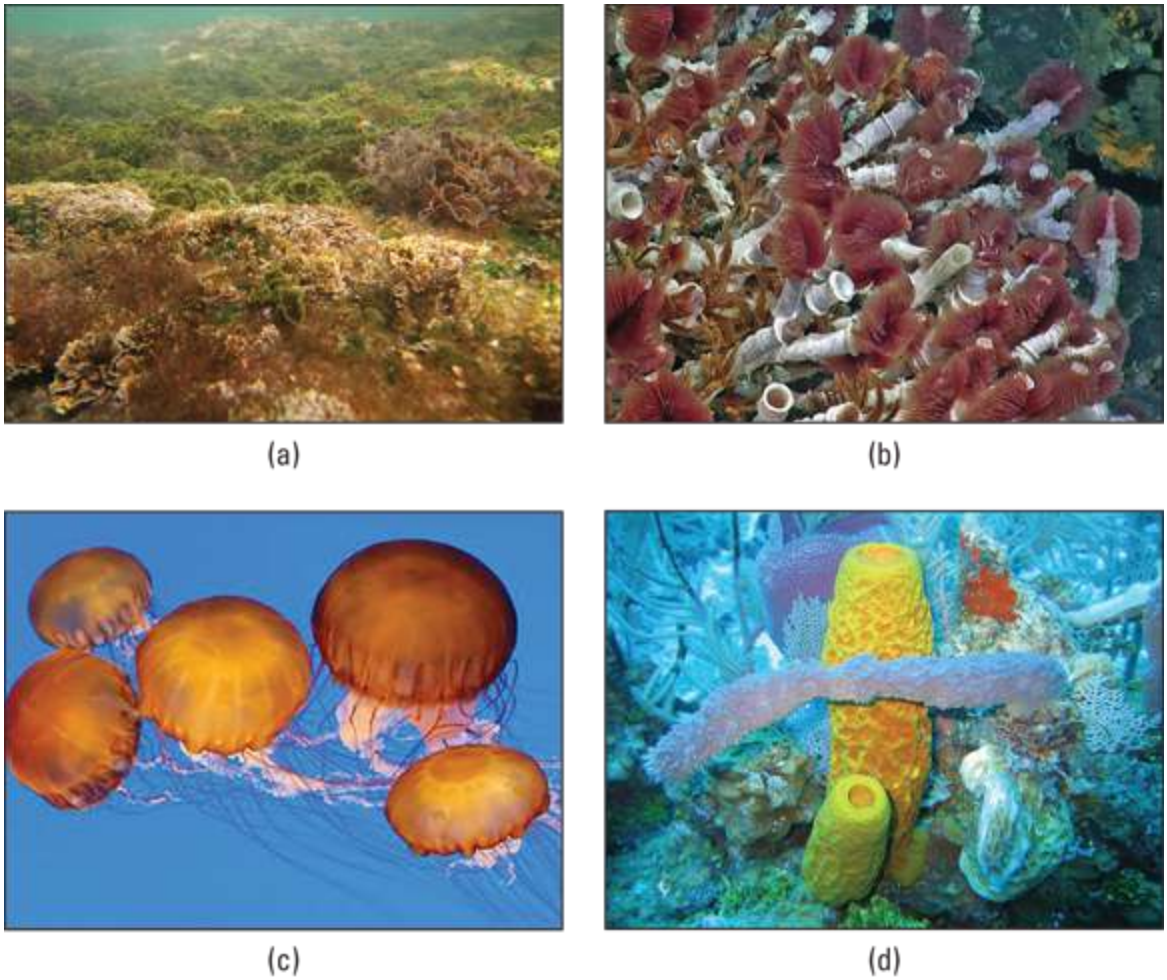
Oxygen and cells



TECHNICAL STUFF The rise of oxygen had important consequences for the machinery of cells. Molecules known as *reactive oxygen species (ROS)*, such as NO, H_2O_2, and HO_2, would have become more abundant at this time. ROS can cause damage to fragile DNA, requiring the development of more sophisticated DNA repair mechanisms. It is thought that this gave rise to key new developments in cells, including the development of a new type of

cell containing a nucleus — *eukaryotes* — and the use of *mitochondria* to generate energy.

REMEMBER The later Proterozoic saw the advent of multicellular life. Some examples of eukaryotes that trace their development to the Proterozoic are shown in Figure 5-6.



Credit: (a) Toby Hudson/Wikimedia Commons/CC BY-SA 4.0 (b) Oregon State University/Flickr/CC BY-SA 2.0 (c) Changku88/Wikimedia Commons/CC BY 4.0 (d) NOAA/Wikimedia Commons/Public domain

FIGURE 5-6: Lifeforms that originated in the Proterozoic: (a) algae; (b) worms; (c) jellyfish; (d) sponges.

Life's Full Richness: The Phanerozoic

Finally, we arrive at the dawn of the Phanerozoic eon, dated to 538.8 million years ago, and the most significant event in the tree of life, known as the *Cambrian Explosion*. This period at the start of the Phanerozoic saw a huge blossoming and divergence of life into many of the forms we see today: flowering plants, birds, reptiles, land animals, and of course — humans.

The Cambrian Explosion



TIP The Cambrian period was marked by a dramatic change in the fossil record. This was noted as far back as 1698 when Edward Lhuyd, curator of the Oxford Museum, described a stratum (rock layer) rich in deposits of a particular fossil, a *trilobite*. These were strange looking sea-dwelling creatures, that may be related to today's horseshoe crabs (see Figure 5-7).



(a) (b)

Credit: (a) Amir Ali Iranshahi 3/Wikimedia Commons/CC0 1.0 (b) Shubham Chatterjee/Wikimedia Commons/CC BY-SA 3.0

FIGURE 5-7: (a) A fossilized trilobite. (b) A horseshoe crab today.



TECHNICAL STUFF The appearance of this layer of fossilized sea creatures — preceded by no apparent evidence of earlier life — posed a serious conundrum to Charles Darwin and his evolutionary theory, since trilobites had apparently appeared "out of the blue" at 539 million years ago, without having evolved from an earlier, simpler creature. The riddle was not solved until much later when evidence for Precambrian life in the Proterozoic was recognized — the problem being that most earlier lifeforms had flimsy bodies lacking skeletons that did not preserve well as fossils.



REMEMBER The causes of the Cambrian Explosion are still debated. A leading contender is environmental changes, including continued oxygenation of the atmosphere, along with decreasing amounts of sulfide in seawater after 800 million years ago, that may have helped complex multicellular life to proliferate.



TECHNICAL STUFF Sulfide interferes with mitochondrial metabolism (energy generation) in eukaryotes (organisms with cell nuclei), and a decrease in ocean sulfide would have allowed eukaryotes greater use of oxygen to grow and diversify. Another atmospheric change that may have helped is an increase in ozone, a heavy oxygen molecule (O_3), that is important in blocking harmful UV sunlight that can damage cells.

Other changes that may have contributed to the Cambrian Explosion that have been proposed include: ecological changes, the development of horizontal gene transfer, and even the development of the eye, which may have precipitated an "arms race" between new predator and prey

species, and leading to the development of more complex cognitive abilities and faster evolution and speciation.

Dinosaurs and extinctions

A discussion of the Phanerozoic eon and its blossoming of life would not be complete without mentioning the sudden dramatic occurrences of the exact opposite: mass extinction events.

Five major extinctions are thought to have occurred in the Phanerozoic:

- **Late Ordovician mass extinction, 445–444 Ma:** This event, occurring at the boundary between the Ordovician and Silurian periods, is estimated to have resulted in the loss of 27 percent of families, 57 percent of genera and 85 percent of species. The initial cause is thought to have been a major episode of global cooling and glaciation, triggered by volcanic activity that released ash that blocked significant amounts of sunlight. A second wave of the extinction occurred following the subsequent thawing.
- **Late Devonian mass extinction, 372 Ma:** The Late Devonian extinctions are thought to have come about due to loss of oxygen in the sea. Land nutrients, perhaps released from volcanoes, were carried into the sea where they caused algal blooms. As the algae died and decomposed on the sea floor, they consumed oxygen, which led to a mass dying of corals and benthic (sea floor) animals, including many trilobites. The loss is estimated at 19 percent of families, 50 percent of genera and 70 percent of species.
- **Permian-Triassic extinction event, 252 Ma:** The Permian-Triassic (P-T) boundary extinction was the largest in the entire Phanerozoic, with 53 percent of marine families, 83 percent of marine genera and 81 percent of marine species disappearing — including the previously ubiquitous trilobites. However, this event allowed opportunities for new land animals to proliferate including crocodilians and — dinosaurs.
- **Triassic-Jurassic extinction event, 201.3 Ma:** This extinction event that occurred during the "rule" of dinosaurs wiped out many of their

competitors (most archosaurs). In this event, 23 percent of families, 48 percent of genera and more than 70 percent of all species became extinct, leaving dinosaurs with little competition on land (see Figure 5-8).

- **Cretaceous-Paleogene extinction event, 66 Ma:** The reign of dinosaurs finally did come to an end, in this most well-known of mass extinctions. This was triggered when a massive asteroid crashed into the Yucatan Peninsula, throwing up debris that blocked sunlight and caused global dying of plants and animals (17 percent of all families, 50 percent of all genera and 75 percent of all species). Although dinosaurs became extinct, mammals began to take the spotlight, further proliferating and diversifying to eventually become … us.



Credit: Evolutionnumber9/Wikimedia Commons/CC BY-SA 4.0

FIGURE 5-8: Reconstructed skeleton of a Tyrannosaurus Rex dubbed “Sue” at the Field Museum in Chicago.

Before moving on, a look at how one of geology’s greatest mysteries in was solved.

WHY DID THE DINOSAURS DIE OUT?

As the field of paleontology (study of fossilized life) developed, more and more different species of vast reptiles — dinosaurs — were discovered in the fossil record. These were found in strata (rock layers) from 230 million years ago to 66 million years ago, when they suddenly vanished. But why? Some sort of climatic change was implicated, but the details were hotly debated. Some scientists advocated for a huge volcanic eruption that occurred at around the same time, whereas others favored a change in sea level. However, the dinosaur extinction appeared to happen too suddenly for these theories to be the right explanation. The puzzle was solved in 1980 when a team of researchers, led by physicist Luis Alvarez, discovered that the 66 million year old rock boundary was rich in a rare metal — iridium — that is scarce in the Earth's crust but more common in asteroids and meteorites. This led them to propose that a giant impact had thrown up gases and dust into the atmosphere, cooling the planet in an abrupt episode of climate change. The hunt for a suitable large impact crater was on, and some believed that the evidence would never be found, due to Earth's constantly moving plates and erosional processes. However, 10 years later, a giant crater measuring 180 km (110 mi) in diameter was identified buried under sediments in the Yucatan Peninsula of Mexico (the Chicxulub crater), and was dated to have formed 66 million years ago. Alvarez's team were vindicated and the mystery was solved.



REMEMBER The study of mass extinctions shows how the changing climate and natural catastrophes can influence the course of life on Earth in dramatic ways, leading to the downfall of previously successful species and new opportunities for others. Mass extinctions are part of a larger pattern where life is seen to evolve in fits and starts — mostly slowly, but sometimes very rapidly. This concept is known as *punctuated equilibrium*.

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Chapter 6

From Chemicals to Cells

IN THIS CHAPTER

- **Finding out the raw ingredients on the Archean Earth that reacted to make life**
- **Discovering how RNA is the ultimate multi-tasking molecule**
- **Learning how RNA colonies made the jump into cells**

Back in Chapter 1, I said that astrobiology seeks to answer two fundamental questions, the first of which is "How did life start on Earth?" In this chapter, I explore this question in detail.



REMEMBER This is the mysterious process scientists refer to as *abiogenesis* — the emergence of complex life from simpler, nonliving matter. Another way to look at this is biology arising from chemistry — just as chemistry in turn arises from physics.

I'll also give away the punchline up front — we don't know the complete answer to this question right now (some scientists may call this job security). Although this may seem a little frustrating, it's also what makes astrobiology an exciting and compelling field. After all, wouldn't *you* like to help to decipher the mysteries of life origins?



TIP Despite our lack of complete knowledge, science is steadily making exciting discoveries and breakthroughs that are chipping away at the edifice of the larger question, which you learn about in coming sections of this chapter.

First, I describe the simple chemicals that we know were present on the early Earth and consider how these could have self-organized in ever more complex ways to form the recognizable building blocks of life. Then, I consider how these building blocks became the home for life — the cell.

Finally, I consider how more complex cells emerged over time from simpler ones, setting the stage for the origin of multicellular life.

Setting the Stage for Life



TIP If abiogenesis can be likened to the baking of a cake — transforming basic ingredients into a complex creation — we need to know what ingredients are available, what cooking methods are at our disposal, and where the baking can take place.

In this section, I set the stage by looking at what ingredients were available, and where and how they could have come together. First, let's revisit some basic chemistry to get reacquainted with how chemistry happens.

Building bridges with carbon bonding

Carbon is literally the stuff of life. This may seem surprising at first, given that we tend to think of carbon as either graphite (pencil lead), dusty black soot, or glittering but lifeless diamonds. But not typically as living material.



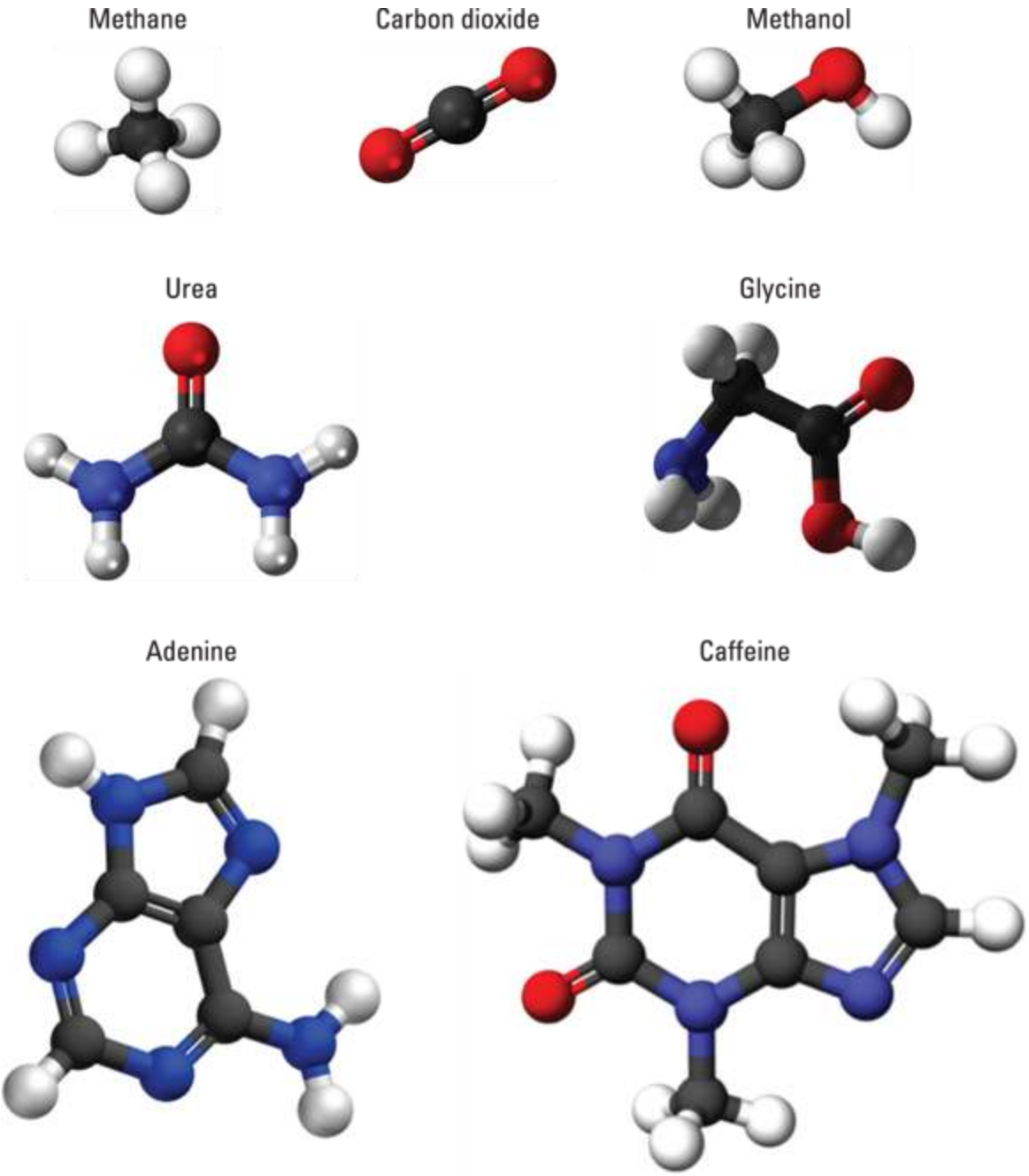
REMEMBER Nevertheless, the sixth element of the periodic table has a secret superpower, which is the ability to form four strong (*covalent*) chemical bonds with other atoms, enabling it to construct a dizzying array of molecules — far more than any other atom. Think of carbon as the universal building brick.

Some common carbon molecules are shown in Figure 6-1, from simpler types at the top row, to more complex at the bottom. There is no limit to the size of carbon-based structures, with some proteins stretching into tens of thousands of atoms.



Carbon-based molecules are sometimes referred to as *organic molecules*, a nod to carbon's importance in building the molecules needed for life. However, not all carbon molecules are associated with life: The planets Uranus and Neptune contain vast amounts of methane (CH_4), whereas the atmospheres of Venus and Mars are largely CO_2. Nevertheless, the larger, more complex carbon molecules on Earth are usually created by life, since they are unlikely to be created randomly by *inorganic* processes.

The molecule urea presents a fascinating example in the evolution of thinking about carbon molecules (see the sidebar, "What Is an Organic Molecule?").



Credit: The author using components from Wikimedia

FIGURE 6-1: From simple to more complex carbon (organic) molecules.

TIP

WHAT IS AN ORGANIC MOLECULE?

The molecule urea (shown in Figure 6-1) — formula $CO(NH_2)_2$ — is an important chemical for life, excreted by many animals and plants as a waste product and way to get rid of toxic ammonia, itself a byproduct of metabolism. Until the 19th century, urea was believed to be a substance that could only be created by life, and hence an important piece of the theory of *vitalism.* Vitalism held that living and nonliving matter were fundamentally different, with living matter imbued with a vital, living energy that was not present in nonliving matter. In 1828, German chemist Friedrich Wöhler discovered how to synthesize (create) urea from simpler ingredients in a laboratory test tube, thereby dealing a mighty blow to the theory of vitalism. As chemists subsequently learned how to create more and more "organic" molecules abiotically, the previously sharp boundary between living and nonliving matter became permanently blurred.

Wöhler's breakthrough in the creation of urea became an important step toward modern ideas about abiogenesis — scientists and philosophers no longer needed to invoke life-giving deities or mysterious acts of creation to explain the origin of life, and could begin to look for chemical explanations for the origins of biology instead.

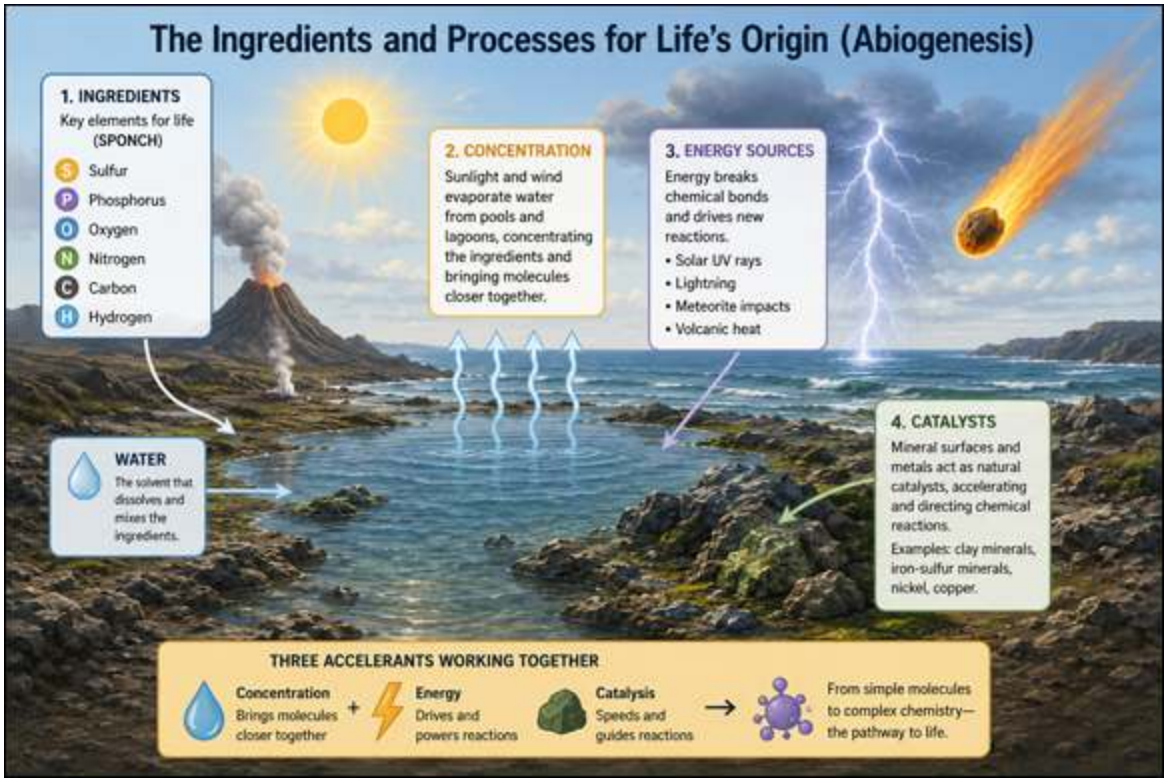
Gathering the ingredients for life



REMEMBER Let's now try to summarize what ingredients we believe were needed for abiogenesis to occur (see Figure 6-2):

- Supplies of the six most critical elements for life: carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulfur. Together these six are sometimes written as "CHNOPS" or even the more fun-to-pronounce "SPONCH." These would have been widely available on the early Earth in the form of water (H_2O), carbon dioxide (CO_2), methane (CH_4), ammonia (NH_3), and various sulfate and phosphate minerals.
- A solvent — water — that enabled the various ingredients to dissolve and mix together.
- A means to concentrate these ingredients, such as, for example, by gradual evaporation of the water solvent, pushing the basic molecules closer together and allowing them to react more quickly.
- Sources of energy to break chemical bonds and accelerate new chemical reactions, which could be solar UV rays, lightning, heating from a meteorite impact, or other forms.

» Possibly a third accelerant for chemical reactions, namely a *catalyst*. Catalysts come naturally in many different types, from metals to rocks, with different catalysts providing unique substrates (surfaces) that accelerate different types of reactions.



Credit: Generated with AI using OpenAI

FIGURE 6-2: Ingredients and processes that could have come together to allow life to emerge on the Earth's surface. Other locations and processes are also viable, such as the deep sea, or even in ice.

Where did life begin?

To continue the baking analogy, we also would like to know what the "kitchen" looked like. This is a place where the basic molecular ingredients (H_2O, CO_2, and so on) were able to come together, become concentrated, energized, and catalyzed to create more complex molecules.



TIP Life almost certainly began in water; however, this may not necessarily have been the open ocean, where it would have been difficult for high concentrations of ingredients to come together.

One theory is that life originated in a pond or pool (see sidebar "Primordial Soup or Warm Little Pond"), where water content gradually diminished, concentrating the ingredients. This may have been a coastal tide pool, or perhaps an inland pond created by rain or river flooding that gradually dried out. A pool on the Earth's surface had the advantage of a natural energy source: UV rays and heat from the Sun.



TIP An important characteristic of the modern version of "Darwin's Pond" is that there were cycles of drying and re-wetting. This would have allowed chemicals to link up during the drying-up spells, and then add more chemicals to growing chains by re-wetting with fresh nutrient-rich water.

Another idea is that life took hold near a deep-sea hydrothermal vent, where plentiful heat and chemical energy were available. In this case, life most likely began as complex molecules clinging to a rocky or mineral surface to prevent dilution into the wider ocean.

Yet another version holds that the basic ingredients for life may have been concentrated in pores within sea ice that gradually closed up, removing water molecules as the pores shrunk, and concentrating the remaining dissolved chemicals. Although this mechanism lacks an obvious energy source, the eventually high concentrations of molecules reached would have provided an accelerating rate of chemical reactions.

PRIMORDIAL SOUP OR WARM LITTLE POND?

When Charles Darwin first formulated his Theory of Evolution by Natural Selection, he pondered how the very first lifeform could have arisen, which later mutated into all the abundant diversity of life that came later. In an 1877 letter to his friend Joseph Hooker, he mused presciently: *"But if (& oh what a big if) we could conceive in some warm little pond with all sorts of ammonia & phosphoric salts, — light, heat, electricity &c present, that a protein compound was chemically formed, ready to undergo still more complex changes …"* This speculation presaged several later ideas along the same lines, most notably by Alexander Oparin in Russia in 1924, who wrote that on the early Earth, abundant ingredients, including carbon, hydrogen, water vapor, and ammonia, could have reacted to form the first organic compounds. A few years later, in 1929, the noted British chemist JBS Haldane suggested the term *soup* to describe the accumulation of organic material and water in the primitive Earth that reacted under stimulation of UV light. These speculations were spectacularly proved correct in 1953 in the famous *Miller-Urey experiment* (see Chapter 8). Today, the "warm pond" (or *primordial soup*) is thought to have been the place life did indeed start on the surface of the Archean Earth.

Building Complex Molecules

With some ideas of basic ingredients and locations for life to arise on the early Earth, we can next think about what sort of "cake" we want to bake. In other words, what sorts of larger molecules must be created as the next steps along the journey toward more complex life?



If we look at life today, we can deconstruct the highly complex molecules of living cells into some more basic molecular types:

- **Nucleobases** used to build *DNA (deoxyribonucleic acid)*, the information-carrying unit that enables a template for replication and modification of the "recipe," and *RNA (ribonucleic acid)*, a workhorse molecule that participates in many functions, including repair and replication
- **Amino acids**, which are key building blocks of *peptide chains*, that in turn link up to form *proteins*
- **Phosphates**, used to store and release energy, and as the structural backbones for DNA and RNA

- **Lipids**, a category of molecules that includes fats, used for multiple purposes including cell walls, energy storage, and signaling
- **Saccharides** or **sugars**, which are important energy storage molecules (as carbohydrates), structural units, and linking molecules in DNA and RNA

It seems logical that if life is to arise from very simple molecules, it must lead down the path of complexity toward some of these larger molecules. But which ones came first, and would any of these be able to "multitask" in isolation, accomplishing several of the roles above? If so, this would provide an easier entry point for life to develop further, adding more diverse and specialized molecules later.

Let's take a look now at what molecules may be able to serve as the "multitasker" of early life.

Stepping into the RNA World



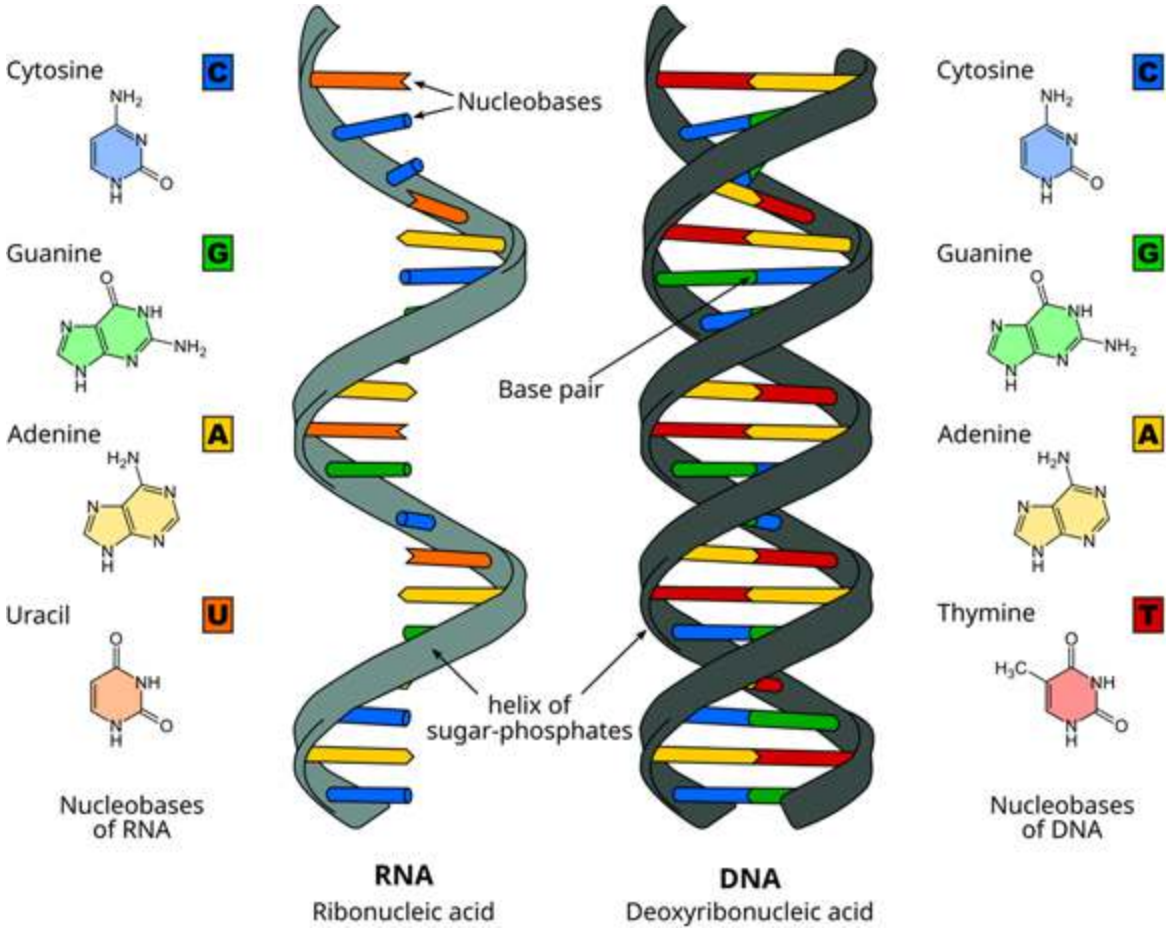
REMEMBER The most widely accepted candidate for the multitasking-molecule of abiogenesis is RNA. Although RNA is probably less familiar to non-biologists than its more famous cousin, DNA, RNA is much more versatile.

RNA is highly similar to DNA in that it is composed of four types of chemical subunits, known as *nucleobases* (see Figure 6-3), bound together into a spiral by a backbone of phosphates and a connecting ribose sugar unit.

However, RNA differs from DNA in three other important respects:

- Although DNA is composed of the molecules cytosine, thymine, guanine, and adenine (often represented by their initials: CTGA), in RNA the thymine unit is replaced by the slightly different variety, uracil (U).

- DNA mostly exists paired with a mirror image version of itself, into a "double helix," whereas RNA mostly is found as a single spiral.
- In DNA, the ribose sugar connecting the nucleobase to the phosphate has an oxygen molecule removed (hence the "deoxy-" part of the name).



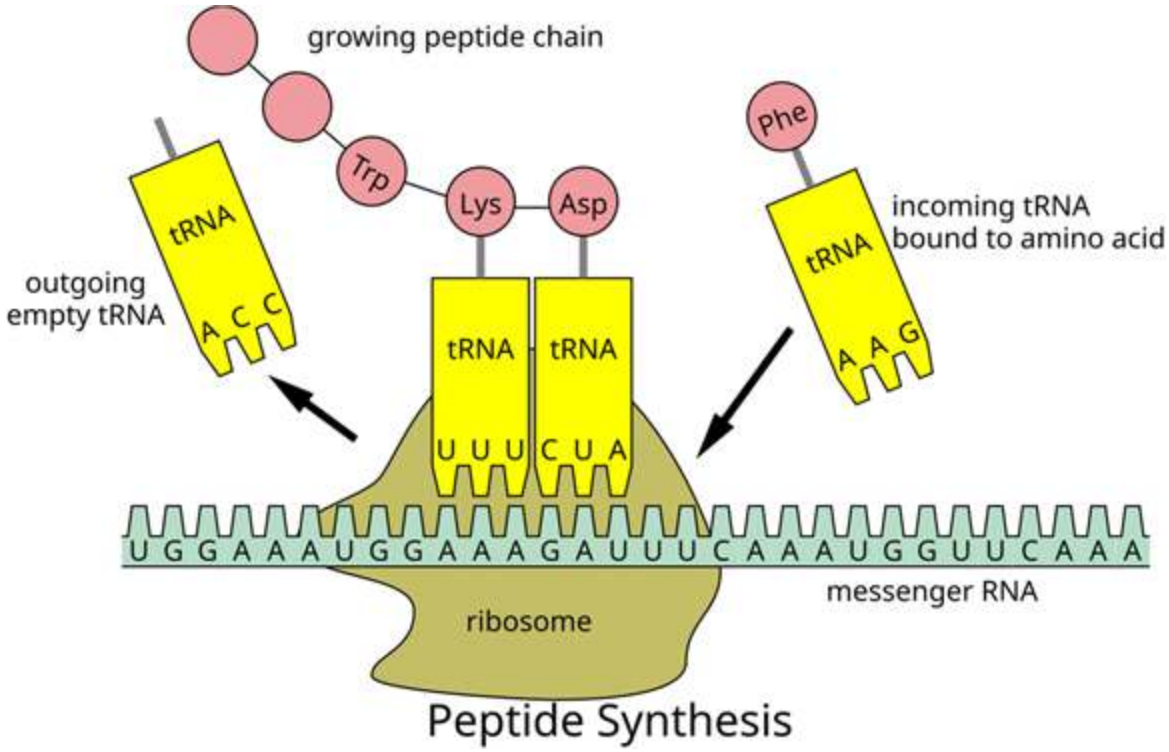
Credit: Sponk/Wikimedia Commons/CC BY-SA 3.0

FIGURE 6-3: Comparison between the DNA and RNA structures.

TECHNICAL STUFF

Whereas DNA primarily does the job of encoding information, RNA exists in many forms and structures and can accomplish a wide variety of tasks:

- **Information coding:** Like DNA, RNA can store and convey information, albeit in less stable form (more like a newspaper than a CD). In fact, so-called "messenger RNA" (mRNA) is used in our cells to store temporary copies of the DNA information as templates for building proteins.
- **Self-replication:** *Transcription RNA (tRNA)* is a worker bee of the cell. tRNA scavenges and gathers peptides, conveying them to a "factory" (ribosome), there adding them together to form peptide chains that make proteins.
- **Catalysis:** *Catalysis* is the process of speeding up, or favoring a certain chemical reaction to occur — an incredibly important process. There are many catalysts involved in life, but the ability of RNA to favor the creation of more building blocks of RNA is an important step toward self-replication. One form of catalytic RNA is ribosomal RNA (rRNA). Ribosomes serve as a kind of "protein factory," a production line for building peptides into protein chains using the mRNA "blueprint," whereas tRNA carries out the work (see Figure 6-4).



Credit: Boumphreyfr/Wikimedia Commons/CC BY-SA 3.0

FIGURE 6-4: Various forms of RNA working together to build proteins.



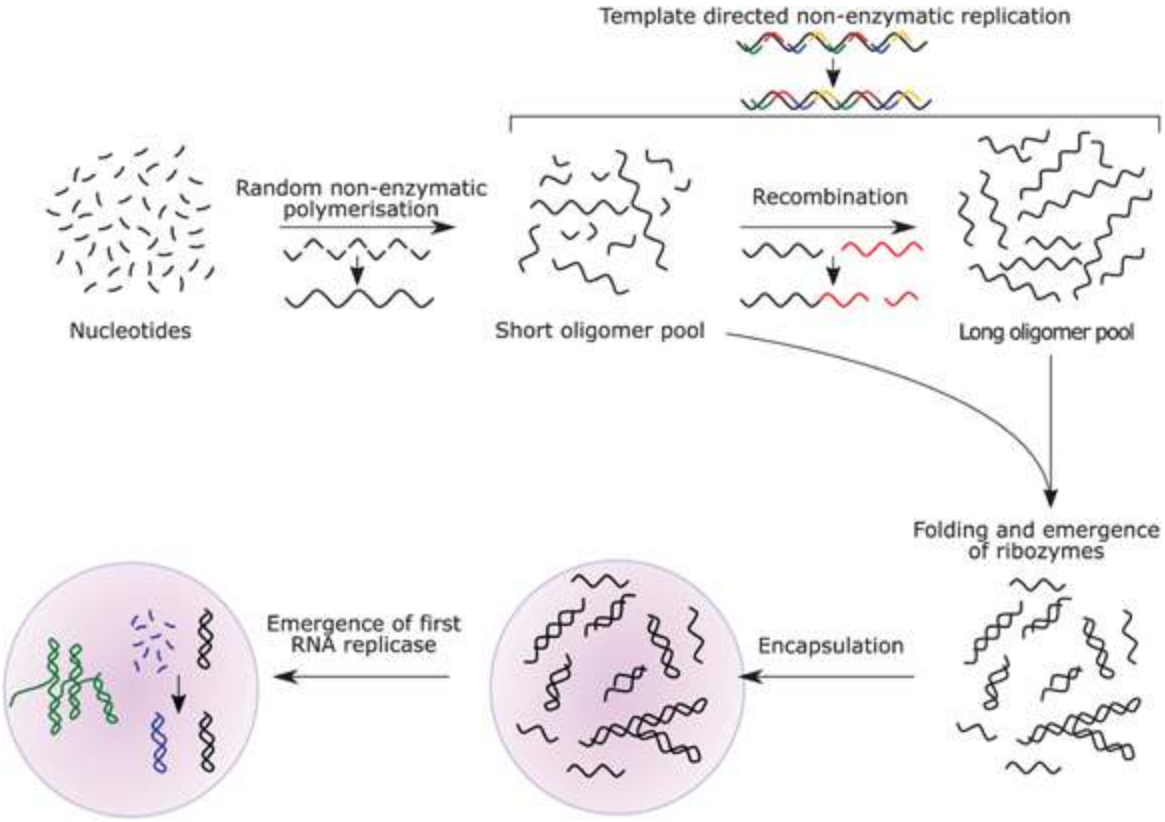
REMEMBER RNA is therefore like a robot that can build factories to make more robots. Figure 6-5 shows a summary of current thinking about how life could have developed from nonlife in the RNA world:

1. The basic building blocks of RNA — the nucleobases adenine, guanine, cytosine and uracil were readily available in the "chemical soup" derived from simple molecules + energy. This seems entirely plausible, as the nucleobases are indeed found in non-living environments such as meteorites and samples returned from asteroids (see Chapter 11).
2. The nucleobases occasionally joined with other nucleobases to form chains known as *oligomers*. Although some chains were unstable and broke up quickly, other chains were stable. These then grew by attracting more and more similar links.
3. After countless generations and combinations, some sets of oligomers developed that were able to autocatalyze (known as *ribozymes*), facilitating further copies of themselves. The development of autocatalytic ribozyme networks from pools of oligomers has been demonstrated experimentally.
4. Competition between ribozymes may then have favored the evolution of cooperation as a selective advantage, leading to the first *protocell*.
5. Eventually some ribozymes developed the ability to catalyze the formation of peptide bonds, allowing them to bind amino acids together into polypeptides and proteins. This would have conferred a further selective advantage to such ribozymes.



REMEMBER RNA is therefore the best candidate we have for the foundation of abiogenesis, being able to carry out many of the needed functions of life alone (in multiple different structures). However, the search continues for even simpler molecules of "pre-RNA world," that could form a more basic bridge between the nonbiological molecules and the RNA world.

Note that, although enormous strides have been made in understanding how abiogenesis could have occurred through the RNA world, there are still many key details to be worked out. This includes the leap from RNA-based information encoding to DNA-based encoding.



Credit: Kristian Le Vay and Hannes Mutschler/Wikimedia Commons/CC BY 4.0

FIGURE 6-5: The RNA world hypothesis.

Forming Protocells

If the RNA world took place in some warm pond, pool, or ice pore or near some undersea vent, it was likely first clinging to a surface as a film. This could have provided catalysis, as well as means for molecules to interact more easily than in an open-water environment.



REMEMBER At some point, however, we know that these ribozymal colonies must have made a leap into cells, the key units of life and Darwinian evolution today. This could have occurred as lipids collected on, or were generated by the ribozymal colony, that then detached into the open water, taking the colony of ribozymes along for the ride.

Inside the new home, the ribozymal community was able to remain compartmentalized from the surroundings, and different communities of ribozymes inside different "protocells" would have competed, or in some cases cooperated, to survive. Today, we only see the winners of the evolutionary race. Let's now take a look at what constitutes a modern cell.

Cellular signaling



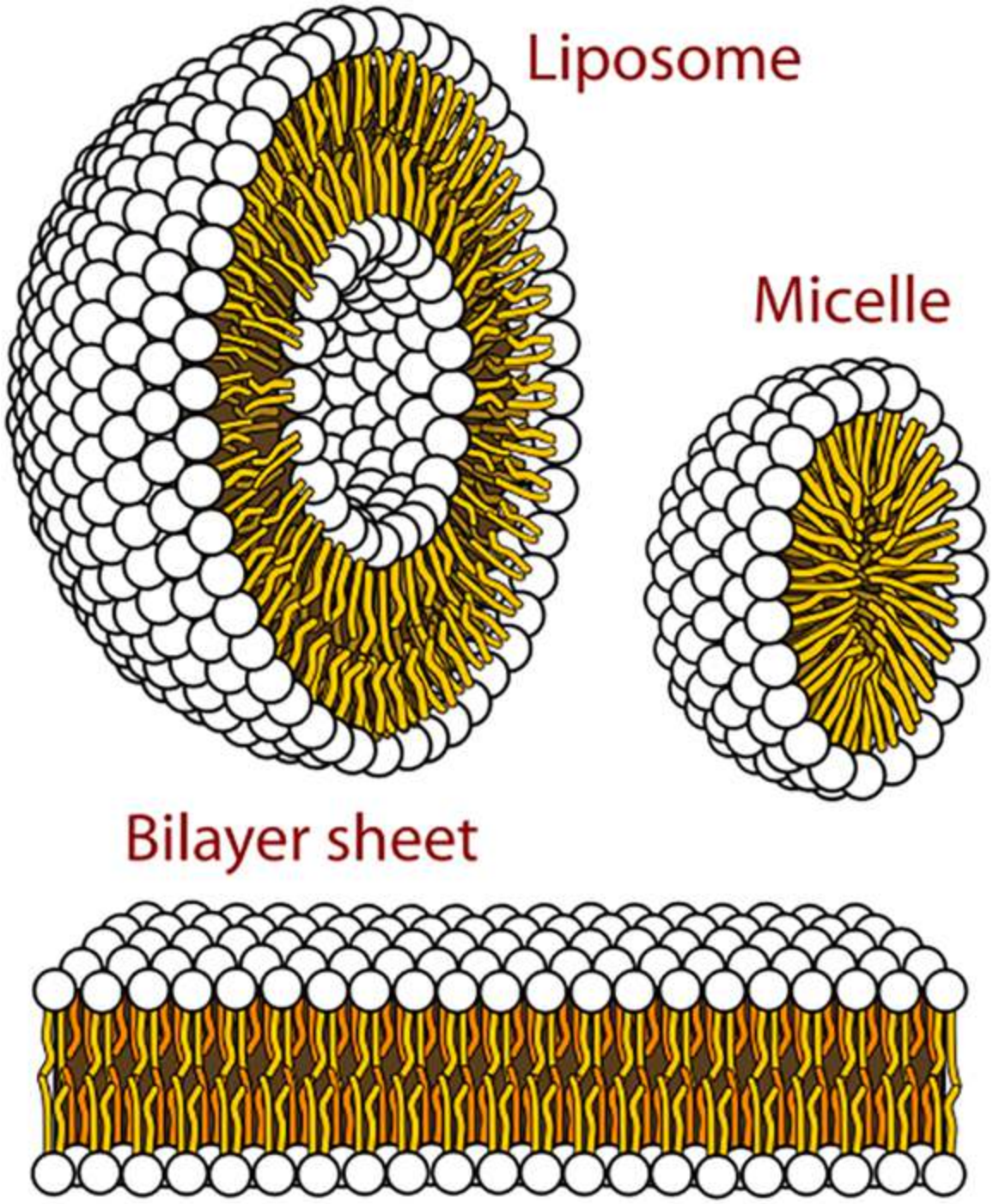
REMEMBER *Lipids* are a broad group of molecules including fats (triglycerides) and others. They are either *hydrophobic* — repelling themselves from water — or *amphiphilic* — where one end is hydrophobic ("hating water") and the other end is hydrophilic ("loving water"). Often, they consist of an electrically polarized "head," which is the part comfortable in water, along with a long "tail," which is an unpolarized carbon chain that rejects water.



TIP For a simple illustration of the hydrophobic nature of some lipids, try dropping a small amount of oil into water. The oil clings to itself, forming a distinct drop, and resists being dispersed into and dissolving in the water.



REMEMBER Because of the dual nature of the head and tail of amphiphilic lipids, they quickly self-organize into spheres — the water-loving head on the outside, dissolved in water, and the water-hating tails all facing inwards, clinging together. This type of structure is called a *micelle* (see Figure 6-6).



Credit: Mariana Ruiz Villarreal, LadyofHats/Wikimedia Commons/CC0 1.0

FIGURE 6-6: Lipid structures.

Amphiphilic lipids can also form into bilayer sheets, or even bilayer spheres called *vesicles* that encapsulate water. These structures form the templates for cells, since unlike the simpler micelles, vesicles can

include water inside, housing the present-day myriad constituents of cells. Long ago, such vesicles, detaching from a solid mineral surface, could have carried along inside them a budding ribozymal colony, forming the first protocell.



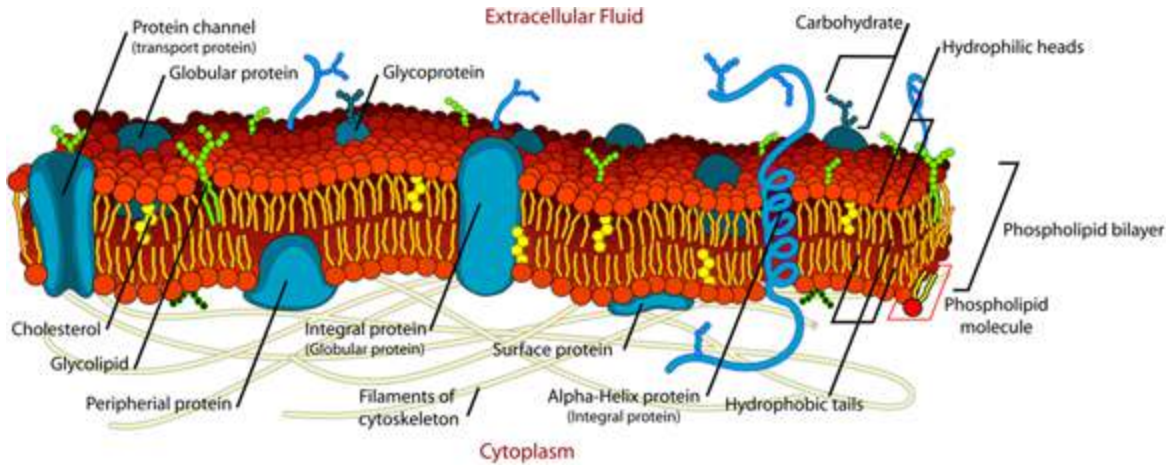
TIP Most cell membranes, as well as the membranes enclosing the cell nucleus and other cell bodies, are composed of a special class of amphiphiles known as *phospholipids*, with a phosphate chemical group giving the polar nature to the head of the amphiphile.

Diversity of membranes



REMEMBER A cell membrane that is composed of all the same molecules is not the most useful. One drawback is that the tight, uniform structure can be impermeable, not permitting nutrients to pass into the cell and waste to pass out. Such a cell would stagnate, being unable to grow or change.

Over time, cell membranes have therefore evolved a wide variety of openings, channels, and appendages to permit *osmosis* (selective movement of molecules through a membrane), *homeostasis* (maintaining constancy of properties inside the cell) and other cell needs. Figure 6-7 shows some structures that occur in the membrane of a modern cell.



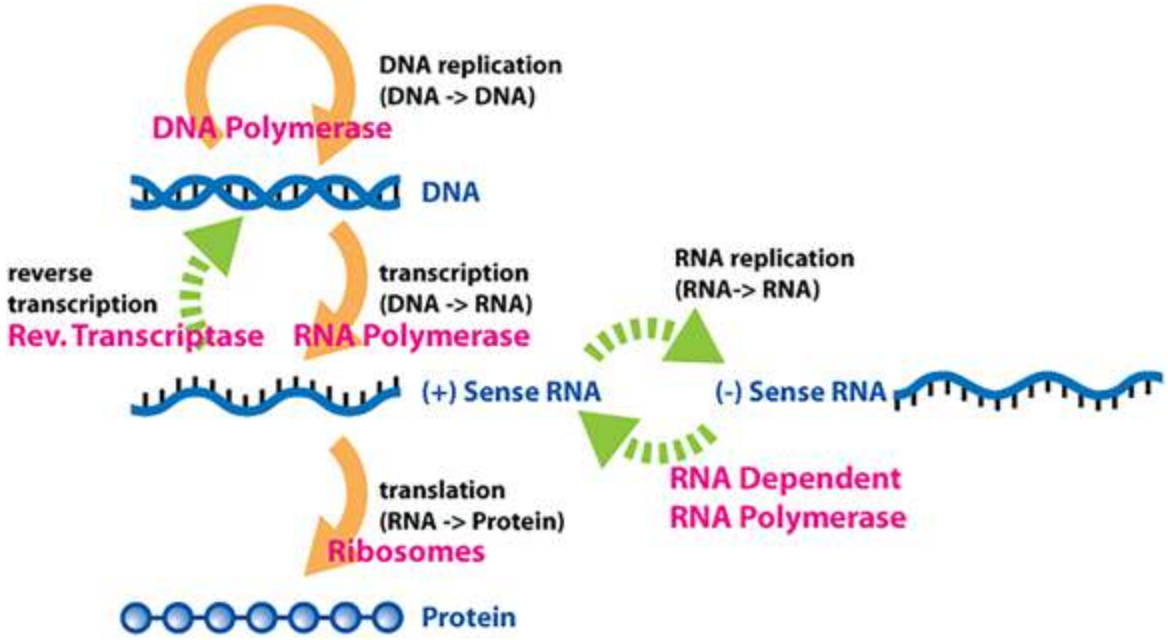
Credit: LadyofHats Mariana Ruiz/Wikimedia Commons/Public domain

FIGURE 6-7: Details of some cell membrane structures.

DNA and Information Encoding

Although highly similar, DNA and RNA have subtle differences that cause RNA to be less stable, even though it's more versatile than DNA. So, the transition that must have occurred from self-replicating RNA, to RNA storing its instructions in a DNA "library" was an important one.

Figure 6-8 shows the typical flows of information in biology (the solid curved arrows) from DNA to RNA to protein. This was named the "central dogma of biology" by Francis Crick, one of the two co-discoverers of the structure of DNA. Note the arrow showing that DNA as well as RNA can self-replicate in present day cells, but proteins cannot (see sidebar).

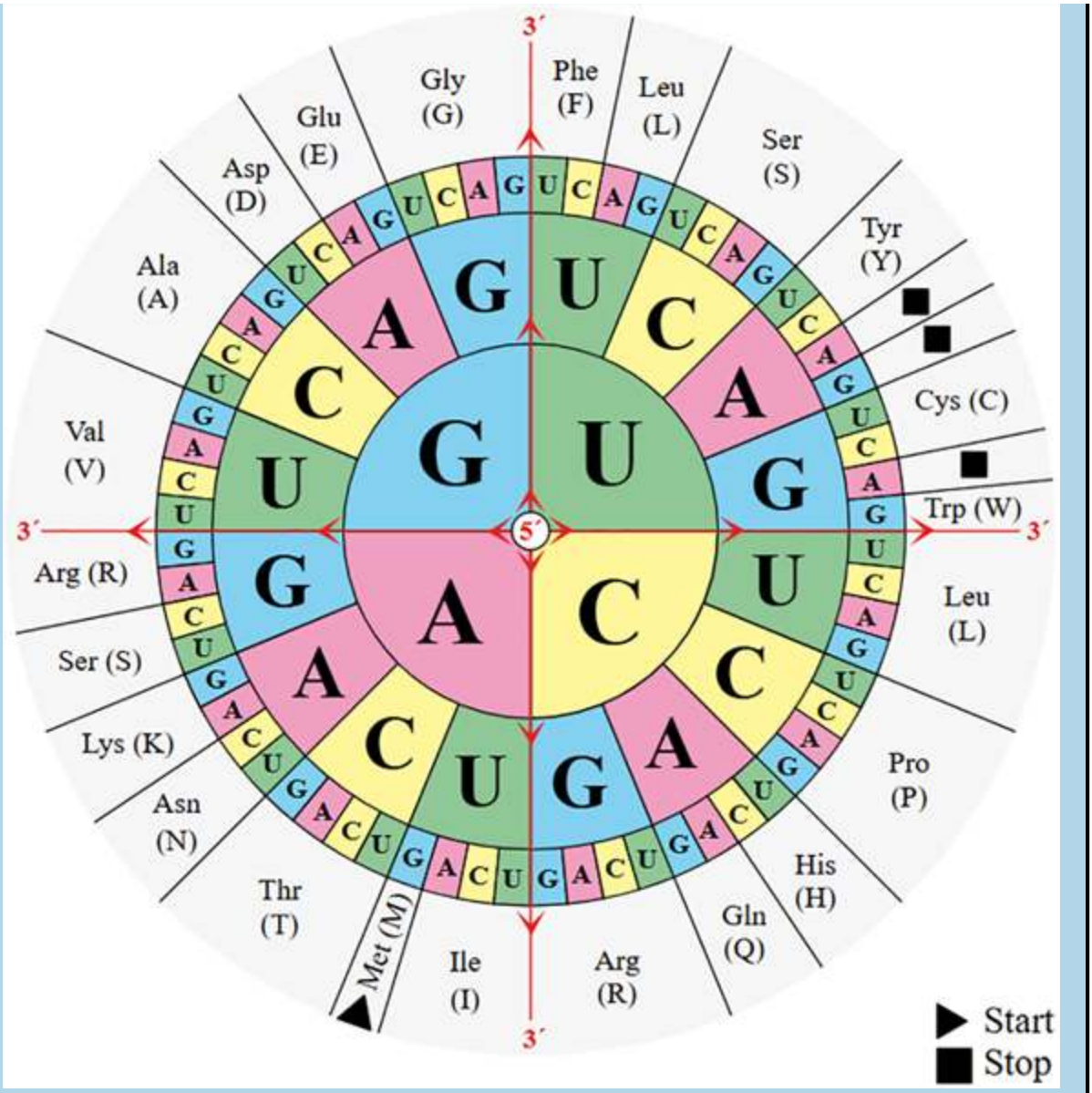


Credit: Daniel Horspool/Wikimedia Commons/CC BY-SA 3.0

FIGURE 6-8: Information flow in biology.

CRACKING THE PROTEIN CODE

After the structure of DNA was discovered, the race was on to determine how DNA coded for each of the 20 fundamental amino acids that make up proteins. With 4 letters to choose from (ACTG), use of two letters (like AT or CG) would permit only 16 possible combinations — not enough to code for the 20 amino acids. Use of three letter "words" such as ATG or CTG would allow for 64 possible permutations — more than enough to code for 20 amino acids. However, if only 20 unique DNA words (called *codons*) were needed, what to do with the other 44 codon possibilities? After years of work, the answers were gradually teased out. Each of the 20 amino acids can be specified by several versions of a codon word (a process known as *redundancy*), although none of 64 possible words ever corresponds to more than one amino acid (*uniqueness).* In addition, several of the codon words are reserved as "punctuation" — the sequence AUG serves to mark the start of a codon "sentence" for a particular protein, while the sequences UAG, UAA and UGA all serve as periods, ending the sentence (see figure below).



Credit: Mouagip/Wikimedia Commons/Public domain



REMEMBER The important step in Figure 6-8 for the history of life appears to have been the step *backwards*, from RNA to DNA, that occurs through a process called *reverse transcription*.



TECHNICAL STUFF Reverse transcription uses enzymes known as *reverse transcriptase* (RT), which allow information in RNA to be copied and stored in DNA. The process is used by healthy cells in various ways, as well as frequently by a type of viruses known as *retroviruses* that includes HIV, to store the code of the active RNA in DNA form.



TIP In the history of life, some RNA ribozymes were able to generate reverse transcriptase molecules, finding that they provided a positive evolutionary advantage by storing the RNA coding in a more permanent form.

Who Ate Whom?

The final step in single cellular development was an act of cannibalism.



REMEMBER The tree of life splits into three main branches: *Bacteria*, *Archaea,* and *Eukaryota*. Bacteria and archaea are both classified as *prokaryotes* — single-cell life forms that lack a cell nucleus, instead storing their DNA in a giant circular loop that is scrunched up to fit inside the cell. Other cell materials are likewise stored free-floating within the cell *cytoplasm*.

Eukaryotes, on the other hand, have their DNA and other useful materials encapsulated, like the zip-up plastic bags you might use for vegetables in a refrigerator drawer. Eukaryotes may be single-celled or multicellular (including us), but their cells always contain the same basic structures.

Powering the cell by symbiosis



REMEMBER One of the structures found in almost all eukaryotic cells (except red blood cells) is a *mitochondrion*. This is an energy-producing structure (*organelle*) that suspiciously resembles a bacterium, having its own separate DNA that closely resembles bacterial DNA. It's like a cell inside a cell.

This discovery led to the idea of an act of cannibalism that likely occurred in the Paleoproterozoic eon (2.5 to 1.6 billion years ago). In a theory proposed by Nobel Laureate Lynn Margulis, an archeon cell was ingested by a bacterium, which turned out to be beneficial for both parties involved.

The archeon benefited from the steady and efficient supply of energy in the form of adenosine triphosphate (ATP), produced via aerobic respiration by the helpful bacterium. This would have been an improvement on alternate mechanisms of energy generation by glycolysis and fermentation previously practiced by the archeon. The bacterium, in turn, was provided with a safe habitat and steady source of nutrients. Such a relationship is known as *endosymbiosis* (internal symbiosis, or partnership).

Greening up

A second episode of symbiotic ingestion led to the formation of green plants, whose cells apparently absorbed a cyanobacterium that became the *chloroplast*, the body that conducts photosynthesis within the plant cell. Like mitochondria, chloroplasts also have remnant bacterial DNA.

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Chapter 7
Multicellular Life

IN THIS CHAPTER

- **Learning how single-celled organisms can work as teams**
- **Discovering the advantages of multicellularity**
- **Finding out how unicellular organisms made the leap to multicellular life**
- **Exploring whether evolution is continuing today**

In the classic children's nursery rhyme, we are told that little girls are made of "sugar and spice and all things nice," while little boys are made of "slugs and snails and puppy dog tails." Fortunately, modern biology has thoroughly debunked these spurious claims — although there are certainly sugar molecules in all living things doing important jobs.



TIP In this chapter, I explore what *does* constitute a large, multicellular organism, including the *Eukaryota* domain, which includes humans (you can revisit Chapter 4 to refresh your memory about biological taxonomy).

I begin by describing how some unicellular organisms find ways to cooperate in teams and colonies that provide mutual benefit to all. In some of these cooperatives, the little protists even begin to specialize and divide up the colony labor — a possible stepping stone toward a true multicellular organism, and a clue to how this may have occurred.

I then look at the advantages of a truly multicellular organism, and explore some of the ways this evolutionary jump may have occurred. However, multicellularity is not all sunshine and roses, so you learn

some of the possible drawbacks that this added complexity brings in. Finally, I revisit evolution, and explain how it is still occurring today.

Working as a Team: Unicellular Cooperatives

Before cells merged into a single, multicellular creature, they likely first functioned as colonies or teams. At some point, some teams of protists evolved to become so interdependent that they could no longer function as individual cells — or the advantages of teamwork were so great that there was no longer any reason to stay single.

I explore how the transition may have occurred later in the chapter, and begin by looking at some teams built by amoebas and archaea.

Building a community: Biofilms

Sometime around 3.25 billion years ago, prokaryotic bacteria and archaea hit upon a neat idea to enhance their survival — clustering together as biofilms.

In a biofilm, one or more unicellular species form a colony on a living or nonliving surface: from rocks to pipes, from teeth to gut walls. These colonies may begin when a single enterprising bacterium attaches to a rock and begins to divide. Or it may attract others of its kind, or even friendly strangers, in a kind of budding settlement.

Soon the colony begins to protect itself by secreting a covering known as EPS (*extracellular polymeric substances*). This is a slimy mixture of polysaccharides, proteins, lipids, and even DNA that forms a shield, protecting the colony from predators, diseases, and toxins, and allows resources to be shared between inhabitants — like a defensive city wall.



TIP Biofilms are ubiquitous in nature — if you've ever slipped on a slimy river rock or had to have a dentist scrape plaque from your

teeth, you've had an encounter with a biofilm. Those stromatolites we encountered back in Chapter 4? Biofilms. Figure 7-1 shows some examples.



(a) (b)

Credit: (a) U.S. Geolological Survey/Public domain (b) leroy/Adobe Stock Photos

FIGURE 7-1: Biofilm examples: (a) slimy biofilm in a streambed, MT, USA; (b) tooth plaque biofilm.

Living the slime life



TECHNICAL STUFF

Like a town, life inside the biofilm is complex and multifaceted. Each cell contributes to the greater good of the whole by contributing in generic and specialized ways:

- All cells can contribute to the slimy covering (EPS), like adding bricks to your city wall. In addition, any digestive enzymes secreted externally (outside the cell) can become trapped in the EPS coating, allowing for some shared external food production (a bit like a food bank).
- The biofilm has watery channels akin to "city streets" that allow traffic back and forth. In the biofilm, the traffic is not cells (which form the "buildings") but enzymes, nutrients and signaling chemicals. In a process called *metabolic cross-feeding*, the excreted waste product of one cell type can form the food source for another.

- *Horizontal gene transfer*: As prokaryotes don't reproduce sexually, their ability to evolve (important for survival) is more limited. However, in slime city, cells can excrete pieces of genetic code into the EPS matrix, and likewise scoop up genetic code from others, like a card-swapping game to improve your hand.

Communication and signaling



Within the colony, each member continuously releases a steady trickle of chemicals called *autoinducers.* These act as signals, saying "I'm here." As the number of cells builds up in a specific location, the density of these signaling molecules also builds up until it reaches a critical level known as *quorum* (like having enough members on a town council to take votes).

When the quorum density is reached, the autoencoders bind to receptor proteins on the cells and trigger a sudden change of behavior: This might be the release of colony members (*dispersal*) because the colony has become too large for its habitat. Or, less unpleasantly, in bioinvasive colonies, quorum can trigger the mass release of toxins to overwhelm a host's defenses.

Getting mobile in a grex

Another type of cooperative venture that some single-celled amoeba can embark on is a *grex* — a mobile, sluglike community (but not a real slug, which is a multicellular organism) of amoebas banding together for mutual survival. Think of it a bit like a 19th-century wagon train of colonists.



A grex is typically formed when the environments that the amoebas live in become less favorable; for example, when food becomes scarce. The stages of a grex are as follows:

1. The unhappy amoebas secrete pheromones that signal stress. These signals are picked up by others and they come together to form a mass, which gradually builds into a tall column.
2. Eventually, the column topples over and enters the sluglike phase. It moves to a new location and the cells also begin to take on specialized roles according to position.
3. The grex settles down and forms a protective shell with a protruding stalk and a tip, known as the *fruiting body*.
4. Finally, the fruiting body rips and splits, releasing spores from inside. The remaining shell and stalk desiccate and die.



TIP A grex is an example of a foray into multicellularity: The amoebas slightly specialize in function; however, they eventually give up the multicellular life when the community dies, and spores are released that lead back to single-celled amoebas.

Lichens



REMEMBER Unlike a biofilm or a grex, which may include individuals of only a single species, a *lichen* is explicitly a *symbiosis* (living cooperative) of two or more species. Specifically, a lichen is comprised a cyanobacterium or alga — photosynthetic organisms that convert sunlight energy into food — along with a fungus.

Lichens come in many shapes and forms (see Figures 7-2a and b) and sometimes resemble mosses or other plants, but they do not have roots and are unrelated to multicellular plants.

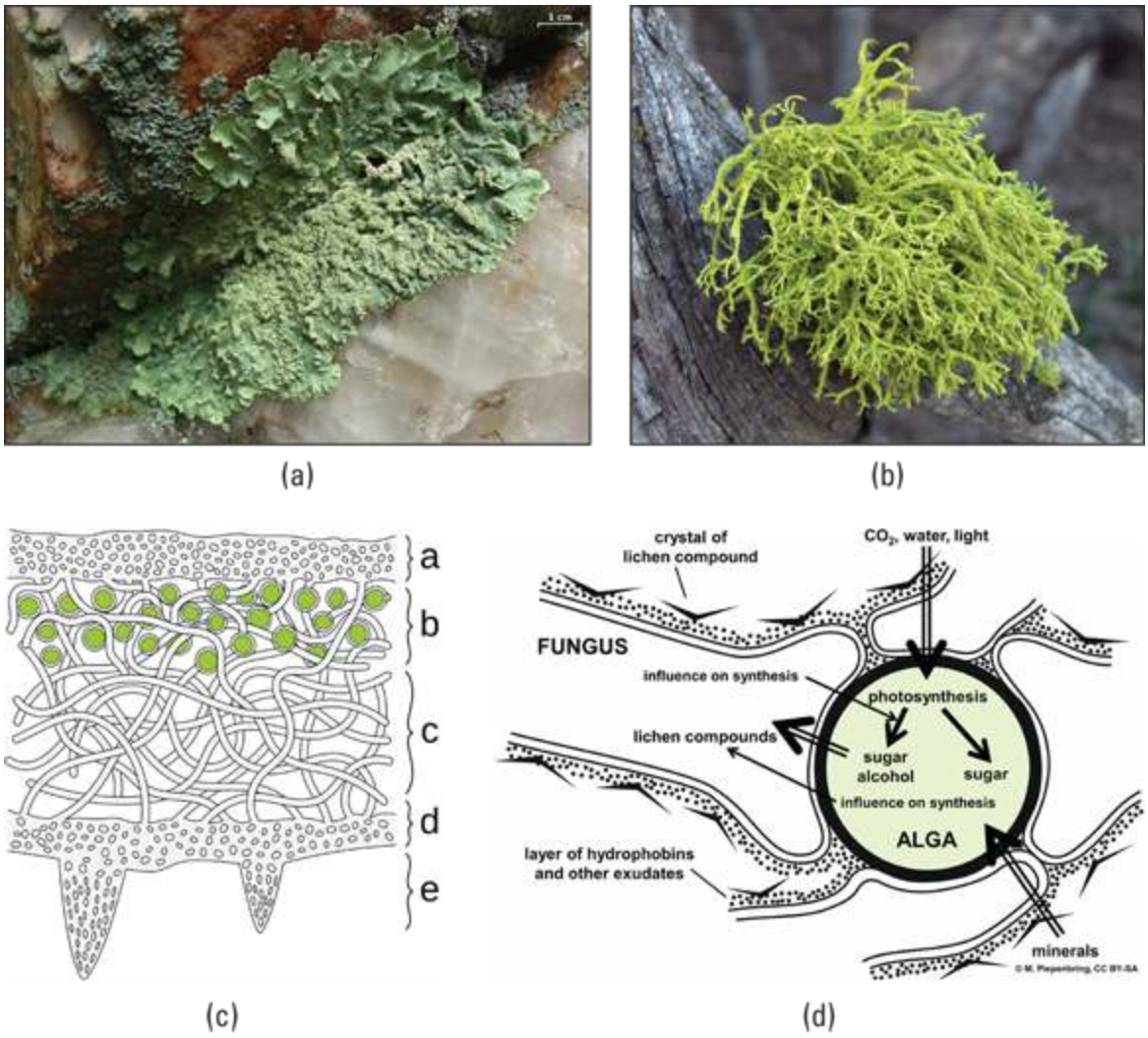
Lichens are found adapted to almost any environment on Earth:

- From sea level to high mountain elevations
- On tree barks, branches, leaves

- On rocks, walls, rooftops
- From dry deserts to lush coastal forests

In a lichen, the fungus benefits from the alga or cyanobacterium, which photosynthesizes to produce food. In return, the fungus provides some structure, anchoring, and protection to the bacterium. However, some scientists view the symbiosis as a little one-sided, since the alga is able to live apart from the fungus, whereas the fungus cannot live without the food-providing algae.

Figure 7-2c shows the structure of a typical lichen, with the photosynthetic algae enclosed in the fungus. Figure 7-2d shows the internal interaction between the two partners, with the fungus feeding off the alga while at the same time providing nutrients to the alga.



Credit: (a) Jason Hollinger/Wikimedia Commons/CC BY 2.0 (b) Jason Hollinger/Wikimedia Commons/CC BY-SA 3.0 (c) Nefronus/Wikimedia Commons/CC BY-SA 4.0 (d) Prof. Meike Piepenbring/Wikimedia Commons/CC BY-SA 3.0

FIGURE 7-2: (a) *Flavoparmelia caperata,* a foliose lichen. (b) *Letharia vulpina*, wolf lichen, has a fruticose growth form. (c) Structure of a lichen showing algae embedded in the fungus. (d) Flow of nutrients and energy between the algae and fungi.

Advantages of Multicellularity

Now that you've seen how some temporary teaming can improve the lot of unicellular organisms, let's enumerate the benefits that could accrue in a permanent multicellular organism.



TIP If you were running a one-person business, you would naturally do everything: taking customers' orders, providing the product or service, accepting and processing the payment, and doing the taxes and regulatory filings. It's exhausting! Soon it may occur to you to grow the business by hiring and specializing, having a different person take care of each function. If everything works properly, the increased attention and skill of each person, who no longer switch between tasks, allows the business to function more smoothly and grow.



TECHNICAL STUFF As with the business example, mother nature has also hit upon this idea of specializing to grow and compete better in the natural environment. Having specialized cells for different functions can provide a number of advantages over single-celled life, including:

- **Cell specialization:** Individual cells differentiate to perform specific functions (like nerve cells for signaling, muscle cells for movement) rather than exhausting energy trying to manage all life processes at once.
- **Increased size:** Larger bodies provide a major survival advantage by making the organism less vulnerable to predators and more capable of fending off or consuming other organisms.
- **Enhanced survivability:** The death of a few individual cells does not threaten the organism's existence, allowing the overall structure to recover from minor damage, diseases, or environmental stresses.
- **Longer lifespan:** Unlike unicellular organisms whose life directly concludes with division or cell death, multicellular bodies can continuously replace and regenerate worn-out cells.
- **Resource storage:** A larger size and mass enable the storage of energy and resources, allowing organisms to survive harsh

conditions and remain active even when external environments are hostile.

Clearly a strong strategy. But there are barriers to becoming multicellular. First, how should it be accomplished? By teaming up with others or by cloning copies of yourself and letting each do only a fraction of the former tasks, forgetting their former skills in other areas?



WARNING If cells from different species are to begin permanently working together, reproduction becomes another problem. The cells that are assigned the reproductive activity initially only have their own DNA to clone, and don't know the DNA of their neighbors. Somehow the DNA from all cells in the organism must be merged into a single blueprint.

Let's now take a look at some of the steps that may have occurred on the way to multicellularity.

Becoming Multicellular



TIP Complex multicellularity has developed on at least 25 known occasions, in six eukaryotic groups: animals; land plants; red, green, and brown algae; some fungi.

There are several theories for how multicellularity arose, and more than one of these may have occurred:

- **From symbiosis:** Several distinct organisms living in symbiosis (think back to the lichens) begin to co-evolve in such a way as to be completely codependent, unable to live apart. Over time, they evolve into separate cell types of the same, now-combined organism. However, this theory fails to explain how the separate symbionts merge their different DNA into a new, combined DNA line.

- **From a colony:** As we saw with the biofilms, single-celled organisms can certainly band together for mutual benefit. And in the case of the grex, the colony members can even begin to specialize and differentiate. What if the colony went a step further, and the colony became a new life form as a multicellular creature? This is a favored theory for development of multicellularity in land-based creatures.
- **From single-celled eukaryotes with multiple nuclei:** The theory envisions that cells with multiple nuclei could have over time developed internal barriers or partitions enclosing the different nuclei, which eventually developed into separate cell types. Again, the problem is that the separate nuclei in such cells have clearly defined functions, and do not have the same DNA.
- **Failed cell division:** A single-cell organism usually reproduces by *mitosis*, cloning its nucleus and then dividing in two in a final stage known as *cytokinesis*. If the cytokinesis does not occur, then the individual nuclei could develop their own membranes and partitions while remaining connected, leading to a multicellular organism. In a variant of this theory, the cytokinesis occurs but only up to the point of development of separate daughter cells, which then fail to separate. This theory appears to work well for protists in aqueous environments.



TIP We don't have a lot of evidence to use to decide exactly when and how the leap to multicellularity took place in different branches of life's tree, since the early multicellular creatures were simple and lacked hard structures such as shell and bone, and consequently are not well preserved in the fossil record.

However, regardless of when and how multicellularity happened, it certainly did occur — since we have ourselves and most of the large multicellular animals and plants in the world as proof. Let's now look at some of the traits of multicellular creatures.

Living the Multicellular Life

In a multicellular lifeform, every cell carries the same DNA, or blueprint. How then do cells in different parts of the organism know how to develop differently, into a leaf or root cell in a plant, or into a liver or nerve cell in a human?

Differentiation and specialization



Cells differentiate through a process known as *differential gene expression*. This is a complex process, but in essence it means that of the entire genome, only certain parts are used — or *expressed* — in each cell. This is a bit like each employee in a company being given a digital copy of the entire company handbook of rules and procedures, but then the employees only look up the parts that relate to their particular job.

For sexually reproducing multicellular organisms, differential gene expression starts at the moment of conception, when the single fertilized egg cell begins to divide. At first, the cells look the same, but then they begin to specialize and branch off, growing the embryonic organism.



Stem cells are a type of multipurpose cell prevalent in the developing organism that have two properties:

- **Self-renewal:** They can continue to divide indefinitely.
- **Potency:** They have the ability to differentiate into different specialized cells.

There are now known to be different types of stem cells with different degrees of potency:

- **Pluripotent** stem cells are the most versatile and can form any part of the adult organism (for example, embryonic stem cells).
- **Multipotent** stem cells are partially specialized, and can go on to form multiple final cell types but not all (for example, blood stem cells).
- **Unipotent** stem cells can develop into only one mature type (for example, skin basal cells).

The development and specialization of cells through differentiation gene expression and epigenetic modifications is a deep topic; check out *Genetics For Dummies* by Rene Fester Kratz and Lisa Spock (Wiley) for a deeper dive into this topic.

Taking one for the team: Cancer and apoptosis

I've already looked at some of the pros of multicellularity, but are there any disadvantages? In fact, yes. The fact that multicellular creatures must constantly renew and regenerate their cells, which also have to specialize and differentiate as they mature, allows many more places for things to go wrong than in a unicellular organism, which doesn't have to constantly build new cells (except in reproduction).



WARNING An example of things going wrong is in cancer in animals, where malignant cells manage to disrupt the normal processes of cell regulation, allowing in some cases for infinite growth and division. Cancer cells also disrupt the normal process of cell specialization, in some cases reverting adult cells back to an embryonic state, allowing them to proliferate into new tissues (known as *metastasis*).

In normal, healthy animals, a safety process known as *apoptosis* is in place, where damaged or unhealthy cells are flagged for destruction. However, in cancer, the apoptosis process is turned off, allowing the cancer to proliferate.

Is Evolution Still Occurring?



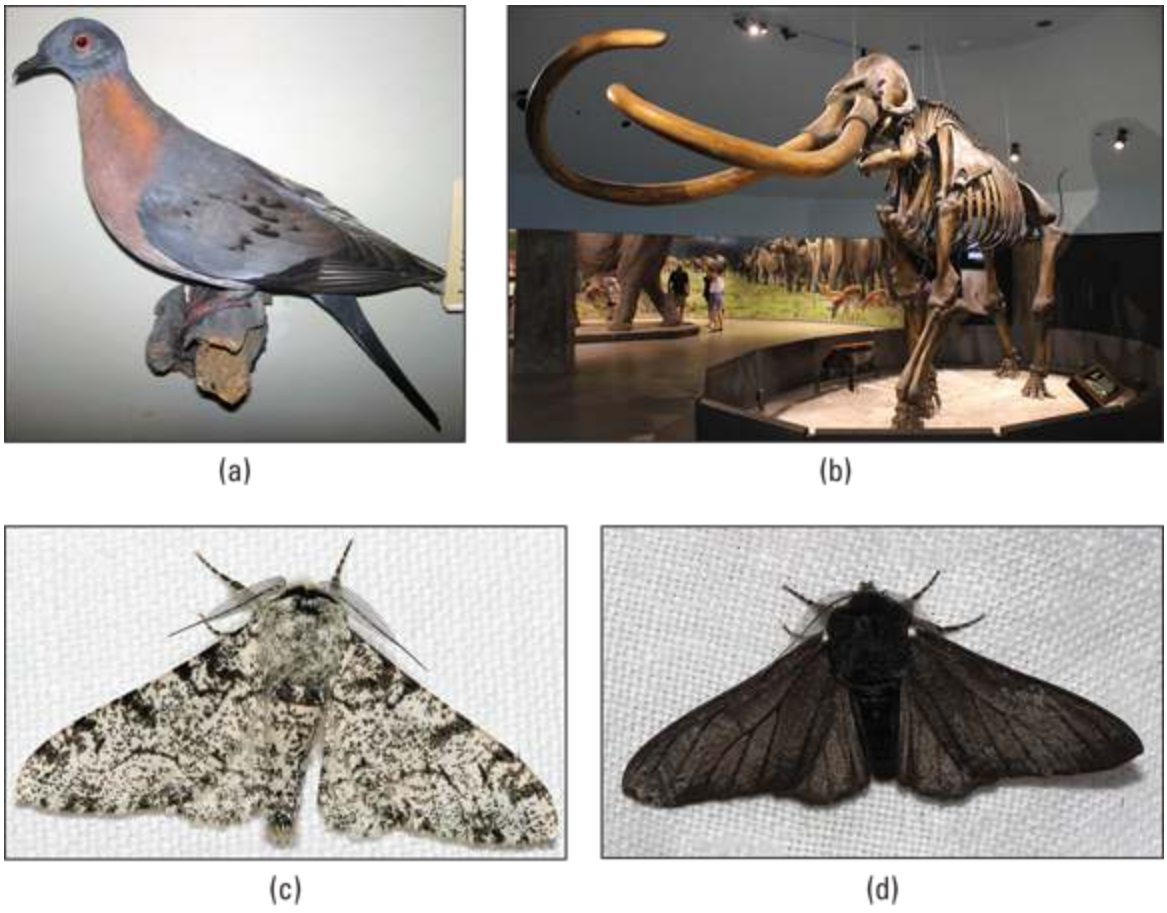
REMEMBER As we wrap up our multichapter tour through biological evolution, you may be wondering if evolution is a process that happened in the past, but isn't ongoing today. It would be easy to think this way, given that we see vast changes in the fossil record, but we don't, for example, see bears, sharks, oak trees, and horseshoe crabs suddenly being replaced by new species in our lifetimes.

However, evolution tends to proceed slowly, sometimes over millions of years. This is why for most of human history we believed that the same set of animals and plants were always present on the Earth, perhaps from an act of creation, and that no significant changes had taken place. It wasn't until the 1800s, when Darwin proposed a coherent theory of evolution, that the once-crazy idea began to be taken seriously.

In fact, evolution certainly is occurring today, albeit at different rates in different types of organisms. Let's look at a few examples:

- **Extinctions:** Although extinctions have occurred throughout the history of life, as some species have failed to adapt to changing environmental conditions or become outcompeted by other species, humans have undoubtedly influenced the natural state of affairs through hunting, forest clearance, or the introduction of invasive species. Just ask the dodo, the passenger pigeon, the quagga, the woolly mammoth, or the ivory-billed woodpecker (if you can find one). See Figure 7-3.
- **Breeding:** At the other end of the scale, humans have created many new subspecies of animals useful to us: cats, dogs, pigs, goats, chickens, cows, horses, and so on among the animals, along with countless vegetable and flower types that didn't exist a few hundred years ago.

» **Human evolution:** As well as affecting other species, *Homo sapiens* is also changing too. In the last tens of thousands of years, migration of humans from an origin in North Africa to other parts of the world led to changes in appearance, with different groups evolving to have lighter or darker skin, and different pigments of eye and hair that conferred advantages in their particular environment. In the last few thousands of years, since the mass switch from hunting and gathering to farming, some groups of humans have evolved increased abilities to digest milk (lactose), gluten, and even alcohol. Since the industrial revolution, there has been a steady increase in average human height, responding to increased availability of food, whereas in the last century there has been an increase in measured IQ.



Credit: (a) James St. John/Flickr/CC BY 2.0 (b) Jonathan Chen/Wikimedia Commons/CC BY-SA 4.0 (c) Chiswick Chap/Wikimedia Commons/CC BY-SA 2.5 (d) Chiswick Chap/Wikimedia Commons/CC BY-SA 2.5

FIGURE 7-3: (a) and (b) Creatures whose extinction was caused or hastened by humans: the passenger pigeon and the wooly mammoth. (c) and (d) The white and black versions of the peppered moth, whose survival was modified by human activity.

BLACK AND WHITE MOTHS

Prior to 19th-century industrialization in England, speckled moths were ubiquitous. Because they blended well with light-colored tree bark and lichen, moths were all light-colored, because any dark-colored moths created by rare mutations were easily spotted and eaten by birds. However, during the 19th-century era of heavy pollution, plants and buildings became covered in dark soot, and soon the light-colored moths were easy prey. In contrast, dark-colored mutants were now favored, and became the dominant coloration. Finally, in the 20th century, clean air regulations reversed the balance once more. Soot disappeared, and along with it, the dark-colored moths. The natural order was restored and the light-colored moths were once more ubiquitous. (Refer to Figure 7-3.)

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Chapter 8

Recreating the Origins of Life

IN THIS CHAPTER

- **Learning how scientists are brewing up life's ingredients in the lab**
- **Finding out how biologists created new bacterial lifeforms**
- **Discovering how computers are being used to investigate evolution**

As you learned in Chapter 5, the origin of life on Earth occurred at least as far back as the Archean Eon 3.5 billion years ago, where we find fossilized evidence of stromatolites — simple photosynthesizing bacteria — in the geologic record. Then, in Chapter 6, you learned about current theories of how this happened — how simple chemicals transformed into complex, self-replicating molecules that then organized themselves into living matter.

However, testing these theories is hard. We can't jump in a time machine to travel back 3.5 billion years (at least not yet) to observe these events occurring and confirm our suspicions. We can hypothesize, but is there a way to put things on a firmer footing, by recreating the conditions of the early Earth in a test tube to see if complexification actually occurs?



TIP In this chapter, you learn about exactly this topic: attempts by scientists to recreate the origin of life in laboratory conditions. You'll also find out about exciting new approaches to "origins of life" (OoL) research using computers to investigate vastly more reaction pathways than we could ever attempt in a test tube.

Cooking Up a Chemical Soup



REMEMBER In Chapter 6, you read about speculations on the origin of life from the likes of Charles Darwin (the famous "warm little pond …") to the "primordial soup" of JBS Haldane and Alexander Oparin. Although these were by no means the first or only such speculations, they garnered attention at the right era, the late 19th and early 20th centuries, because experimental biochemistry was emerging as a distinct field. This soon led to the first serious experimental attempts to re-create the origin of life in a test tube.

The Miller-Urey experiment

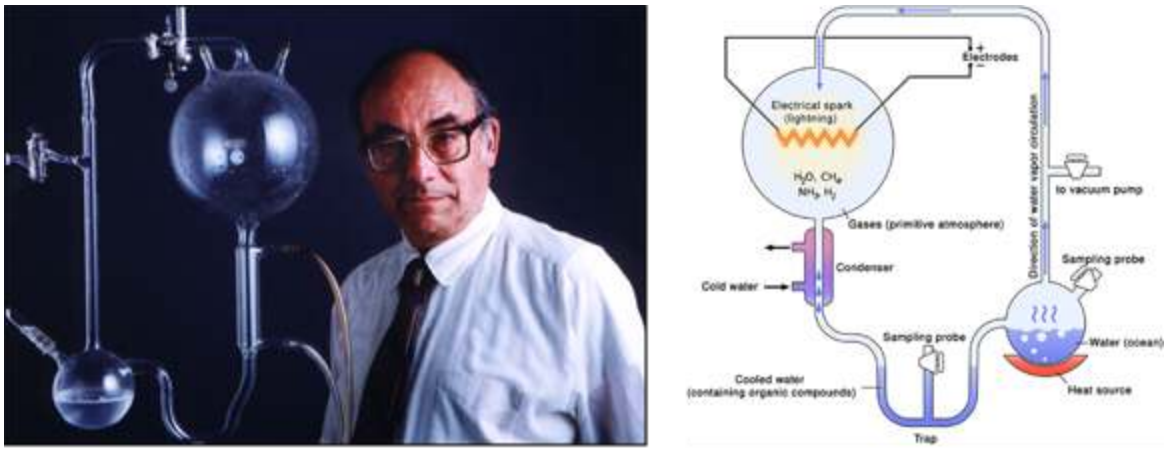
In 1952, two scientists at the University of Chicago decided to try an experimental verification of the origin of life. These were Nobel laureate Harold Urey and his graduate student Stanley Miller, who had badgered Urey to allow him to conduct the experiment based on Urey's own musings about the atmosphere of the Archean Earth.



TIP The experiment was deceptively simple (see Figure 8-1) and consisted of several key components designed to replicate the conditions on the Archean Earth:

- **Atmosphere:** A glass bulb contained the suspected gases of the early Earth's atmosphere: methane (CH_4), hydrogen (H_2), ammonia (NH_3), and water (H_2O).
- **Ocean:** A second glass vessel contained heated water, replicating an early ocean, and providing a steady source of water to the "atmosphere," as well as an aqueous medium for further reactions to occur.

- **Energy:** Miller used a continuous electrical discharge (spark) applied to the atmosphere, mimicking the lightning on Earth, to provide a source of reaction energy.
- **Collector:** A U-bend–shaped glass pipe to collect products from the reaction vessel.



(a) (b)

Credit: (a) Unknown author/Wikimedia Commons/Public domain (b) YassineMrabet/Wikimedia Commons/CC BY-SA 3.0

FIGURE 8-1: (a) Stanley Miller beside his famous experiment. (b) Diagram of the Miller-Urey apparatus.

REMEMBER The gas mixture was chosen to replicate chemicals that could readily be supplied by comets, or outgassed from the Earth itself (refer to the "Late Veneer" hypothesis in Chapter 11). These ingredients provided the four key elements — CHON — known to be essential to form the amino acids and proteins of life (flip back to Chapter 6 for a reminder on these bio-essential elements).

TECHNICAL STUFF Note that there was no oxygen (O_2) in the reaction vessel — remember that oxygen gas was not abundant in the Earth's atmosphere until 2.5 billion years ago, following the Great

Oxidation Event (GOE, see Chapter 5) when photosynthetic cyanobacteria transformed atmospheric CO_2 into O_2. This lack of oxygen was crucial in allowing complex reactions to ensue without ending up only with simple oxidized substances such as water and carbon dioxide.

After setting up the apparatus, Miller then flipped a switch to turn on the power supply and sat back to see what chemical magic would happen. After some days of running the experiment, the power was switched off, acid was added to stop any reactions, and the reaction products collected in a U-shaped trap at the bottom were analyzed.



REMEMBER It was immediately clear that something important *had* happened. Using the technique of paper chromatography, which separates chemicals based on their mobility in a water solution, Miller was able to determine that at least three amino acids essential to life had been created: glycine, α-alanine and β-alanine.



TECHNICAL STUFF In the years since the results were published in 1953, scientists have been able to understand how this transformation of simple chemicals into more complex ones occurred:

- In the gas phase, two two-element molecules, water (H_2O) and methane (CH_4), were combined to become molecules with three elements: methanol (CH_3OH) and formaldehyde (CH_2O).
- Meanwhile, ammonia (NH_3) was reacting with methane (CH_4) to produce the key three-element molecule hydrogen cyanide (HCN).
- The formaldehyde and hydrogen cyanide could then combine in the presence of ammonia to produce the simple amino acid, glycine: NH_2-CH_2-COOH, a process known as *Strecker Synthesis*.



REMEMBER The Miller-Urey experiment was a pivotal moment in the understanding of the origins of life. It showed that simple gases that almost certainly were present on the early Earth could readily transform into the complex building blocks of life without any special conditions — only a nearby watery ocean and a source of atmospheric energy were sufficient.

The Miller-Urey experiment has not been without criticism, however. One notable and justifiable objection pertains to the gas mixture used. Since the time of the original experiment, we now know that the atmosphere of the early Earth most likely did not have much methane, or hydrogen, either. Although it would certainly have had water vapor, any carbon would have been mostly in the form of carbon dioxide (CO_2), which unfortunately does not react in the same manner as methane to produce organic molecules.



REMEMBER Nevertheless, the Miller-Urey experiment was influential and has led over time to a whole field today devoted to variations of such experiments: changing the gases in the mixture, changing the energy sources, temperatures, pressures, and more. These experiments have sought to widen and further understand the range of conditions that could have permitted amino acid synthesis on the early Earth.



TIP As well as replicating the conditions of the early Earth, scientists have also sought to change the gases and conditions to mimic suspected conditions of early Mars, Venus, and other worlds, including exoplanets. One of the variations that has drawn the most attention is the "Titan version" of the Miller-Urey experiment, which I discuss next.

Getting "muddy" with Titan's "tholins"

Saturn's moon Titan (for more info, refer to Chapter 13) is a remarkable world: the only moon with an atmosphere. Titan's atmosphere is mostly composed of nitrogen gas (N_2), making it similar to the Earth's atmosphere, which is also mostly N_2. However, Titan also doesn't have any oxygen (O_2) in its air, which is different from the Earth today (take a deep breath to make sure), but is similar to the Archean Earth, a period before the GOE.

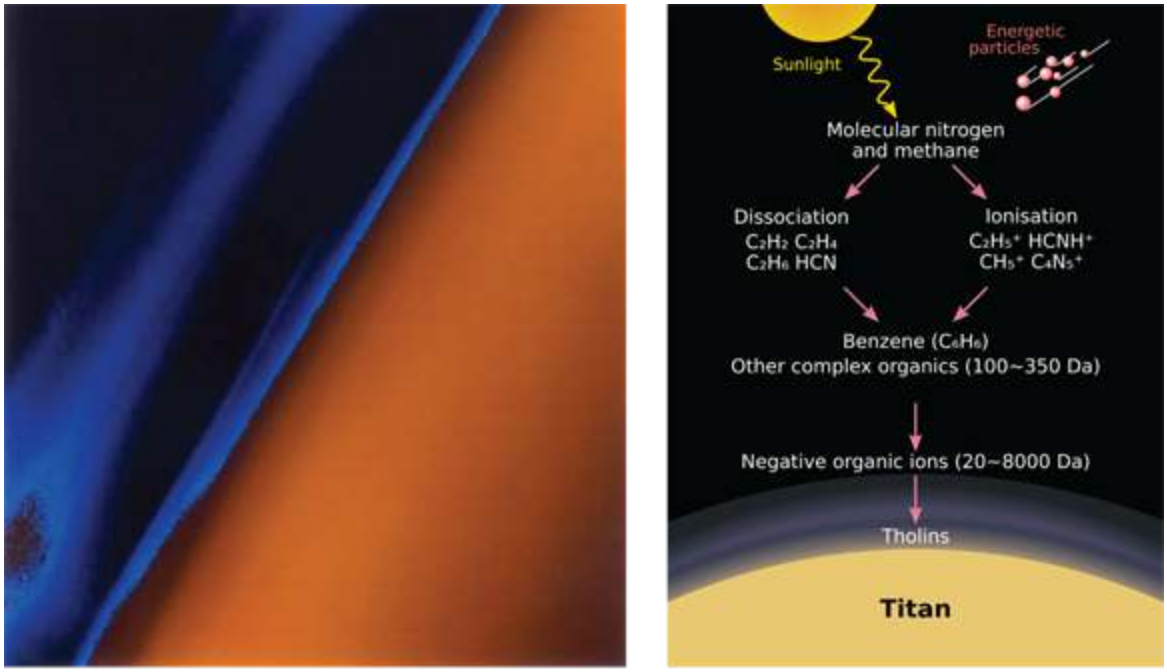
Titan's atmosphere is also rich in those other molecular goodies (such as methane and hydrogen) that were used as precursors (or raw ingredients) in the Miller-Urey experiment to generate complex molecules such as amino acids. This has led scientists — most prominently the Cornell astronomer and science communicator Carl Sagan (see Chapter 17) — to propose that Titan today may be a good parallel (or "analog") to the conditions of the early Earth — despite being a lot further from the Sun and hence a lot colder.

Because spacecraft have already visited Titan and made measurements of its atmosphere (see Chapter 13), we already know some of the chemical products being created in this natural experiment. These include the important molecule hydrogen cyanide (HCN), as well as its larger cousin, cyanoacetylene (HC_3N). Moreover, Titan has a dense haze or smog (see Figure 8-2a), causing its famous yellow-orange color, which we now know to be a chemical residue from the action of sunlight causing complex reactions among Titan's gases (see Figure 8-2b).



Titan-like versions of the Miller-Urey experiment were soon performed. The gas mixtures and temperature conditions are different from the terrestrial version, and with much less water, leading to somewhat different products. These experiments can replicate the formation of the oily-brown smog particles (called *tholins* by Sagan, after the Greek word for *muddy*) and organic

molecules that lack only oxygen to become amino acids. However, a simple addition of water, which could occur during impacts on Titan's surface or in the subsurface, can transform these to amino acids.



Credit: (a) Voyager Project/JPL/NASA/Public domain (b) NASA Jet Propulsion Laboratory (NASA-JPL)/Wikimedia Commons/Public domain

FIGURE 8-2: (a) Haze in Titan's atmosphere as seen by the Voyager 1 spacecraft in 1980. (b) A simplified chemical network showing how simple molecules react to form the haze, or *tholin*, material.



REMEMBER You can now see why Titan fascinates scientists: It appears to host similar processes to those that occurred on the early Earth, probably leading to similar "prebiotic" molecules on its surface. But have these molecules gone farther, reacting in ways that have led to exotic life on Titan? We still don't know the answer to this question, but NASA is sending a new space mission, *Dragonfly*, to find out (see Chapter 21).

Oró's Experiments Brew Up Adenine

A second seminal origins-of-life experiment took place just a few years after Miller-Urey. Scientists had noted that one of the five key nucleobases, adenine, didn't require any oxygen in its chemical formula, but rather five atoms each of hydrogen, carbon, and nitrogen: $H_5C_5N_5$. So, an obvious question arose: Could the adenine molecule be created by simply gluing together five HCN molecules in chemical reactions? This would simplify one of the pathways to life even further, because only a single type of molecule would be required.

Catalan chemist Juan Oró, working at the University of Houston in the US, provided the experimental verification in several experiments from 1959-1962. His first attempt showed that heating an aqueous solution of ammonium cyanide (NH_4CN, formed from adding HCN to ammonia, NH_3) to 70°C and letting the mixture stand for several days, produced a small yield of 0.5 percent adenine. This was a success, but most of the ammonium cyanide went into creating other chemicals rather than adenine. However, a second experiment, this time using pure HCN in anhydrous (water-free) NH_3 liquid led to much higher yields of 20 percent.



REMEMBER This experiment was significant because it showed the relative ease with which a complex biological molecule could be created. Moreover, HCN is a molecule abundant in space, including in comets (see Chapter 10), furthering speculation that life could have been "seeded" from outside the Earth. Indeed, adenine has now been found in material returned from primitive asteroids such as Bennu and Ryugu (see Chapter 11).

Mimicking Deep-Sea Vents



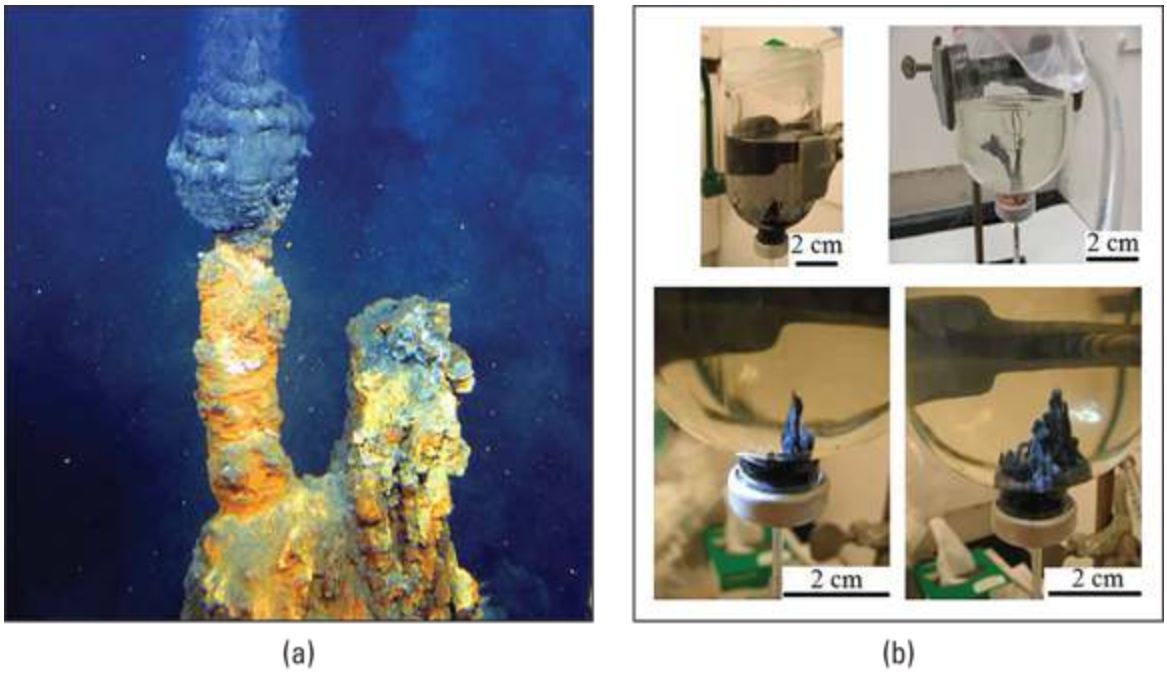
TIP The exact origin of life is still a matter of debate. Although some favor a "warm little pond" on the Earth's surface, where gases can react in the presence of water, there are more extreme environments where energy may be more concentrated, allowing reactions to proceed more quickly.



REMEMBER One type of location known to be surprisingly abundant in life today are deep-sea vents on the sea floor, where hot water and other chemicals come together in an explosion of exotic life forms (more on this in the next chapter). Acidic vents known as "black smokers," as well as the more alkaline "white smokers," discovered by deep-sea probes are surrounded by specialized life: Could these in fact have been the first colonists on Earth?

As technology has advanced, scientists now have the ability to re-create these deep-sea conditions in the laboratory, learning how the formation of chemicals can be catalyzed (accelerated) around the vents.

One such experiment was undertaken at NASA's Jet Propulsion Laboratory (JPL) in 2016. Researchers first created "chimneys" by injecting solutions containing iron, sulfur, and silicon into glass vessels (see Figure 8-3). Then, alkaline solutions containing complex molecules such as ribosomes (the building blocks of RNA; refer to Chapter 6) were injected up the chimneys.



Credit: (a) NOAA/Public domain (b) Burcar et al. 2015/with permission of Sage Publications

FIGURE 8-3: (a) Deep sea "black smoker" vents. (b) Laboratory re-creation of black smokers at NASA JPL.

The JPL results showed that the ribosomes could be coaxed to link up into longer RNA chains under certain alkaline conditions, but not if the water was made more acidic. This work provides an exciting glimpse of how chemistry could proceed to build up important strands of life far from the energy of the Sun.



REMEMBER In another experiment, which was performed at University College London in 2019, scientists explored whether stable cell-like structures known as *vesicles* could form close to simulated hydrothermal vents from an initial mixture of long-carbon chain molecules. By adjusting the molecular mixture along with the pH of the solution and the salinity, they succeeded in creating vesicles in hot water after previous experiments had failed.



TIP Together, these experiments and others are changing our perception of the types of environments where life may have originated.

Testing Self-Replicating DNA



REMEMBER Although Miller-Urey and other experiments have shown how large complex amino-acid molecules can form, the next key step to the progression of life is showing that such molecules can self-replicate: Life after all must reproduce. According to the RNA world hypothesis (refer to Chapter 6) this would require a specialized type of RNA molecule known as a ribozyme: a molecule that can copy itself.

One example of this type of research was demonstrated at the Laboratory for Molecular Biology of the UK's Medical Research Council. The scientists hypothesized that reactions could be accelerated in freezing water, a seemingly counterintuitive idea. Chemical reactions normally proceed more quickly at higher temperatures, where more energy is available to break chemical bonds, so why would cold water help?



TECHNICAL STUFF In fact, when water begins to freeze, non-water molecules are left behind in the remaining pores or cracks between the forming ice crystals. This increases the concentration of the non-water molecules in the remaining solution, pushing them together to react more rapidly.

The MRC scientists found that they could make a self-replicating ribozyme under such conditions, providing that they used triplet-RNA nucleobases, adding three at a time, rather than a single unit. This helped to overcome the natural resistance of the coiled and folded RNA to add new units.

Minimal DNA Cells

Although the experiments you've learned about so far in this chapter take a "bottom-up" approach of building successively more complex molecules, another approach to investigating life experimentally could be termed "top-down."



REMEMBER Over several decades, the J. Craig Venter Institute (JCVI) has been attempting to discover the minimum possible set of genes necessary for a living organism. To do this, they started with several bacterial strains that already had very tiny genomes — *Mycoplasma genitalium* and later *Mycoplasma mycoides* — and tried paring away genes in a trial-and-error approach to see which ones could be removed and still have a viable, self-reproducing organism.

The first product of this research was an organism they dubbed "Mycoplasma laboratorium," "JCVI-syn1.0," or "Synthia." Synthia was created by generating a new version of the genome of *M. mycoides* and placing it inside the cell of a different organism — *M. capricolum* — that had had its DNA removed. The new Synthia organism, comprised of the DNA of one species in the "body" of another, was able to reproduce.

In a later, more ambitious experiment, the JCVI group created something that could more accurately be described as the first artificial lifeform. The scientists removed as many genes as possible from *M. mycoides,* finding that a viable lifeform could be generated with only about half (473) of the original genes, around half a million base-pair amino acids. This "JCVI-syn3.0" is now considered the world's first truly synthetic organism.



REMEMBER This groundbreaking "minimal genome research" has shown us which genes are truly essential for life and which may be less necessary. In turn, this leads us closer to understanding the origins of life, since the more critical genes are likely to be among the earliest ones to have evolved from self-replicating RNA.

Computer Simulations

Although laboratory research has proven capable of many breakthroughs in origin of life research, some experiments are difficult to perform in laboratory conditions. In addition, there are almost an infinite number of possible starting conditions and ingredients to check, so by performing only laboratory experiments — important as they are — we may miss finding some vital pathways to life because of our own injected prejudices about the starting conditions.



TIP This is where the field of "artificial life" comes into its own. Inside a computer, a vast number of starting conditions and chemical permutations can be checked, as well as high-level conceptual understanding of the overall "parameter space" itself.

Competing for resources in Avida

One example of a high-level investigation is the Avida program at Michigan State University created by Professor Chris Adami and colleagues in 1993. Avida creates an "artificial world" inside a computer, where billions of possible "artificial lifeforms" coded as computer programs compete against one another to replicate and survive.



Each "lifeform" in Avida is a set of simple instructions, randomly combined to create a unique recipe for life inside the simulation. If the set of instructions (lifeform) can replicate, it will gradually out-compete other, less capable sets of instructions. Adami and colleagues found that by creating a billion different starting lifeforms, only 27 were able to successfully reproduce. These were then allowed to "evolve" by introducing small changes to the code during copying, to see if they could become "selected" in the Darwinian sense for improved copying and functionality.

The Avida simulation was important in showing that even when there are large numbers of possible starting combinations — as we expect for chemical combinations of ingredients in the real world — it only takes a few workable combinations to create self-sustaining life. Although the number of natural experiments needed to find the right combination is large, in the physical world there is also the possibility for billions of combinations to be tried in the process of natural molecular chemistry.

Simulating chemical reactions in Allchemy

A different, more physically-based approach was taken by scientists at the Polish Academy of Sciences in 2018. These researchers began with a very large database of possible organic chemical reactions (from the online *Beilstein Handbook*) and applied all possible pathways to a set of initial simple ingredients assumed to be present on the early Earth: ammonia, water, hydrogen sulfide, hydrogen cyanide, methane, and nitrogen.



The researchers tried a vast number of possible pathways in the *Beilstein* list, leading from the simple starting chemical species to more complex, pre-biotic molecules. Only reactions that could have occurred under presumed early-Earth conditions were permitted.

The program went through the same steps seven times. After each new generation of molecules was produced, unstable and invalid structures were eliminated, but new, stable molecules were added back into the mix with the six original species for the next round.

After seven rounds of reactions, the Allchemy simulation had produced an amazing 37,000 different chemical compounds from the original six chemicals. Of these, only 82 were considered "biotic," of which 41 were peptides, building blocks of proteins.



REMEMBER Comparison of this resulting set of biotic molecules to the abiotic molecules turned up some remarkable patterns:

- **Greater thermodynamic stability:** The biotic molecules were more resistant to changes induced by heat.
- **Less hydrophobicity:** The biotic molecules were less insoluble, or conversely more soluble, in water.
- **Fewer functional groups:** The biotic molecules had fewer types of these chemical side-attachments, and these were also less likely to be chemically active in the biotic molecules.
- **Synthetic redundancy:** There were multiple possible pathways to reach the biotic molecules, compared to similar-sized abiotic molecules that had fewer pathways.

The results of the Allchemy simulation have been truly eye-opening for origins-of-life researchers, finding trends and patterns that would probably never have been fully realized from limited experimentation alone, showing the power of the computational approach.

Burcar, B. T., Barge, L. M., Trail, D., Watson, E. B., Russell, M. J., & McGown, L. B. (2015). RNA oligomerization in laboratory analogues of alkaline hydrothermal vent systems. Astrobiology, 15(7), 509–522.

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Chapter 9

Life in the Extremes

IN THIS CHAPTER

- **Learning which types of life can survive in extreme environments on Earth**
- **Uncovering the biological tricks and adaptions that enable extremophile survival**
- **Discovering the role extremophiles may have played in the origin of life**
- **Finding out why astrobiologists are excited by extremophiles**

Some parts of Earth are just peachy for life: think of temperate woodlands, lush grasslands, and placid lagoons. OK, so critters living there may have some competition, but hey, at least the climate is cooperative.

At the other end of the scale, you'd imagine that the least hospitable spots — boiling hot springs, freezing mountain tops, dry deserts and dark ocean depths — would be uninhabited, right? Not so. Some forms of life seem unfazed in the face of adversity, and have evolved specialized cell walls, food sources, and survival tricks called *adaptions* that enable them to not only survive but even thrive in these locations.

In this chapter, you learn how different extremophiles have adapted to the toughest spots on Earth. You also find out why astrobiologists study extremophiles and what clues they provide about where to search for life in space.

Introducing the Extremophiles

Organisms that love life on the edge are called *extremophiles.* Astrobiologists study extremophiles because they show us how far life can adapt on Earth, which helps to expand our concepts of where to search for life in space.



Some extremophiles can cope with multiple types of harsh conditions, such as extreme heat, acidity, and pressure found near volcanic vents on the seabed. The technical name for these is *polyextremophiles*, although another term might be "show offs."

Check out Table 9-1 for some types of extremophiles, along with their preferred environments.

TABLE 9-1 Extremophile Types and Environments

Extremophile	*Environments*
Acidophile	Tolerate and thrive in highly acidic (low pH) environments.
Alkaliphile	An organism with optimal growth in highly alkaline (high pH) conditions.
Capnophile	Organisms that can withstand high levels of carbon dioxide, such as in an animal's digestive tract.
Halophile	Organisms that live in extremely salty water.
Osmophile	Organisms with optimal growth in high sugar concentrations.
Piezophile	Organisms that grow at high pressures — in ocean depths, or the deep surface of the Earth.
Psychrophile	Lives in cold places, such as polar regions and deep ocean depths.
Radioresistant	Organisms that can survive high levels of damaging radiation, include UV light, X-rays and gamma rays.
Thermophile	Thrives in heat, typically hot springs or near mid-ocean seafloor volcanic vents.
Xerophile	Organisms that can withstand extreme dryness, for example a desert.

You can get acquainted with many of these extremophiles in the sections that follow.

Some Like It Hot: Thermophiles

Thermophiles are organisms that just love the heat, basking in hot springs, hanging out near deep sea hydrothermal vents, or getting toasty in mounds of decaying plant matter. They're often single-celled lifeforms known as archaea, but can be bacteria or fungi instead (see Chapter 6 if you need a reminder about these types).

Thermophiles are classified depending on how much heat they can tolerate:

- **Typical thermophiles:** 50–65°C (122–149°F)
- **Extreme thermophiles:** 65–80°C (149–176°F)
- **Hyperthermophiles:** Greater than 80°C (176°F)



TECHNICAL STUFF Thermophiles that can tolerate both heat and cooler temperatures are called *facultative* thermophiles. On the other hand, *obligate* thermophiles require high temperatures for growth.

Thermophile adaptions

Remember that *adaptions* are evolutionary changes (see Chapter 4) to a species that occur over many generations, improving its survival in a particular environment. The long neck of a giraffe to enable it to eat leaves from tall trees is a great example. Thermophiles have accumulated adaptions that aid their survival in hot places, such as:

- **More rigid proteins:** Proteins are more tightly packed with stronger internal bonds and fewer flexible elements, making them more resistant to *denaturing* — unfolding and losing structure.
- **Heat-loving enzymes:** Those all-important reaction catalysts are specially selected in thermophiles to work well at high temperatures.

- **Tougher amino acids:** The mixture of amino acids used in the cell is modified to use more of the heat-stable amino acids (such as arginine, glutamic acid, lysine) and fewer of the heat-sensitive ones (such as glutamine, threonine, serine).
- **Stronger cell membranes:** Archaeon types make use of robust monolayers, with their lipids linked by ether bonds, where an oxygen atom serves to link them together like a dab of superglue. Bacteria use more straight-chain saturated fatty acids to increase strength.
- **Chaperone proteins:** Special proteins that help to repair other proteins that have started to unfold.

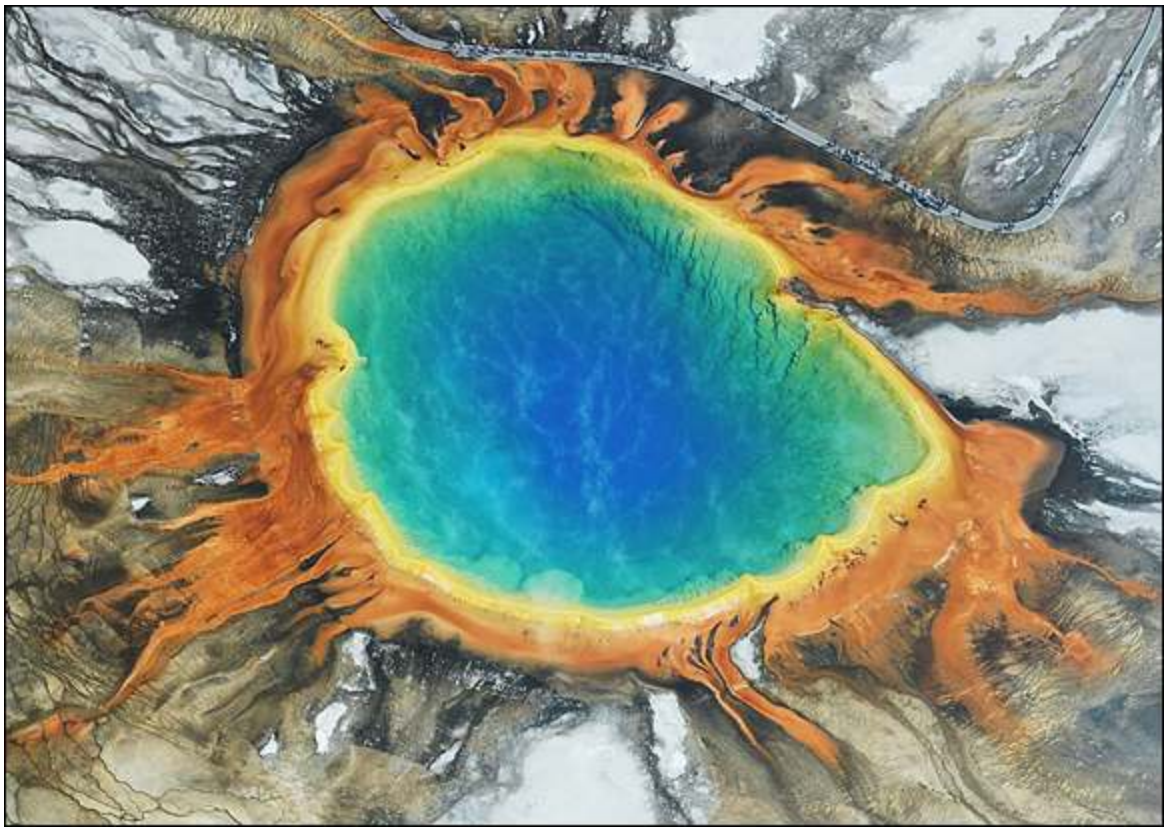
With these adaptions, thermophiles are well-placed to tough it out in the hottest spots on Earth.



REMEMBER Proteins are like little pieces of origami: Their function depends on their shape, as well as their chemical composition. If they lose their shape, their function is also lost, and they may become tangled up with each other — like items in your messy kitchen drawer. Many thermophile adaptions are designed to prevent proteins from losing shape so they can keep working as intended.



TIP Many types of thermophiles have been discovered in the hot springs of Yellowstone National Park, and one of the most striking of these is the Grand Prismatic Spring (see Figure 9-1). The thermophiles form into rings around the spring, varying in color from oranges and reds to blues and greens. The blue/green thermophiles are rich in chlorophyll (like green plants), and the red/orange colors are due to pigments known as *carotenoids* — yes, the same pigments that make carrots orange — that help to stabilize cell membranes in very hot conditions.



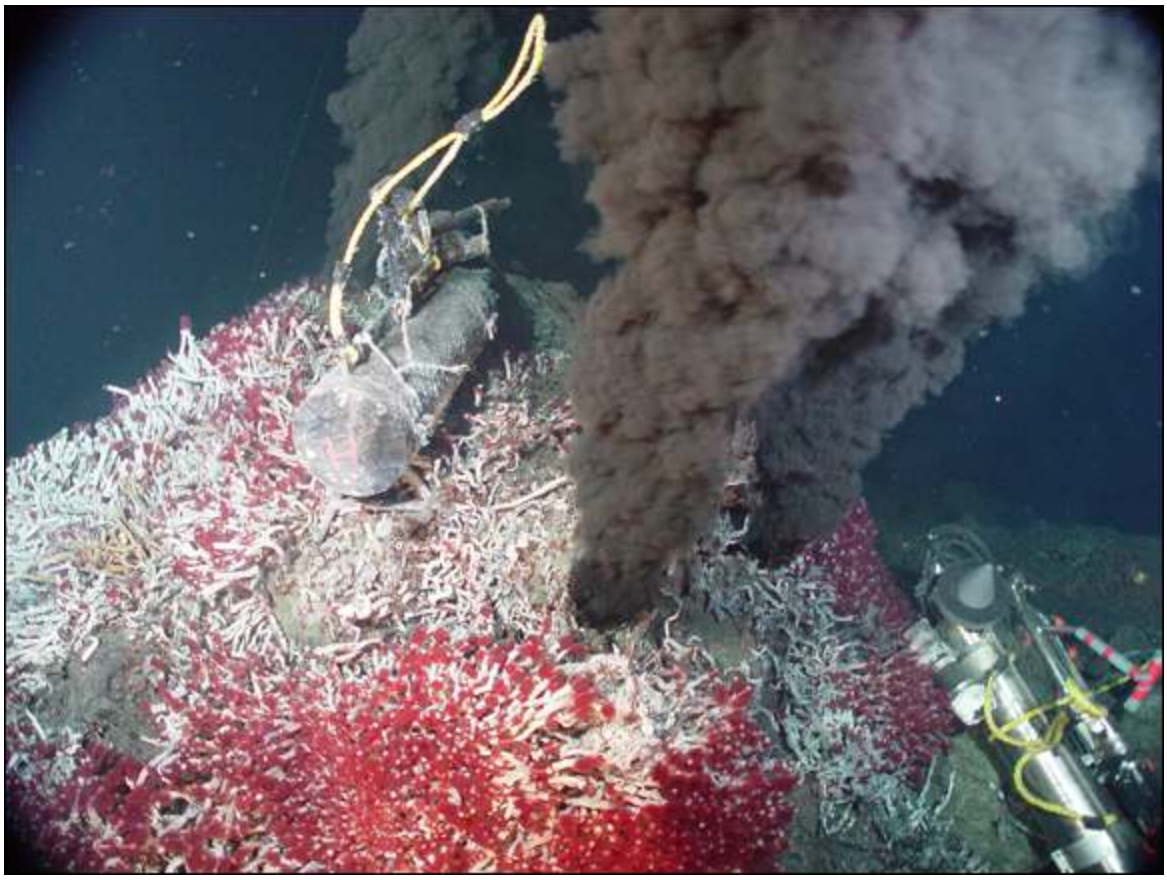
Carsten Steger/Wikimedia Commons/CC BY-SA 4.0

FIGURE 9-1: Grand Prismatic Spring, Yellowstone National Park.

Black smokers

Another category of thermophiles are those that live near hot deep-sea (hydrothermal) vents. These vents are fissures in the seabed, usually at places of volcanic activity, such as where tectonic plates are moving apart. The heated water dissolves minerals out of crustal rocks and carries them up and out of the vent, where clusters of hungry extremophiles lie in wait to gorge on the chemical nutrients.

The most well-known types are the "black smokers" (see Figure 9-2), which look like chimney stacks, belching out black clouds from the seabed. The black appearance is due to sulfide minerals, and organisms known as *chemotrophs* love to use this as an energy source. In contrast, "white smokers" are just the opposite — vents of white cloudy ash containing minerals such as calcium, barium, and silicon that also tend to be cooler than the black smokers. (More about white smokers later in this chapter when you meet the *alkaliphiles*.)



NOAA/Public domain

FIGURE 9-2: Sully Vent in the Main Endeavour Vent Field of the northeastern Pacific Ocean. Giant tube worms are visible clustering around the vent to absorb nutrients.



TIP Black smokers are famous for the unexpected abundance and diversity of the lifeforms that colonize them: from giant 2-meter (6.6 ft) tube worms, to hairy-clawed "yeti crabs" and foot-long eels that hide out in crevices and wait to ambush passing crustaceans.

Life in the Freezer: Psychrophiles

At the other end of the heat spectrum are cold-loving *psychrophiles*, who just love to chill out, so to speak. Psychrophiles are defined as organisms that thrive below 10°C (50°F), although some are even active below the freezing point of water (0°C, 32°F). Psychrophiles can be bacteria,

archaea, fungi, algae, and even small tough animals called *tardigrades* that you'll meet again later in the chapter.

Psychrophile adaptions

Psychrophiles use some of the opposite types of adaptions that you saw with their heat-loving thermophile cousins. Let's look closer at what keeps these cold-loving critters ticking over:

- **Increased molecular flexibility:** Enzymes have more loops and a high content of small amino acids (for example, alanine, glycine). Cell walls use more unsaturated fatty acids with lower melting points.
- **Antifreeze proteins:** Special proteins that bind to any forming ice crystals, preventing them from growing and damaging the cells' internal workings.
- **Cold shock proteins:** Proteins that bind to DNA, stabilizing its structure and preventing damage during cold spells.
- **Chaperones:** As we saw with the thermophiles, chaperone proteins help to refold proteins and prevent aggregation.
- **Cryoprotectants:** A wide class of molecules, including glycerol and glucose, that help to reduce the freezing point, preventing ice crystal formation and reducing dehydration.



Vitrification is the process of forming a solid without ice crystals, also known as an amorphous solid or glass. Cryoprotectant molecules allow organisms to undergo slow vitrification, reducing the damage that would otherwise occur when large ice crystals form. They also bind to important biomolecules with hydrogen bonds, helping them to retain their shape and structure. After thawing, the cryoprotectants unbind, releasing the biomolecules to resume their cellular functions.

Lichen the c-c-cold

You may have heard that a late frost in spring can be bad for crops. You'll even see many tasty edibles such as tomatoes and peppers being raised snug and warm in a transparent plastic tent. Not so with some psychrophile plants, who just love a nice cold snap.

Figure 9-3a shows the lichen *Rusavskia elegans* photographed living on a patch of sandstone rock in Canada's alpine zone. This hardy species can photosynthesize at a frosty −24°C (−11°F) and also survived 18 months living outside the International Space Station, exposed to heat, cold and radiation.



TIP The space exposure provides astrobiologists with evidence that life might be able to hop between planets by hitching a ride on meteorites. These are rocks blasted into space from a planetary surface by asteroid impacts that later reach a different planet — such as the pieces of Mars found on Earth (yep, really — see Chapter 11).

Algae are another lifeform that have superstar psychrophiles: Check out this "snow algae" (see Figure 9-3b) living happily on a patch of snow in Sweden.



TIP The first report of this "red snow" lifeform came from the Greek scientist Aristotle over 2,000 years ago (an early astrobiologist of sorts). Researchers have been actively studying *C. Nivalis* for over 100 years due to its ability to live in challenging environments.



Image credits (a) Jason Hollinger/Wikimedia Commons/CC BY-SA 3.0 (b) Ökologix/Wikimedia Commons/CC BY-SA 3.0

FIGURE 9-3: Two cold-loving species, (a) the "sunburst lichen" *Rusavskia elegans;* (b) the "snow algae" *Chlamydomonas nivalis.*

Passing the Acid Test: Acidophiles

Next on our list of extreme organisms are the *acidophiles*, creatures that thrive when surrounded by tingly hydrogen ions (protons) that would snuff out other lifeforms. Similarly to the thermophiles, we can divide the acidophiles into classes depending on their level of pH tolerance:

- **Extreme acidophiles** grow at pH less than 3.
- **Moderate acidophiles** prefer to live at pH 3 to 5.
- **Acid-tolerant species** have optimal growth above pH 5, but are tolerant at lower pHs.

Acidophile adaptions

Let's now see how acidophiles survive their harsh surroundings. Key adaptions include:

- **Less permeable cell membranes:** Acidophile cell membranes have reduced pore sizes and special lipids that make it less easy for protons (such as hydrogen) to enter.

- **Proton efflux systems:** For any protons that do make it into the cell, there are special proteins waiting to pump the invaders back out again, like repelling boarders from a pirate ship. Begone!
- **DNA and protein repair systems:** As with other extremophiles, it's important to have repair mechanisms in place for any damage that does occur.
- **Alkali production:** *Alkalis* are the chemical opposites of acids, so the production of alkalis can help neutralize protons, resulting in less harmful salts.
- **Proton consumption:** Instead of throwing the invading protons back outside, some acidophiles simply harness the proton gradient — high numbers of protons outside, but low counts inside the cell — to generate ATP (adenosine triphosphate), which stores energy for the cell.

Munching on iron

One example of an acidophile is *Acidithiobacillus ferrooxidans* whose name means "acidic sulfur rod that oxidizes iron" (now there's a mouthful). The bacterium does exactly what its name suggests: It feeds on pyrite — iron sulfide, or FeS_2 — and releases energy by oxidizing the iron and sulfur. A side product is H_2SO_4 which any chemistry students reading this book will immediately recognize as sulfuric acid, hence the need to survive in low pH conditions. *A. ferrooxidans* is literally living in an acid bath.



TIP *A. ferrooxidans* is being investigated for use in mining and in recycling of electronic waste, including batteries, due to its ability to extract and concentrate valuable metals such as copper, silver, and gold — a process known as *bioleaching*. That's one valuable bacterium!



An organism such as *A. ferrooxidans* that derives chemical energy from rock is known as a *chemolithoautotroph*. This long name comes from *autotroph* — an organism that derives its own energy rather than feeding on other animate or plant life — and *chemolitho* — meaning that the energy is chemical energy derived from rock. (Good to have your dictionary handy when studying bacteria.)

Back to Basics: Alkaliphiles

The opposite of an *acidophile* is an *alkaliphile* — organisms that detest low pH levels and love the alkaline life instead (pH 8.5–11). Curiously, like acidophiles, alkaliphiles have also been found living on the deep seabed near hydrothermal vents. However, rather than inhabiting the iron- and sulfur-laden "black smoker" vents, alkaliphiles cluster around the somewhat cooler "white smoker" vents that are rich in the elements calcium, barium, and silicon (see later section, Discovering the "Lost City").



Alkaliphiles can be categorized as *obligate* — needing highly alkaline conditions to survive — or *facultative* — preferring but not requiring such conditions for growth.

Alkaliphile adaptions

It's not an easy life surviving in highly alkaline environments, which can cause loss of DNA shape, instability of the cell membrane, and inactivation of enzymes if the pH inside the cell becomes too high. So what's an obligate alkaliphile to do?



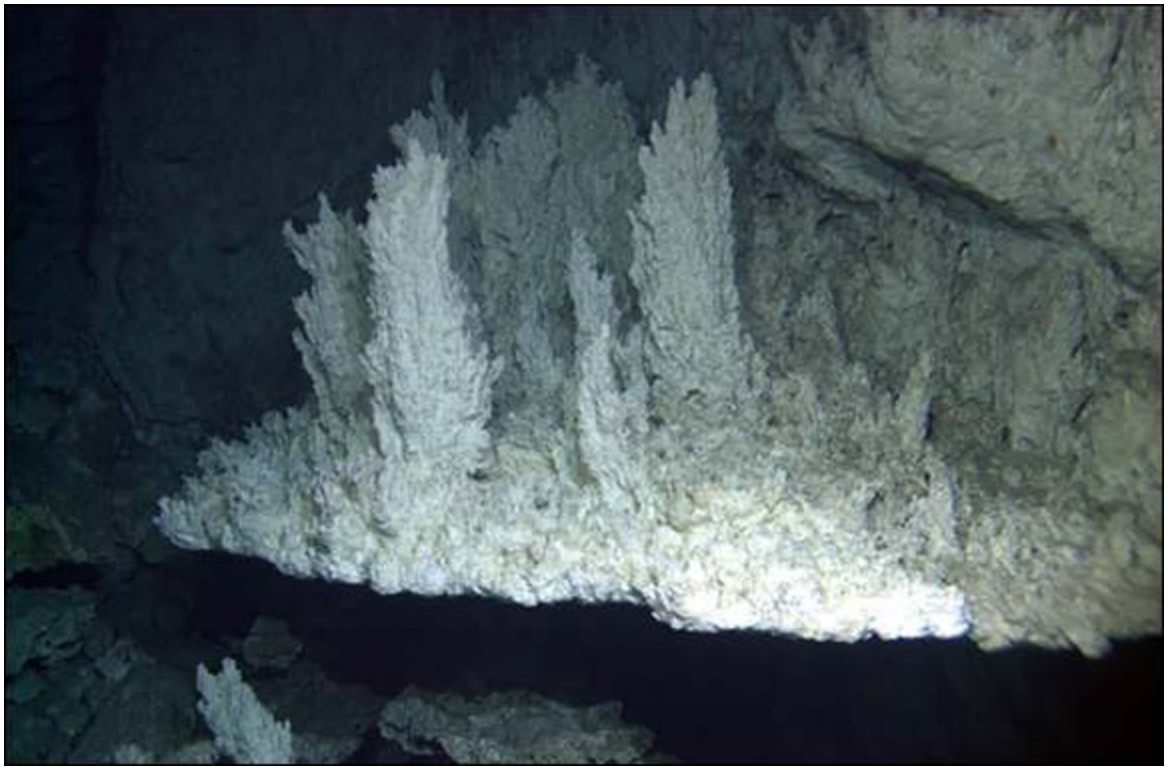
TIP Alkaliphiles face many of the same problems as halophiles (see later in this chapter), and have evolved similar sophisticated adaption techniques:

- **Cytosol acidification:** Enzymes only work properly if the fluid inside the cell, or *cytosol*, is at the right pH level, requiring *homeostasis* — action to maintain stability of the cell. This balancing act can be tricky if the external environment is highly alkaline and prone to leak sodium ions inside the cell. To counteract this, alkaliphiles have evolved sophisticated techniques to swap the unwanted Na^+ ions for acidifying H^+ ions. Kind of like swapping that baseball card you have too many duplicates of for the one you really want.
- **Stabilized membranes:** Cell membranes composed of more branched-chain fatty acids help to stabilize the cell membrane and prevent proton leakage.
- **Sodium-driven energy:** When H^+ ions are in short supply, adapted alkaliphiles can compensate by using sodium ion gradients to power energy storage (ATP synthesis) instead.
- **Alkaline-stable proteins:** Alkaliphiles use proteins and enzymes that are more stable at high pH levels, often composed with a higher fraction of acidic amino acids than used in typical proteins and enzymes.
- **Osmotic stress management:** To prevent too much water loss through osmosis, cells accumulate solutes such as glycerol and betaine that counteract osmotic loss.

Discovering the "Lost City"

In a deep dive in 2000, the crew of the submersible Alvin were astonished to discover towering mineral growths (see Figure 9-4) on the seabed in the region of the mid-Atlantic ridge — a juncture in the tectonic plates where the North American and Eurasian continental

plates are moving apart. In this location, chemical reactions known as *serpentinization* led to the production of methane and hydrogen gases — molecules that can be used as chemical energy sources by biota. The oxidation of methane and hydrogen releases energy in a way that's similar to the ways consuming sugar in your body or burning gasoline in a car engine release energy. Microorganisms living near these high-pH vents are typically alkaliphiles, as well as being thermophiles and piezophiles to boot — talk about multitasking!



National Science Foundation/Public domain

FIGURE 9-4: A ledge on the side of chimney in the Lost City Hydrothermal Field sprouts tree-like growths of carbonate rock. These occur when mineral-rich fluids seep out and encounter cold seawater, causing the dissolved minerals to precipitate.

Getting Salty: Halophiles

Halophiles are organisms that love highly salty conditions, ranging from seawater-levels of salt to much higher:

- **Slight halophiles** at 1.7–4.8 percent salt concentration, around the same range as seawater at 3.5 percent.
- **Moderate halophiles** at 4.8 percent to 20 percent salt concentration.
- **Extreme halophiles** at 20–30 percent salt concentration.



REMEMBER Like other extremophiles, most halophiles identified by biologists are archaea, but some bacterial species and fungi are also included.

The challenge of living in a salty environment is *osmotic pressure*: The salty surroundings tend to draw water out of the cell through its pores to even up the salinity inside and outside the cell, so halophiles have had to adapt to survive.

Halophile adaptions

Halophiles have evolved at least two strategies to cope with the hypersaline surroundings:

- **Osmoprotectants:** Cells accumulate organic compounds in their cytoplasm with properties that reduce the osmotic pressure and prevent water escaping. Osmoprotectants are also used by plants in another context — to prevent desiccation damage during drought conditions.
- **Potassium accumulation:** A more radical strategy adopted by species living in extremely salty conditions is to build up potassium ions inside the cell. Potassium may be thought of as a different type of salt from the more common sodium, that is easier for the cell to handle. A downside of this strategy is that the entire chemical workings of the cell must be adapted to the high potassium environment — a much bigger adaption than simply keeping the cell interior at normal salinity levels.

Living the salt life

Halophiles have been found in salty lakes and seas such as Owens Lake, California, and the Great Salt Lake of Utah in the USA; the Dead Sea in the Middle East; and the Aral Sea in Asia. The growth of bacteria and archaea is often recognizable by the bright pink, red, and purple colorations of the carotenoids in these animals that serve a role in protecting them from harsh solar ultraviolet (UV) rays. If that sounds familiar, refer back to Figure 9-1.



TIP Although too much salt can be toxic, moderate levels of salt are healthy and necessary for all living things. In the human body, we get salt from food and some drinks, such as milk. Salt circulates in our blood, is regulated by our liver and kidneys, and is lost through excretions such as sweat, tears, and urine.



TECHNICAL STUFF As with acidophiles and other extremophiles, humans are finding practical uses for halophiles besides being cool critters to study. Halophiles can be used to help clean up hypersaline wastewater and soils, a process known as *bioremediation*, and to ferment biomass to make fuels. They have even been studied for possible future use in space to help with recycling wastewater.

Surviving a drought: Xerophiles

You've probably heard that we should all drink several liters of water a day. Perhaps you even carry a large refillable water bottle with you everywhere, from home to your school or office, in the car and to the gym? There's no doubt that staying properly hydrated is good for our health. At least — for humans.

Xerophiles scoff at such notions. They live in the driest places on Earth, such as the Atacama Desert of South America, and the aptly named Dry Valleys of Antarctica where the water "activity" (availability) can be 20 percent or more below levels where most life flourishes.

Xerophile adaptions

Xerophiles have to be hardy, often contending with high heat and sometimes salty conditions as well as extreme aridity. A few of the biological "tricks" they've learned include:

- **Compatible solutes:** Xerophiles accumulate substances like glycine betaine, trehalose, or sugars to increase internal osmotic pressure — drawing and holding water inside the cell.
- **Membrane stabilization:** Phospholipids composing the cell membranes are modified to prevent damaging changes during water loss.
- **DNA and protein protection:** Xerophiles secrete protective proteins and antioxidant enzymes to shield molecules in the cell from damage. Physical damage, such as protein denaturation (unfolding) and cell membrane collapse, can accumulate due to desiccation. Reactive oxygen species (ROS) such as hydroxyl (OH) and hydroperoxyl (HO_2) cause chemical damage, attacking DNA and proteins.
- **Dormancy and spore formation:** Some can safely enter a state of dormancy known as *anhydrobiosis* (life without water) or form highly resistant spores with low metabolic rates.
- **Water retention:** They reduce water loss through reduced metabolic activity and changes to the cell wall or outer membrane.
- **Efficient repair:** Xerophiles have enhanced DNA repair mechanisms and increase antioxidant enzymes to combat oxidative stress.

The high life of the Atacama



REMEMBER The Atacama Desert is one of the driest places on Earth, with an average annual rainfall of less than 2 mm (0.08 in) — less than even the Sahara and Kalahari deserts of Africa. Here, it's a struggle for even the hardiest organisms to survive, although miraculously some do.

Scientific teams from NASA and various universities have been coming to the Atacama for decades, since its lifeforms — including lichens, fungi, and cyanobacteria — may provide clues to help guide a search for life on Mars. Life in the Atacama has proved resourceful about finding ecological niches that provide some benefits and shelter from sweltering heat, salinity, and aridity:

- **Biocrusts:** Lichens — which are actually *symbionts* (partnerships) between algae and bacteria (refer to Chapter 7) — have been discovered binding together gritty sand particles in more coastal regions of the Atacama.
- **Hypoliths:** In more arid conditions, life can cling to the underside of translucent rocks, including quartz. In this slightly cooler microclimate (cooler compared to the exposed top surfaces), organisms including bacteria and archaea have learned to use frequent fog as a water source, rather than waiting for rain that may never come.
- **Endoliths:** In the driest parts of the Atacama, clever critters make a home inside translucent rocks such as gypsum, which let in just enough light for photosynthesis and also trap precious water in their crystalline structure. Endoliths were discovered as blue-green veins inside the rocks, which turned out to be photosynthesizing cyanobacteria.

Heading south: Antarctica

The best substitute (or analog) scientists have for the surface of Mars on Earth are the windswept Dry Valleys of Antarctica, which are both dry

and also very cold. Average temperatures hover well below freezing at -15°C to -30°C (5°F to -21°F) but can get much colder: down to a frigid -66°C (-86°F). *Brrr* — better bring your parka if you want to go sightseeing here!

Organisms living here adopt many of the same strategies we saw in the Atacama, such as hiding beneath or inside rocks, or in soil crust, rather than being exposed. Problems they have to solve include generating energy, collecting nutrients, and preventing freezing and desiccation — quite a tall order. Nevertheless, clever strategies enable them to survive, including the following:

- **Cellular antifreeze:** Organisms create internal solutes (sugars, salts) and specialized proteins to lower freezing points and prevent ice crystal formation in cells.
- **Cold-active enzymes:** They produce enzymes with high flexibility and catalytic efficiency at low temperatures, allowing metabolic processes to function in the cold.
- **Energy from chemistry:** Some microbes use chemical reactions with iron and sulfur in rocks for energy (*chemolithotrophy*).
- **Dormancy and resilient structures:** Mosses, for instance, can become dormant and rely on wind dispersal during extreme dry periods.

Living under pressure: Piezophiles

Have you ever felt under pressure to meet a tight deadline at school or work? If so, you probably haven't felt the pressure quite like *piezophiles* — organisms that love to live deep in the ocean or far underground.

Like other extremophiles, we can categorize piezophiles, in this case according to how much pressure they can tolerate:

- **Piezotolerant** organisms that prefer to live at pressures up to 10 megapascals (MPa) (99 atm or 1500 psi) but can tolerate higher pressures.

- **Moderate piezophiles** like to live at pressures beyond 10 MPa (99 atm, 1,500 psi) and up to 50 MPa (493 atm, 7,252 psi). If they need these high pressures for growth, they are known as *obligate* piezophiles.
- **Hyperpiezophiles** really like to feel the pressure, beyond 50 MPa (493 atm, 7,252 psi).

For context, the typical oceanic floor (3,800 m or 12,500 ft depth) is around 380 atm (38.5 MPa, 5,500 psi).



The first piezophile to be discovered (*Colwellia marinimaniae*) was found in the decaying body of a crustacean at the bottom of the Mariana Trench — the deepest point in the seabed (almost 11 km or 36,000 ft below sea level)—. This tough critter likes not only high pressure (1072 atm, 108.6 MPa or 15,750 psi) but cold as well (1-4°C, 34-39°F), making it a psychrophile (see earlier in this chapter) as well as a piezophile.

Piezophile adaptions

Now let's look at piezophile adaptions — how they manage to survive at intense pressures that would squish the rest of us:

- **Modified cell membranes:** High pressures tend to reduce the flexibility and permeability of cell membranes — a problem when the organism needs to take in nutrients or excrete waste. To counteract this, piezophiles have evolved changes to the molecules that make up the cell membrane, including more unsaturated and branched fatty acids to increase flexibility, and modified heads and chain lengths of these molecules as well.
- **More rigid proteins:** Proteins are specialized molecules often working like keys to locks, where their shape is as important as their chemical elements. Piezophiles tend to use proteins that are denser and more rigid than those used by regular surface-dwelling

organisms, which consequently change their shape less under pressure.

- **Pressure-tolerant enzymes:** Enzymes are the important molecules (often proteins) that catalyze (or speed up) reactions in the cell. Piezophiles favor tolerant enzymes that work over a broad range of pressure and temperature, sometimes even working better as the pressure cranks up.



REMEMBER Piezophiles are very interesting to astrobiologists, since some of the habitats found in space — oceans buried deep under the crusts of icy moons of Jupiter and Saturn — appear similar to the deep oceans on Earth. I talk more about this topic later in the chapter.

Drilling deep

Lake Vostok is a vast subglacial freshwater lake, hiding 4 km (13,000 ft) beneath inland ice in Antarctica (see Figure 9-5). A team of Russian scientists spent decades on an ambitious project to drill down from the surface into the water beneath, with a goal to search for life that can survive at extreme depths and isolated from any energy sources, including sunlight from the outside world.

The lake water was reached in 2012, and although some potentially new organisms were discovered, scientific opinion is mixed on whether these were true lake inhabiting piezophiles, or life from above that hitched a ride down on the drill.

This debate highlights some of the difficulties scientists will encounter when searching for life on Mars or Europa, especially the problem of contaminating the planetary samples with life brought from Earth. This problem is part of a wider field known as “planetary protection.”

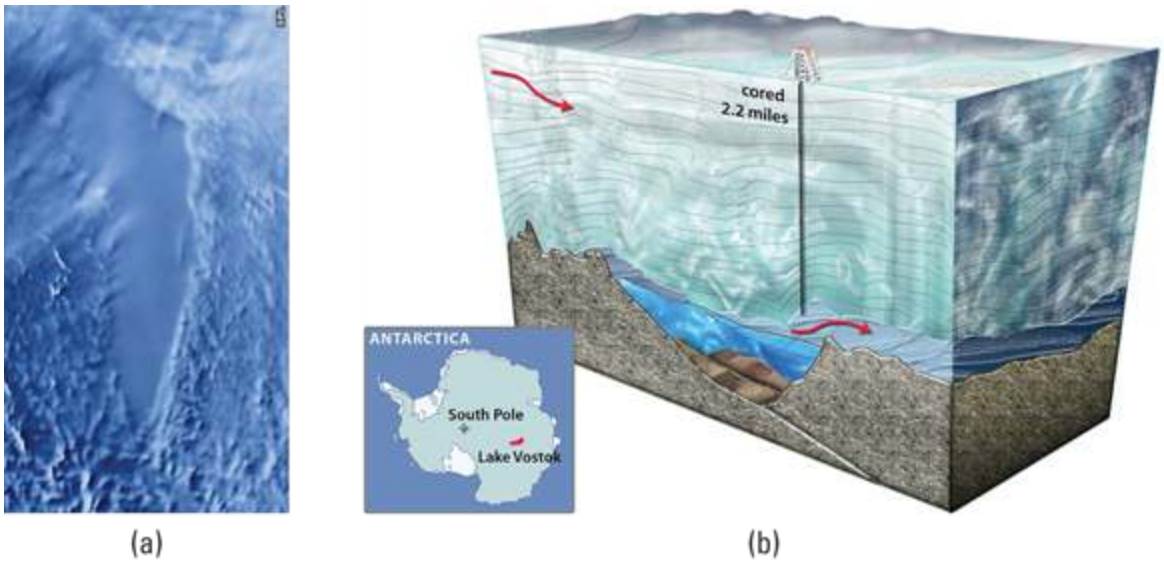


Image credits: (a) NASA/Wikimedia Commons/Public domain (b) Nicolle Rager-Fuller/National Science Foundation/Public domain

FIGURE 9-5: Left — Lake Vostok seen from space extending 160 miles (250 km) in length and 30 miles (50 km) in width. On the right, a conceptual diagram of the drilling project.

Radio Ga Ga: Radioresistant organisms

TIP *Radioresistant* organisms are those who can tolerate radiation that would kill other lifeforms. The term is formally defined as taking more than 1000 Grays (Gy) of radiation before having a 90 percent reduction in population. That's more than 200 times the survivable dose for a human!

The world's most radiation-resistant organism

The first radioresistant organism was discovered living in a can of meat in Oregon in 1956. A scientist named Arthur Anderson was trying to sterilize the food using gamma radiation — a type of ray normally associated with nuclear reactions and explosions. After attempted sterilization with "lethal" doses of gamma rays, the meat still spoiled, showing that something had survived. After the bacterium was isolated and studied, it was named *Deinococcus radiodurans* — a Latin name that roughly translates to "terrible berry that survives radiation."



TIP The toughness of *D. radiodurans* goes beyond merely surviving toxic radiation — it can also handle extremes of cold, dehydration, vacuum environments, and acid as well, making it a profligate *polyextremophile,* and leading to the nickname "Conan the Bacterium". *You*'ll find out more about how these other extreme resistances were uncovered in the next section.



TECHNICAL STUFF For a long while, *D. radiodurans* held the title of "most radiation-resistant organism" — that is, until 2003, when an upstart came along to steal the crown. The newcomer was *Thermococcus gammatolerans,* discovered lurking near hydrothermal vents at depths of 2,600 m (8,500 ft) in the Guaymas Basin of the Gulf of California. *T. gammatolerans* not only lives at near boiling temperatures (70–95°C, 158–203°F) and high pressures but has also proved to withstand radiation doses of 30,000 Gy — 6,000 times as much as you or I could take.

Adaptions for radiation-resistance



REMEMBER How do *D. radiodurans, T. gammatolerans* and their ilk survive the pummeling that strong radiation inflicts on DNA and other cell structures?

- **DNA structure:** DNA is the key information-encoding molecule in any living organism, and if it gets too damaged, the cell won't be able to reproduce. Our hardy friend *D. radiodurans* has several neat strategies that help to prevent this happening, including packing its DNA into defensive, donut-shaped structures known as *toroids*. It also keeps multiple spare copies of its DNA genome.

- **DNA repair:** *D. radiodurans* is also adept at patching up any damage to its DNA that does occur, including both single strand and double strand breaks. Single strand breaks are repaired by using one of the fully intact spare copies of the DNA as a template to add to the damaged, broken strands, making them whole again. Double-strand breaks are repaired using undamaged segments from other DNA strands to patch up the broken DNA.
- **DNA donations:** *D. radiodurans* is a social creature and individuals like to stick together with three others in a group known as a *tetrad*. This may also be a smart survival strategy: If the DNA in one of the members becomes too badly damaged for any of usual repair mechanisms to work, it can absorb DNA donations from a neighbor to patch its own DNA up.

Superfungi



TIP *D. radiodurans* isn't the only radiation-resistant organism hogging the limelight. Scientists examining survival of life around the site of the Chernobyl nuclear reactor disaster have found fungi that appear to be leaning *toward* the sources of radiation rather than away — leading to a realization that they are actively using the radiation as an energy source for growth.



TECHNICAL STUFF An example is the species *Cladosporium sphaerospermum*, which is observed to grow faster in the laboratory when radiation levels are 500 times normal. The radiation resistance of these super-shrooms appears to be linked to their clever use of melanin — the same substance that causes skin darkening and tanning in humans. *C. sphaerospermum* uses melanin to enhance its survival in several ways:

- To harness gamma radiation in much the same way chlorophyll is used to capture sunlight, to convert to chemical energy;
- Melanin neutralizes reactive oxygen species that could otherwise damage cellular machinery;
- Deposited in cell walls, melanin adds structural rigidity and chemical resistance against toxins.

Going above and beyond

Space — the final frontier. For humans, space is an inhospitable environment, with extremes of heat and cold, harsh radiation, and airless vacuum. For some extremophiles, however, these conditions are a walk in the park.



An experimental apparatus aptly known as EXPOSE ("Exposing Organisms to a Space Environment") attaches palettes of chemical and biological material to space on the exterior of the International Space Station (ISS) — see Figure 9-6 — to assess how well they can withstand the stresses of vacuum and radiation. Although some samples were given the full blast of solar rays, others were partially shielded from the most damaging UV rays, to simulate conditions on the Martian surface instead, where the thin atmosphere provides partial protection.

One notable bacterial species *Chroococcidiopsis* — originally found clinging to the underside of rocks in deserts from Antarctica to the Mojave — proved particularly hardy. After 18 months of exposure in space on the ISS, it was rehydrated and resuscitated itself quickly after return to a lab on Earth, repairing any cellular damage that occurred, and happily continuing to divide as though nothing had happened.

And that's not all: this tough character can also survive temperature down to -80°C (-112°F), entering a glass-like state of dormancy (cryptobiosis) that protects it from damaging ice crystal formation. It can

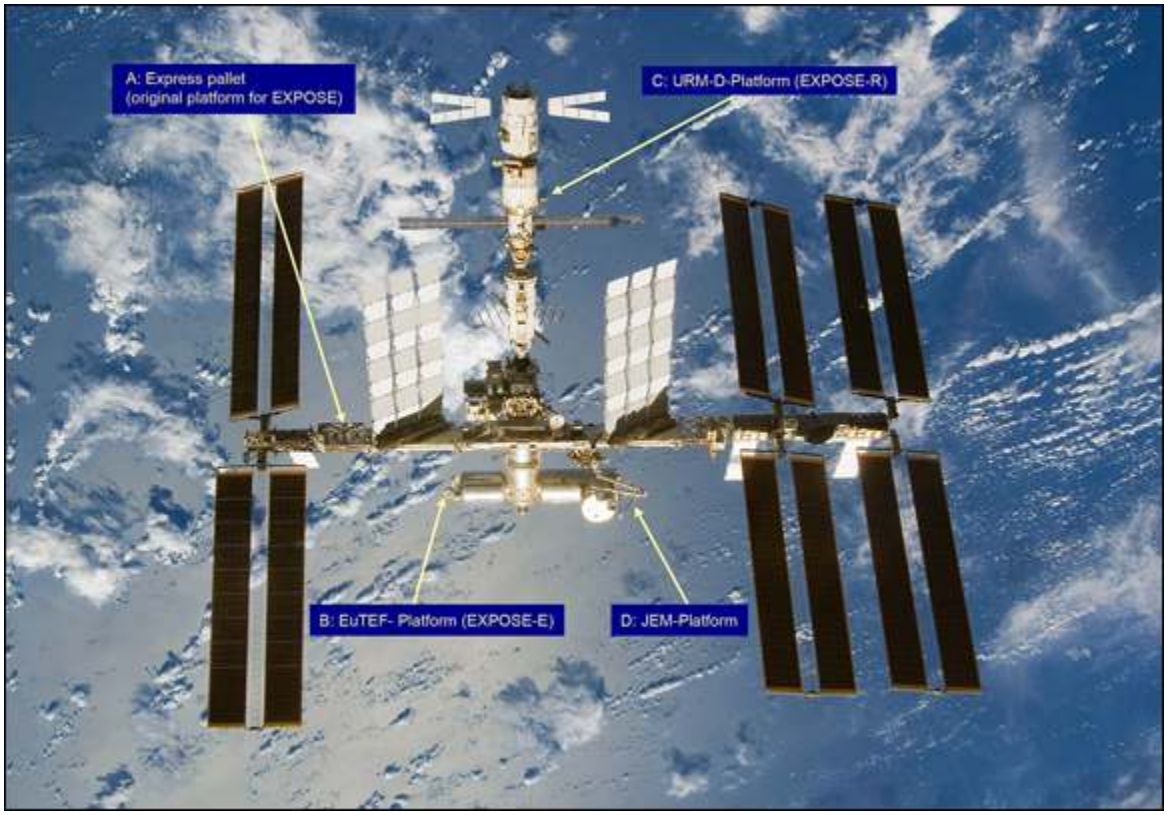
even live entirely on Lunar or Martian rock, producing oxygen via photosynthesis that could someday be used to generate an atmosphere on Mars.

Bears in space!

Perhaps the most famous of all extremophiles is also the cutest. Formally named *tardigrades* ("slow walkers") and also known as "water bears," they are tiny eight-legged micro-animals found living almost everywhere on Earth, from deserts to the deep sea, and everywhere in between. They are relatives of *arthropods*, a group that includes spiders, aphids, and caterpillars but form a distinct phylum unto themselves.



TIP Tardigrades are often found on moss, leading to another cute nickname "moss piglets" (*aww*) so go check your garden (see Figure 9-7). But make sure to have a microscope handy, since they are only around 0.5 mm (0.02 in) in length.



Credit: NASA/Wikimedia Commons/Public domain

FIGURE 9-6: The International Space Station, showing the locations on the exteriors of several different modules where the EXPOSE experimental payloads have been placed.

Despite their cute, pudgy appearance, tardigrades are one the toughest lifeforms on the planet — which perhaps explains why they have been around for at least 500 million years. Despite loving water, they have an amazing ability to withstand total desiccation (drying) to enter a "tun" state of *cryptobiosis* where they survive without food or water for years.

Scientists have subjected these cute critters to a huge array of insanely tough tests, from freezing down to almost absolute zero at temperatures of -272°C (-458°F) to baking them at 149°C (300°F) for short durations. They have proved able to survive deprivation of oxygen, ionizing radiation, exposure to the vacuum of space, and high pressures. They can even take impacts of 1.14 GPa (165,000 psi).

In 2007, tardigrades went on the ultimate adventure into space on a Russian Soyuz rocket for a 10-day sojourn in Earth orbit. A majority (68 percent) of tardigrades that had been dehydrated before launch reanimated themselves back to life after the cruise, although fully hydrated specimens survived less well in space.

These tests had led some scientists to speculate that tardigrades could be examples of the type of organisms that could have populated the Earth by hitchhiking on a meteorite from another world — an idea known as *panspermia,* discussed in more detail in the next chapter.



Photo: rukanoga/Adobe Stock Photos

FIGURE 9-7: Tardigrades or “water bears” are the toughest extreme animals.

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Part 3

Searching for Life in Our Solar System

IN THIS PART …

Discover why astrobiologists get excited about new cometary apparitions and meteorite falls.

Learn about the ongoing search for life on other worlds, from the sands of Mars to hidden oceans in the icy moons of Jupiter and Saturn.

Ponder the possibilities of exotic life in the clouds of Venus and Jupiter.

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Chapter 10
Comets

IN THIS CHAPTER

- **Delving into the mysteries of comet origins**
- **Learning what comets are made of**
- **Finding out how comets may have helped life start on Earth**

From time to time, you've probably seen a news feature about the arrival of a new comet in the sky, tracing a long, feathery trail across the heavens as it visits us for a brief few months and soon vanishes. Perhaps you've even gone outside to look at a comet using your unaided eyes, binoculars, or even a telescope. Meanwhile, you hear that professional astronomers across the world are doing the same, albeit with much fancier instruments.

Why are we so fascinated by comets? One reason is surely their temporary nature: The stars are mostly static during our human lifetimes, and the planets come and go, but always return. Comets, however, are one of the truly ephemeral objects in the night sky, so they have by turns enthralled and even terrified us (more about that later) throughout human history.



TIP For professional scientists, comets are beautiful but also objects of intense study, holding clues to the origin of the solar system, and perhaps even for the origin of life on Earth. In this chapter, you learn all the key facts about comets: where they come from, what gives rise to their spectacular appearance (see Figure 10-1), and what they can tell us about astrobiology.



Photo: E. Kolmhofer, H. Raab; Johannes-Kepler-Observatory, Linz, Austria/Wikimedia Commons/CC BY-SA 3.0

FIGURE 10-1: The bright comet Hale-Bopp photographed in 1997.

Comets in History

Comets have intrigued and perplexed philosophers for millennia. Theories have abounded from the religious to the scientific, but a true understanding of their nature would not arrive until the 1500s.

Omens and harbingers

As the night sky is generally so predictable, the appearance of comets was highly unsettling to ancient peoples. Across most cultures, comets were interpreted as a message from the gods — usually one of displeasure signaling a change in a ruler, a great defeat or victory, or a natural disaster such as famine, fire, flood, earthquake, tsunami, or plague. Because these events were not uncommon, it was not difficult to find an association of a cometary appearance with a disaster or upheaval soon afterwards, and many battles were even instigated after the sighting of a comet.



REMEMBER A famous example is the Norman conquest of England in the year 1066. The invading William, Duke of Normandy in northern France defeated the Anglo-Saxon King Harold, marking a major change in the history of England. The invasion followed soon after the sighting of a very bright comet, which was much later determined to be the famous *Halley's Comet* — more on that coming up. Both the decisive Battle of Hastings and the comet sighting became immortalized in the renowned Bayeux Tapestry, a 230-ft (70 m) long embroidered record of the war (see Figure 10-2).



Credit: Myrabella/Wikimedia Commons/Public domain

FIGURE 10-2: The depiction of a comet appearing to soldiers in the Bayeux Tapestry, presaging the Norman invasion of England. The Latin inscription says, “They wondered at the star.”

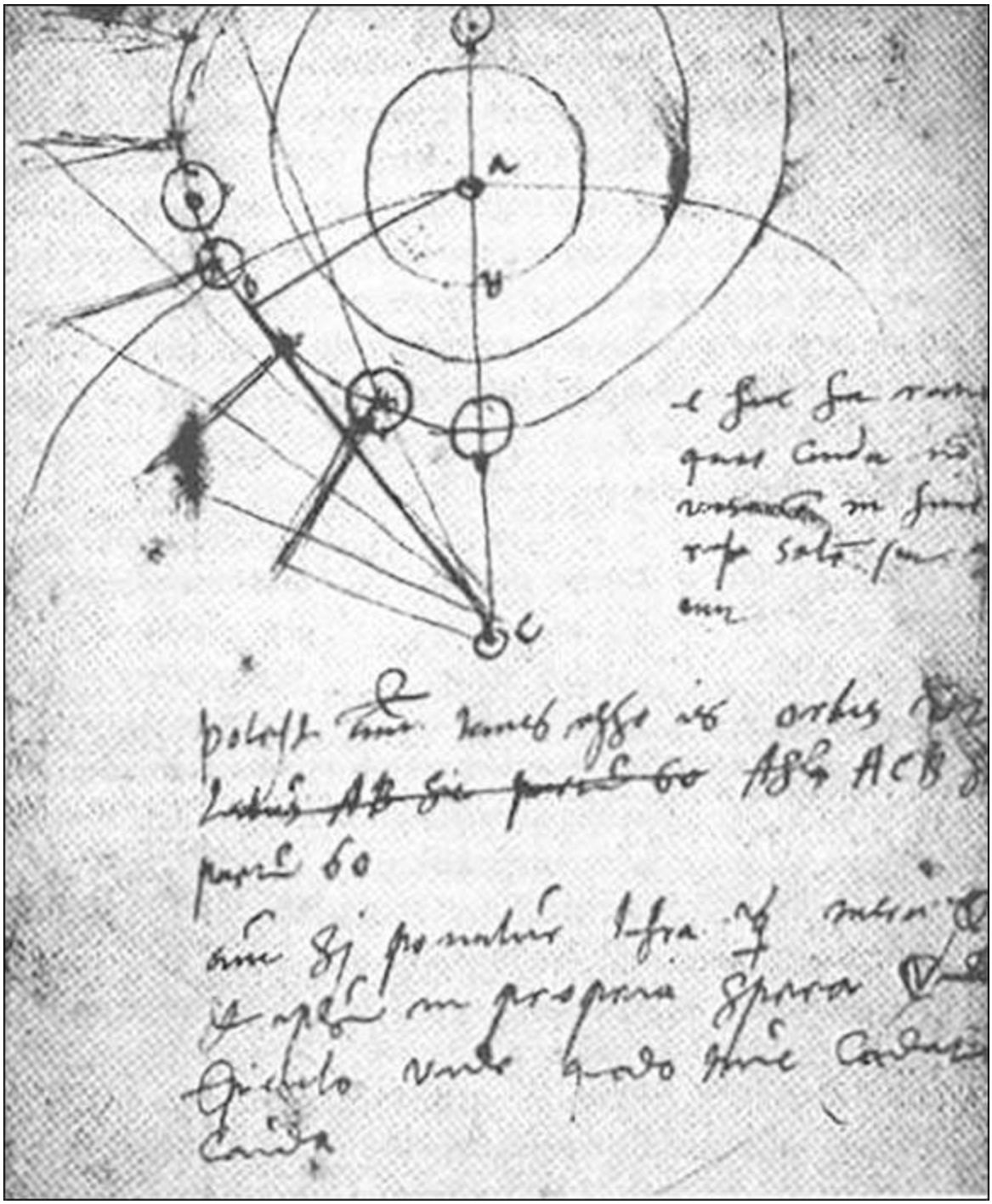
Aristotle’s theory of atmospheric vapors

As in many other areas of astronomy, Aristotle’s explanation of comets — well-intentioned but incorrect — became the accepted dogma in western science for two millennia.



REMEMBER Aristotle's theory of the Universe (refer to Chapter 2) was built on the idea of four elements — water, earth, fire, and air. He also believed that the visible world was divided into two parts, the Earth and the Heavens. Because comets appeared fleeting and imperfect (vaporous), he fitted them into the "Earth" category, which included other atmospheric phenomena — clouds, meteors, and the aurorae. Comets he considered to be similar to shooting stars but more long-lived.

Aristotle's theory survived until the 1500s when it was comprehensively dismantled by the renowned Danish astronomer Tycho Brahe following observations of the Great Comet of 1577. Brahe noted that it did not appear to move relative to the stars when viewed on similar dates from different parts of Europe, as would be expected if it was inside the Earth's atmosphere. Rather, he calculated it must be at a distance of at least 230 times the radius of the Earth, placing it between the orbits of Mercury and Venus. He also carefully noted that the tail always pointed away from the position of the Sun (see Figure 10-3).



Credit: Tycho Brahe/Wikimedia Commons/Public domain

FIGURE 10-3: Sketches of the appearance of the Great Comet of 1577 in the notebook of Tycho Brahe, depicting the tail as always pointing away from the Sun.

Halley's Comet

The most famous comet of all time is the eponymous *Halley's Comet*. In 1705, British scientist Edmund Halley applied Newton's laws of gravity to historical observational records of 23 comets. He soon found to his surprise that 3 of the 23 appeared to have almost the same orbit around the Sun, appearing in 1531, 1607, and 1682 — about 76 years apart.



REMEMBER This led Halley to boldly propose that these were in fact repeat appearances of the same comet, and he went on to predict that the comet would be seen again around 1758–1759, tracing the same orbit. Although he didn't live to see the return, his predictions were borne out, and the comet was appropriately named in his honor. This discovery revolutionized our understanding of comets and opened the door to significant work on understanding their orbits and origins — work that continues to this day.

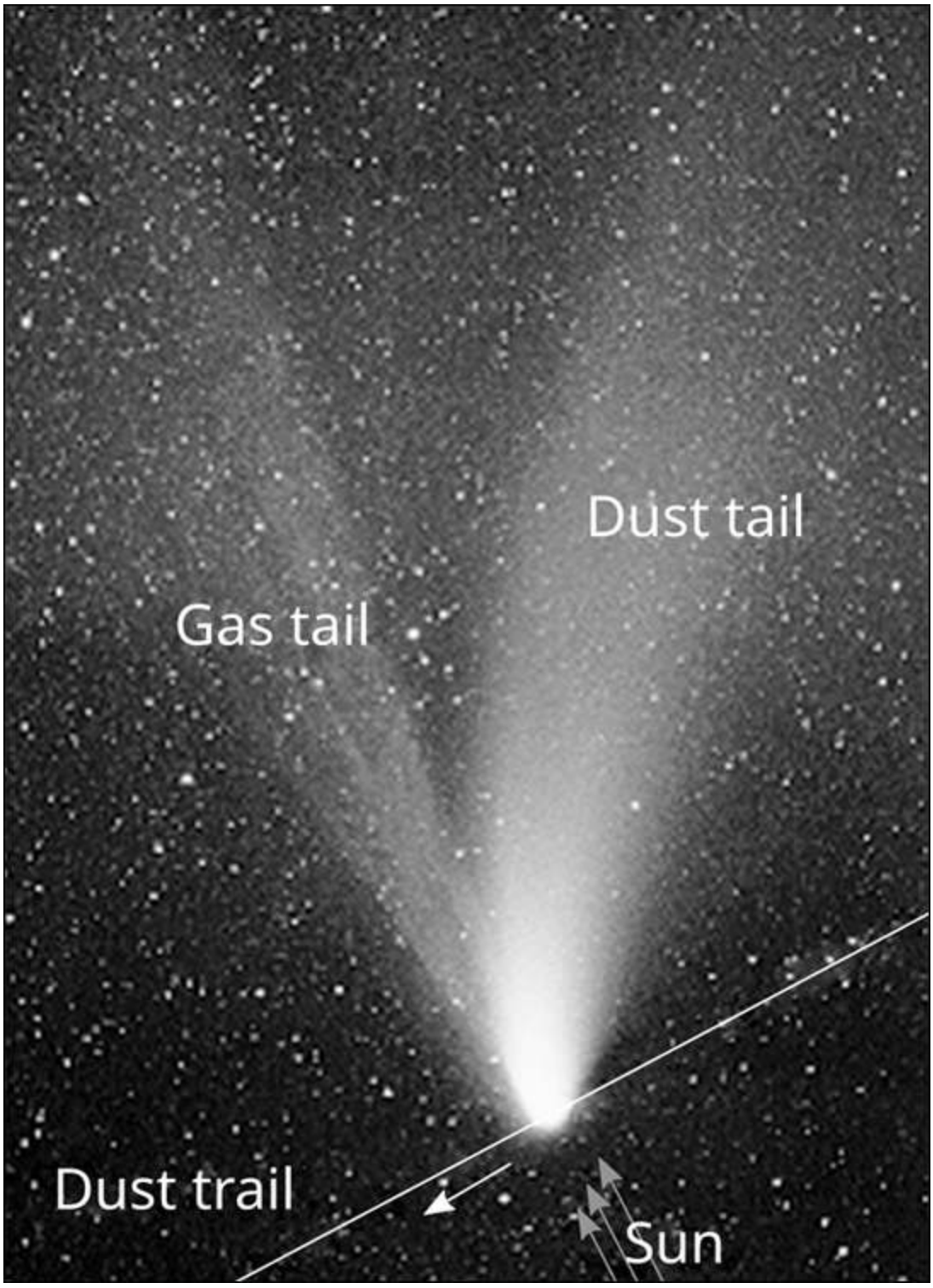
Comet Appearance and Composition



REMEMBER Each appearance of a comet is known in English as an *apparition* (there's more of that mystical language again). While far from the Sun, a comet is invisible to even the largest telescopes, but as it approaches the Sun, it brightens, developing a fuzzy head known as a *coma* and trailing an elongated *tail* like a fairytale bride walking to the altar.



TIP Comets are famous for their glorious tails (not to mention *tales*), which often make for fantastic backyard sky-gazing with a small telescope or even the naked eye. Many comets in fact develop two distinct tails, like the tail of a swift — see Figure 10-4.



Credit: NASA Ames Research Center/K. Jobse, P. Jenniskens/Wikimedia Commons/Public domain

FIGURE 10-4: Appearance of a bright comet.

Anatomy of a comet

Let's look at the parts of a comet in more detail:

- **Nucleus:** Like the nucleus of a cell or atom, the nucleus of a comet is a small, solid mass in the center of the much larger visual object. In fact, the nucleus *is* the comet — everything else is gas and dust ejected from the nucleus. Far from the Sun the comet is just the nucleus — a lumpy ball of ice and rock typically no larger than 10 miles (16 km) across.
- **Coma:** As the comet approaches the Sun, frozen gases, including water ice, begin to vaporize and the comet acquires an "atmosphere" — the coma. This appears as a bright, fuzzy ball enabling the comet to be seen, hiding the tiny nucleus at the center. A comet coma can be thousands to millions of miles across — even larger than the Sun.
- **Tail:** As material escapes the comet's gravity, it begins to trail behind in a tail that can extend for tens of millions of miles. Two tails can often be seen: a *gas tail*, often bluish in color, and a yellower *dust tail.*

Sandbanks or snowballs?

For many years, debate raged among astronomers about the exact nature of the cometary nucleus, since it was far too small to be visible. British astronomer Raymond Lyttleton championed the idea of a "flying sandbank" — something like a hail of ice-coated pebbles flying together in close formation.



REMEMBER American Fred Whipple proposed a different model in the mid-20th century: A comet nucleus, he said, was a distinct, albeit fragile single object — a "dirty snowball" of dust and rocks held together by a binding of ice. The debate was finally settled in 1986 when several spacecraft sent to visit Halley's Comet (the "Halley Armada" — see later) took close-up pictures of the nucleus showing a single object, and the "dirty snowball" model triumphed.

Blazing a trail: Meteor showers

You may have been awed to watch a meteor shower on a warm summer night, when streaks of light arc across the night sky, sometimes coming many per minute. These showers have names due to the constellation directions from which they appear to come, such as the bright *Perseids* shower in mid-August (see Figure 10-5), and the *Leonids* in mid-November.

For millennia, sky-watchers could only marvel at these phenomena, and ascribe to them mystical significances. Clarity finally began to emerge in the mid-1800s, when astronomers such as Denison Olmsted in the US speculated that these were caused by the Earth passing through a cloud of space debris.



REMEMBER A great breakthrough came in 1866 when Italian Giovanni Schiaparelli calculated that the material causing the Leonid shower was on the same orbit as the well-known Comet Tempel-Tuttle. This finally explained the origin of meteor showers — they are the debris from comet tails. In the years since, more than 100 meteor showers have been linked to the passages of various comets.



Credit: bt1976/Adobe Stock Photos

FIGURE 10-5: Photograph of the dramatic Perseid meteor shower.

Comet Origins and Populations

You now know that comets are icy, rocky snowballs, relatively modest in diameter. But where do they come from?

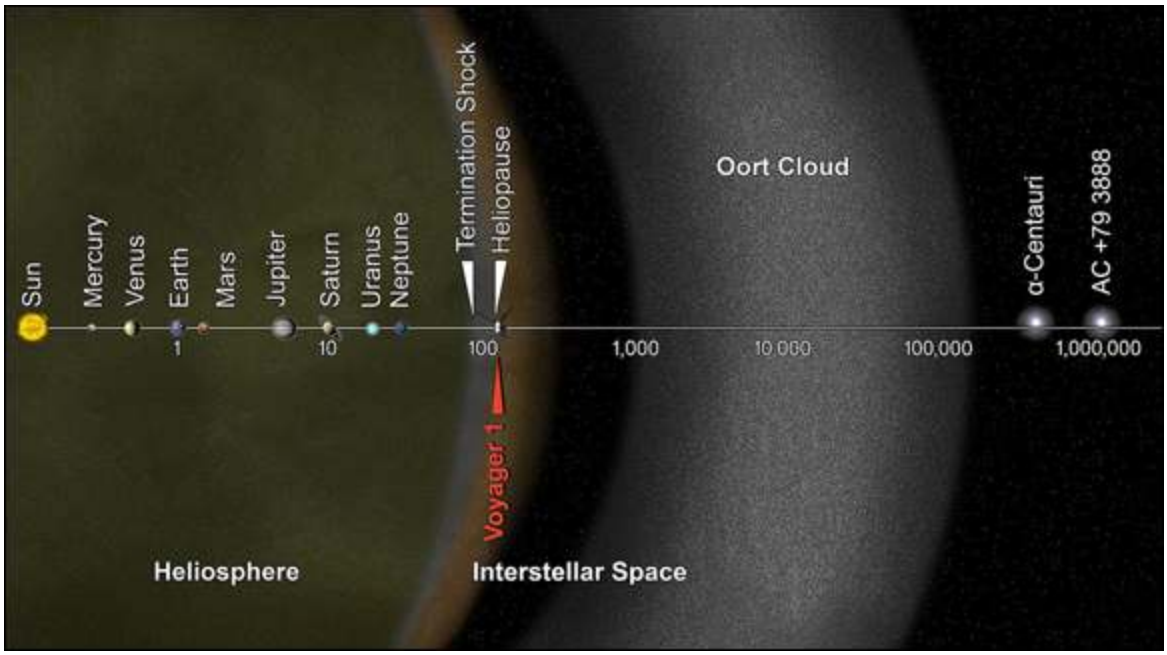
Visitors from the outer solar system

Short-period comets (SPCs) are those that originate from a distant part of the solar system known as the *Kuiper Belt*, making frequent returns to the inner solar system with orbits under 200 years. The Kuiper Belt (see Figure 10-6) is a disc of mostly small, icy objects lying beyond the orbit of Neptune at 40-200 AU (astronomical units, or Sun-Earth distances) from the Sun, remnants of the original disk of material that formed the solar system that did not get swept up into the making of planets and moons.



TIP At the present time, Pluto and its moon Charon are counted among the larger and closer KBOs — Kuiper belt objects. The most famous short-period comet is of course, Halley.

Long period comets (LPCs) come from a different and even further region of the solar system, a spherical cloud of icy objects known as the Oort Cloud (see Figure 10-6) ranging from 2,000 to 100,000 AU — at the very edges of the Sun's gravitational influence. Here the icy comets can wait for billions of years in slow orbits around the distant Sun, until the gravitational influence of a passing star dislodges them from their perch and they fall inwards toward the Sun. Hale-Bopp (refer to Figure 10-1) is an example of an LPC, with an orbital period currently around 2,400 years in length.



Credit: NASA/JPL-Caltech/Public domain

FIGURE 10-6: Diagram of the solar system showing location of the Oort cloud, the origin population for long period comets, extending from the edge of the solar system halfway to the next nearest star system.

Interstellar objects

In recent years, some objects have been found to be moving so fast that they are not bound to the Sun's gravity at all and are instead passing through our solar system from elsewhere in the galaxy. The first of these was discovered in 2017 and named *'Oumuamua* — a Hawaiian word that roughly translates to *scout*. It was discovered after it had already passed its closest point to the Earth and Sun, and was already departing the solar system, so we had a relatively short period (80 days) to observe it before it was lost to sight.



TECHNICAL STUFF During the brief time we could observe 'Oumuamua, astronomers struggled to decide if it was an interstellar comet, or something else entirely. On the one hand, it didn't develop the vaporous coma (fuzzy head) and tail that are the usual hallmarks of comet appearances. However, it was seen to move with sudden direction changes (so-called "non-gravitational accelerations" in astronomer-speak) that were perhaps due to jolts from jets of escaping but unseen gases, which is typical cometary behavior.



REMEMBER Lastly — although we couldn't see it closely enough to determine its shape, 'Oumuamua was seen to be brightening and dimming, like a flashing lighthouse. This led scientists to speculate that it was perhaps a tumbling, elongated object — like a lobbed baseball bat or length of pipe — anything from 300 to 3,000 ft (100-1,000 m) in length and perhaps a tenth of that in thickness (see Figure 10-7).



TIP Due to 'Oumuamua's unusual behavior, some scientists went too far as to suggest that it was not a natural object at all, but some kind of visiting craft of alien manufacture (for more see Chapter 18).

However, the vast majority of cometary experts remain unconvinced, agreeing with the late Carl Sagan that: “Extraordinary claims require extraordinary evidence” — and evidence for such an incredible conclusion remains lacking.



Credit: ESO/M. Kornmesser/Wikimedia Commons/CC BY-SA 4.0

FIGURE 10-7: ‘Oumuamua.



REMEMBER Since ‘Oumuamua, two more “interstellar objects” have been discovered. Comet Borisov was seen from Earth during 2019–2020 and, unlike ‘Oumuamua, appeared with a bright coma and elongated tail as a typical comet. Borisov had a sudden brightening in early 2020 when it may have lost a sizeable chunk of itself passing the Sun. More recently Comet Atlas passed through the solar system in 2025–2026, and observations with the James Webb Space Telescope have shown that it may be 8–10 billion years old — much older than our own solar system and Sun at 4.6 billion years.

Comets and Life

The early history of the Earth was a rough period. After the Earth formed, the solar system remained populated with a variety of smaller objects, ranging from the size of moons down to mere boulders. These were perturbed by the gravity of the larger planets, veering across their orbits and occasionally colliding in catastrophic impacts. The Earth undoubtedly suffered many such events, with its surface cooling and solidifying for centuries, only to be re-melted again after another mighty blow — such as the Moon-forming impact by Theia (refer to Chapter 11).

The constant hammering would have made it impossible for the early Earth to sustain surface water for long. Any primordial oceans would have been frequently boiled off into space after yet another mighty impact — at least until things calmed down after the first half-billion or so years. This series of catastrophes would have posed a huge obstacle for early life forms arising in the ocean — life may have needed to begin afresh more than once.

Watering the Earth from space



REMEMBER The inevitable boil-off of Earth's early oceans gives rise to the question: Where do the Earth's *present-day* oceans come from? Was the water later outgassed from rocks within the crust and mantle (scientists say *endogenous* water), or was it replenished externally (*exogenously*)? The idea that smaller impacts later in the Earth's history (post-Theia) could have re-watered a dry, thirsty planet is known as the *late veneer hypothesis*.



TECHNICAL STUFF Key evidence for the late veneer idea comes from measurements of isotopes of noble gases, especially xenon. Xenon comes in a range of masses (like a car model with different sub-types), and the distinctive pattern of relative amounts of different isotopes of xenon can be used as a "fingerprint" to determine the origin of different materials. When the xenon isotopes of the Earth's atmosphere were compared to those of the deep interior, the fingerprint was different — indicating the atmosphere was sourced from different materials to the rest of the Earth. Isotopes of hydrogen and even abundances of gold and silver all seem to tell the same story.

The question then arises: If the atmosphere and oceans are a *late veneer*, what was the source, asteroids or comets? Asteroids mostly originate from the region between Mars and Jupiter — the asteroid belt — whereas comets, as we saw earlier in the chapter, come from further out. Each has a unique signature of isotopes of hydrogen. When scientists ran the numbers, the results were clear: It was carbonaceous asteroids doing most of the heavy lifting with the water delivery, and comets likely contributed only 1/1,000 of the "new water."

Seeding the Earth: Panspermia



TIP So, comets didn't deliver much water. But what if they delivered other important chemical goodies to the nascent Earth, helping life to get started? This is one example of a wider concept known as *panspermia*, that the ingredients of life can become spread across space, from one planet to another (*lithopanspermia*) or originated in space and then seeded the planets.

This latter concept has several flavors, ranging from the more modest notion that complex chemicals found widely in space (see Chapter 15) could provide ingredients for life to develop on Earth, to a stronger

hypothesis that life itself originated in space, and was seeded from there to the Earth by comet dust and meteorites (see Figure 10-8).



Credit: Generated with AI using OpenAI

FIGURE 10-8: Illustration of panspermia.



Although the idea of "life from space" can be traced back as far as the Greek philosopher Anaxagoras (refer to Chapter 2), the modern form of panspermia comes from William Thomson, Lord Kelvin, who suggested in an 1871 lecture that life could be seeded from space on meteorites, in analogy to pollen borne on the wind. The Swedish scientist Svante Arrhenius subsequently elaborated on Kelvin's notion in 1908 by suggesting a transport mechanism — the newly discovered solar wind, and also coined the term *panspermia*.

In its strongest form — where life came directly from space — panspermia solved several problems that appeared thorny at the time:

- **Inhospitable early Earth:** Giant impacts soon after the Earth's formation would have sterilized the surface repeatedly, and the resulting surface after a billion years of bombardment would have been devoid of chemicals needed to originate life. On the other hand, comets could have been ideal places for complex molecules to develop.
- **Difficulties with abiogenesis:** When panspermia was in favor in the early 1900s, it was hard to conceive how life could develop from non-living materials. Therefore, its proponents suggested instead that life had always existed — in line with the *steady-state theory* of the universe, which holds that the universe has no beginning or end in time.

However, scientific developments in the 20th century soon reduced the need to invoke panspermia as an origin-of-life hypothesis:

- Evidence for the **Big Bang** from the 1920s meant that life could not always have existed — abiogenesis must have occurred somewhere, at some time. So, panspermia merely pushed the problem to another time and to a place other than Earth.
- **The Miller-Urey experiment** in 1953 (refer to Chapter 5) showed that complex chemicals could form relatively easily from simpler molecules in a reducing atmosphere similar to the Archean Earth. This would in turn provide ingredients for abiogenesis on Earth without the need for chemicals from space.



TIP Over time, the idea of panspermia has evolved but not quite vanished. In its stronger form, akin to the proposition of "alien life," it remains completely unproven (see Chapter 17). However, recent missions to sample comets have also painted a much more

nuanced picture, showing that highly complex molecules do exist in comets — which you learn about in the next section.

Comet Missions

For thousands of years, comets had remained enigmatic objects: unpredictable visitors, spectacular light shows, harbingers of doom, and even bringers of life on Earth. Not surprisingly, therefore, scientists were eager to reach a comet with a space mission as soon as the space age took off. However, comets — even "periodic" ones — often arrive at erratic intervals, making mission planning difficult.



TIP In this final section on comets, you learn how comets were eventually reached and sampled, and some of the surprising information they revealed.

Visiting a comet: The "Halley Armada"

Not surprisingly given its fame, Comet Halley was the first to be targeted for spacecraft visits. The timing was also good, since Halley was expected to reach *perihelion* (closest point to the Sun) in 1986 as the technology for deep space missions was becoming mature.

The so-called "Halley Armada" of five spacecraft from different nations was comprised of:

- ***Vega 1* and *2* (USSR/France):** Two sophisticated, multi-part spacecraft from the Soviet Union. The twin *Vega 1* and *2* missions first flew by Venus, dropping off a balloon and a lander each, before the "mothership" of each mission continued on to encounter Halley in early March 1986. *Vega 1* and *2* took the first-ever images of a comet nucleus.
- ***Suisei* and *Sakigake* (ISAS):** *Sakigake* was Japan's first deep space probe and observed Halley from a distant standpoint of 7 million km,

helping to guide its sister craft *Suisei* to a much closer encounter 150,000 km upwind of the comet.

- ***Giotto* (ESA):** Aided by measurements and photographs from the other four spacecraft, the European *Giotto* spacecraft was able to make an extremely close flyby of the nucleus at a distance of 596 km, taking the first close-up images of the nucleus and showing its shape (see Figure 10-9). These images finally confirmed that the nucleus was indeed a compact object — Whipple's "dirty snowball," and not a "flying sandbank."



Credit: (a) NASA/Public domain (b) ESA/MPS/https://www.esa.int/ESA_Multimedia/Images/2012/11/Comet_Halley_close_up/CC BY-SA 3.0 IGO/last accessed Oct. 11, 2026

FIGURE 10-9: (a) The European *Giotto* spacecraft; (b) close-up image of Comet Halley's nucleus taken by *Giotto*.

Sampling a comet with Stardust

REMEMBER Launched in 1999, *Stardust* (see Figure 10-10a) was an ambitious, low-cost mission to collect samples from a comet and return them to Earth. Rather than attempting to encounter the erratic and unstable nucleus directly (a feat accomplished later for several asteroids — see Chapter 11), the *Stardust* mission was designed to fly through the coma and collect escaping dust particles.



TECHNICAL STUFF Collecting dust grains from a speeding comet was no easy feat. Due to differing velocities of the comet and spacecraft, dust grains would slam into the collecting plate at 1000 mph (447 m/s). If any type of hard material was used, the precious samples would be instantly vaporized. To overcome this difficulty, NASA used *aerogel*, an incredible sponge-like material that is 99.8 percent empty space. Dust particles impacting the aerogel would therefore be slowed down over a distance, allowing them to be safely captured.



REMEMBER *Stardust* encountered its target, Comet Wild-2, on January 2, 2004, at a distance of 147 miles (237 km), taking close-up images of the nucleus (see Figure 10-10b) and collecting dust samples on an exposed plate of aerogel about the size of a tennis racket (see Figure 10-10c). After safe return to Earth, close-up imaging of the aerogel showed ten large dust grains and many thousands of smaller particles embedded in the aerogel (see Figure 10-10d) — the first-ever pristine samples of a comet.



TECHNICAL STUFF Analysis of the grains is still ongoing today, and existing results show intriguing organic molecules, carbon chains, and silicate grains. These have provided valuable insights into the earliest stages of formation of the solar system, when the proto-solar cloud was collapsing from the wider galactic material. However, no signs of life were found that could provide evidence for the strong panspermia hypothesis.

Landing on a comet: Rosetta

The most ambitious comet mission to date was *Rosetta*, comprised of a large "mothership" (*Rosetta*) and a smaller lander dubbed *Philae*. The mission of *Rosetta*: to land on a comet.



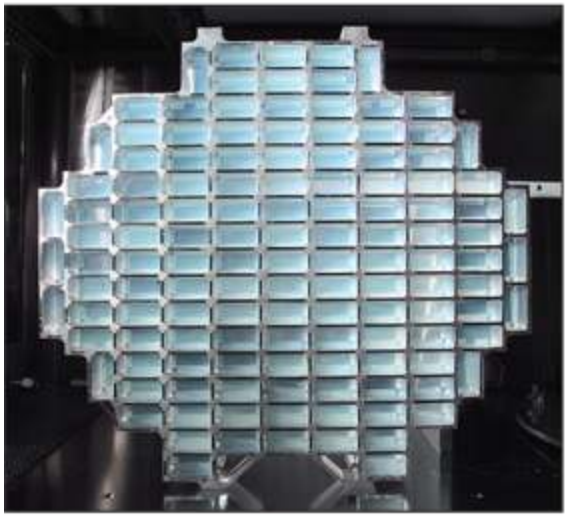
Rosetta's target was Comet 67P/*Churyumov–Gerasimenko,* named after the two Soviet scientists who discovered it in 1969. The complex mission was launched in March 2004 but didn't rendezvous with 67P until August 2014, when it became the first spacecraft to orbit a comet.



(a)



(b)



(c)



(d)

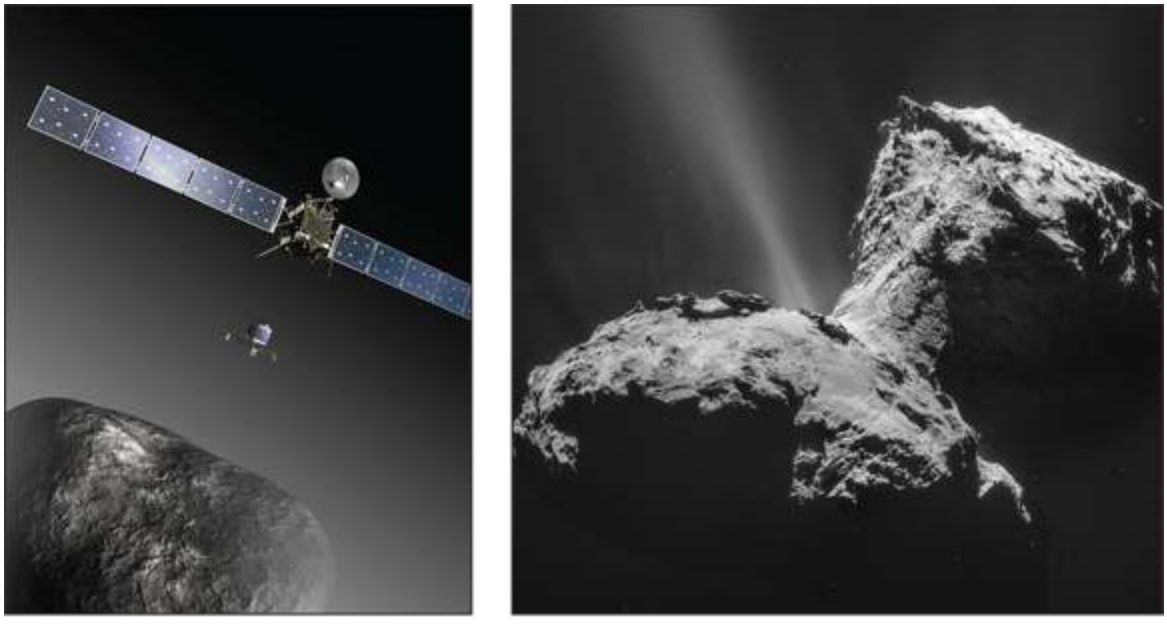
Credit: (a) NASA/JPL-Caltech/Public domain (b) NASA/Wikimedia Commons/Public domain (c) NASA/JPL-Caltech/Public domain (d) NASA/JPL/Public domain

FIGURE 10-10: The *Stardust* mission: (a) artistic image of the spacecraft in flight; (b) image of the nucleus of Wild-2 from *Stardust*; (c) the aerogel collector palette before launch; (d) close-up of aerogel section after recovery, showing embedded dust grains.



REMEMBER On November 12, the *Philae* lander attempted to land and attach to the comet surface using harpoons (see Figure 10-11a), but these misfired and *Philae* bounced and tumbled across the surface in a dramatic fashion, returning only a portion of the intended data. After several years of orbiting the comet and acquiring a rich dataset and images (see Figure 10-11b), the *Rosetta* spacecraft itself landed bumpily on the comet surface in 2016, where it now resides.

The data returned from *Rosetta*'s many instruments revealed the make-up of a comet in unprecedented detail, including the detection of many organic molecules, and a surprising amount of oxygen surrounding the comet. *Rosetta* data also showed that its water has similar isotopic ratios to those on Earth, providing greater support for the contribution of comets to the "late veneer" that reconstituted the Earth's oceans.



(a) (b)

Credit: (a) European Space Agency/Wikimedia Commons/CC BY-SA 3.0 IGO (b) ESA/Rosetta/NAVCAM – CC BY-SA IGO 3.0

FIGURE 10-11: The *Rosetta* mission: (a) artistic image of the *Rosetta* spacecraft releasing the *Philae* probe; (b) a close-up image of comet 67P.

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Chapter 11

Impacts and Origins: Meteorites

IN THIS CHAPTER

- **Uncovering the solar system's chaotic past**
- **Finding out how rocks fall from the sky**
- **Learning how meteorites can tell us about life's chemicals**

Back in Chapter 1, I said that astrobiology is focused on answering several big questions: How did life arise on Earth? What are the limits of life? Is there life anywhere else other than Earth? These questions are tied together, and we want to gather as many clues as possible to answer them by examining any materials we can access from across the solar system.



TIP Accessing materials from places other than Earth is difficult, and prior to the 1960s, we had no way to collect samples directly. However, nature has been kind enough to provide *some* samples for us, in the form of meteorites which are mostly pieces of asteroids (with some exciting exceptions).

In this chapter, I take you on a trip through time and space to see how the solar system formed and evolved, and buckle up, it's going to be a wild ride. For although our planetary system began as a placid cloud of gas and dust, things soon began to heat up — literally. You see how planets grew from building blocks known as *planetesimals,* some of which escaped the planet-forming process to become asteroids, relics of our past.



REMEMBER You then learn how, over time, collisions occurred between asteroids and planets, showering space debris across the solar system, some of which even ended up in our own backyards. These "rocks from space" — meteorites — and how they provide clues about the origins of life are the subject of this chapter.

Order from Chaos: The Early Solar System

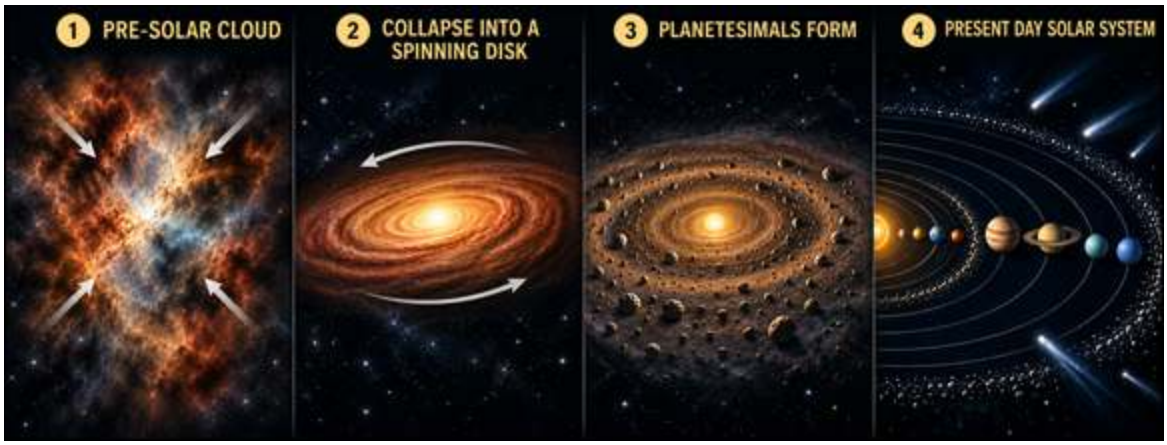
To understand what meteorites can tell us about astrobiology, I first need to give a quick primer on where they come from, which takes us back to the earliest stages of solar system formation. In the short version (which gets us quickly to the astrobiology part), the main stages are as follows (see Figure 11-1):

- **The protosolar cloud:** A slowly rotating cloud of gas and dust, including material from earlier generations of stars as well as the Big Bang itself, gradually began to collapse under its own gravity. It may have been helped along by the tug of a passing star, or a shock wave from an exploding star (supernova). The center of the cloud was the densest part and began the baby Sun, whereas the remainder became the …
- **The protoplanetary disk:** Like a deflated football, the cloud collapsed into a spinning disk with the Sun at the center.
- **Planetesimal formation:** Irregularities in the disk became clumps, and the clumps in turn collapsed under gravity into agglomerations of rock and ice, ranging in size from small boulders to mountain-sized masses. These *planetesimals* tugged and collided with each other, resulting in larger planetesimals growing ever larger by absorbing mass from smaller neighbors. Soon, the largest of these became the cores of planets.

- **Planet formation:** As the Sun grew hotter, it began to send out a stream of particles — the solar wind. Planetary cores closer to the Sun lost much of their lighter, more volatile elements, becoming the inner planets: Mercury, Venus, Earth, and Mars. Meanwhile, in the colder, less windy outer solar system, planets were able to hold onto light elements such as hydrogen and helium, and gases including methane and ammonia. These became the giant, outer planets: Jupiter, Saturn, Uranus, and Neptune.
- **Migrations and impacts:** As the planets grew in size, scooping up the remaining disk material in a process known as *accretion*, they began to interact with each other more strongly due to gravity. Computer models can't replicate the current positions and sizes of the planets if they formed in place, so scientists are now convinced that their orbits have changed over time, and at least several smaller planets were lost through collisions (see next section). A final burst of large impacts known as the Late Heavy Bombardment (LHB) may have occurred around 4.2 to 3.9 billion years ago in a final planetary reshuffle which scattered most of the remaining planetesimals.



TIP For a fuller description on solar system formation, check out the companion books in the *For Dummies* series, *Astronomy For Dummies* by Stephen P. Maran and Richard Tresch Fienberg (Wiley) and *Astrophysics For Dummies* by Cynthia Phillips and Shana Priwer (Wiley).



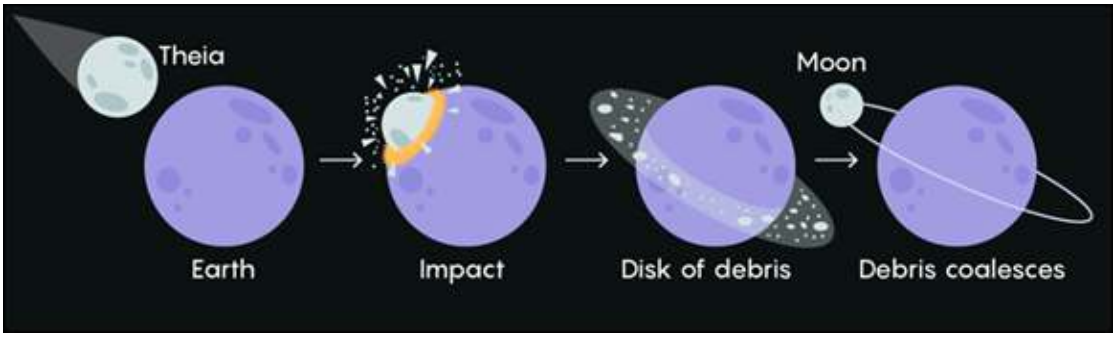
Credit: Generated with AI using OpenAI

FIGURE 11-1: Stages in solar-system formation.

Packing a punch: The largest impacts

By the time things finally settled down, all the surviving planets in the solar system had been impacted — literally — by the tumults of the earliest years. We can see the traces today of early giant impacts, whether they are in impact scars, changed rotations, or unusual systems of Moons. Here's just a few notable examples:

- **Origin of the Earth's Moon:** For years, scientists debated whether the Moon formed alongside the Earth as a "sister," or perhaps a piece spun off from the early crust as a "daughter." However, opinion now favors a third hypothesis: that a Mars-sized impactor called "Theia" impacted the early Earth in a cataclysmic collision (see Figure 11-2), and that debris left orbiting the Earth re-condensed to form the Moon. Evidence for this includes the close similarity between Earth's rocks to those brought back from the Moon.



Credit: Citronade/Wikimedia Commons/CC BY-SA 4.0

FIGURE 11-2: Diagram of the Moon-forming impact scenario.

- **Lunar maria:** The large, dark regions of the lunar nearside (maria) are thought to all be formed from giant impact basins (very large craters) mostly formed during the LHB period, that were later filled in with lava flows. Similar huge impact basins are found across the solar system, from Mercury to Pluto and beyond.
- **Hemispheric difference on Mars:** Mars' northern hemisphere is significantly lower in elevation than the southern hemisphere and may even have been filled in the past with water in a "Boreal Ocean." However, the elevation difference is difficult to explain by any means other than a giant impact.
- **Planetary tilts:** The tilts of Venus and Uranus that were mentioned earlier are also likely due to giant impacts.



REMEMBER You get the picture here: There were a lot of impacts in the early solar system, and they determined many of observed planetary characteristics and appearances that we see today. Remember also that smaller impacts that didn't create new moons or continent-sized topography changes still had important consequences. An example is the Chicxulub impact that wiped out the dinosaurs discussed in Chapter 5 — although note that this occurred relatively recently compared to the age of the solar system.



TIP Now we've set the stage by looking at impacts, let's see how some of the pieces arrived on Earth.

Meteorite Falls and Finds

For centuries, eyewitnesses have reported fireballs in the sky, sometimes followed by showers of stones that fell on the ground, even resulting in

small craters with glowing hot stones or pieces of metal in the center. Often, these events were investigated by credible officials, who interviewed local people, collected samples, and documented the sightings. And yet, the scientific establishment disbelieved these reports. After all, how could stones fall from the sky? What would have held them up there?



REMEMBER Opinions finally began to change following a huge fireball and fall of stones at L'Aigle, France in 1803. The eminent scientist Jean-Baptiste Biot was duly sent to document the event and collect samples. The sheer scale of the event, the number of eyewitness reports, and the volume of samples (over 3,000 collected) put the matter beyond doubt: Rocks had fallen out of the sky. Thus was born the field of *meteoritics* — the study of meteorites.



TIP Today, meteorites are known as either *falls* or *finds.* If a fireball explosion was witnessed prior to collection on the ground, the meteorite is a *fall.* However, some meteorites are found on the ground, either by lucky accident, or by organized search campaign. These are known as *finds*.

Falling stars

Ever since L'Aigle, scientists have searched avidly for meteorites on the ground following reports of fireball explosions, due to the scientific information they can reveal.



REMEMBER Meteorite *falls* range from small events witnessed by just a few people to enormous, mid-air explosions that can be witnessed by thousands. These detonations are caused when the original object

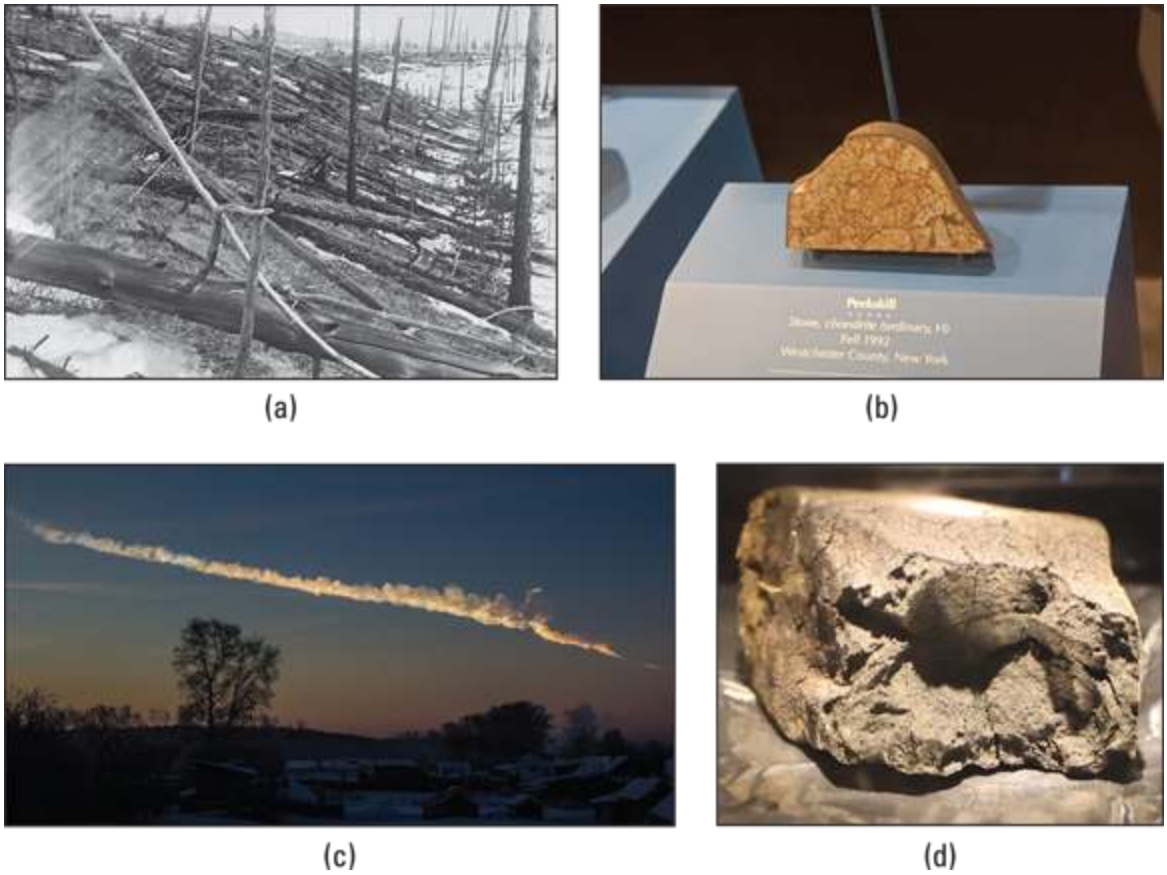
from space (called a *bolide*) becomes superheated during entry to the atmosphere and explodes.

Now take a look at some of the most famous witnessed meteorite fireballs and falls (see Figure 11-3):

- **Tunguska (1908):** On June 30th, 1908, in a remote part of Russian Siberia, the early morning calm was shattered by an enormous mid-air explosion, later calculated to be equivalent to 3–50 megatons of high explosive (TNT). The blast felled trees over an area of 2,150 km^2 (830 sq mi), and possibly killed several onlookers. The original object was estimated to be 50–60 m wide (160–200 ft) and entered the atmosphere at a speed of 98,000 km/h, exploding several miles above the surface. No meteorite pieces were ever recovered, although analysis of soil at the impact site showed high levels of the metal iridium, which is scarce in the Earth's crustal rocks, but more abundant in meteorites. The Tunguska event is thought to be the largest meteorite explosion in recorded human history.
- **Peekskill (1992):** On the evening of Friday, October 9, 1992, residents in the US mid-Atlantic region were amazed to see a greenish fireball explosion light up at sky. Because many people were out watching high school football games, the explosion was caught on at least 16 separate cameras. After breaking up over the state of Kentucky, the largest piece of meteorite finally came to Earth in Peekskill, New York, where it hit a parked car, smashing into the trunk. The 12.6 kg meteorite (27 lbs) was recovered by the car's teenage owner and sold, more than covering the cost of replacing the car.
- **Chelyabinsk (2013):** At 9:20 AM local time on February 15, 2013, a large meteorite entered the Earth's atmosphere and exploded in a fireball over the town of Chelyabinsk in the Ural mountains of Russia. The explosion, seen and felt by thousands of people (many of whom also sustained injuries), was visible from as far as 100 km (62 miles) away and was the largest meteorite event in over a century. Many small pieces of the original stony object were recovered (helped by a snowy terrain) and eventually a very large

(654 kg, 1,442 lb) fragment was recovered from the bottom of an ice-covered lake.

- **Winchcombe (2021):** A recent event in England occurred in the evening of February 28, 2021, when a meteor trail was filmed by cameras of the UK Fireball Alliance, as well as by doorbell cameras. A search of the local area around the village of Winchcombe collected fragments weighing 602 g (21 oz).



Credit: (a) Leonid Kulik/Wikimedia Commons/Public domain (b) Wknight94/Wikimedia Commons/CC BY-SA 3.0 (c) Alex Alishevskikh/Wikimedia Commons/CC BY-SA 2.0 (d) Geni/Wikimedia Commons/CC BY-SA 4.0

FIGURE 11-3: Witnessed meteorite falls: (a) flattened trees at Tunguska, 1908. (b) Peekskill meteorite, 1992. (c) Fireball streak over Chelyabinsk, 2013. (d) Piece of the Winchcombe meteorite, 2021.

Although the largest events do not always produce the most interesting meteorites, their explosions are reminders that our own history has been

shaped by giant meteorite strikes in the past and may be again in the future.

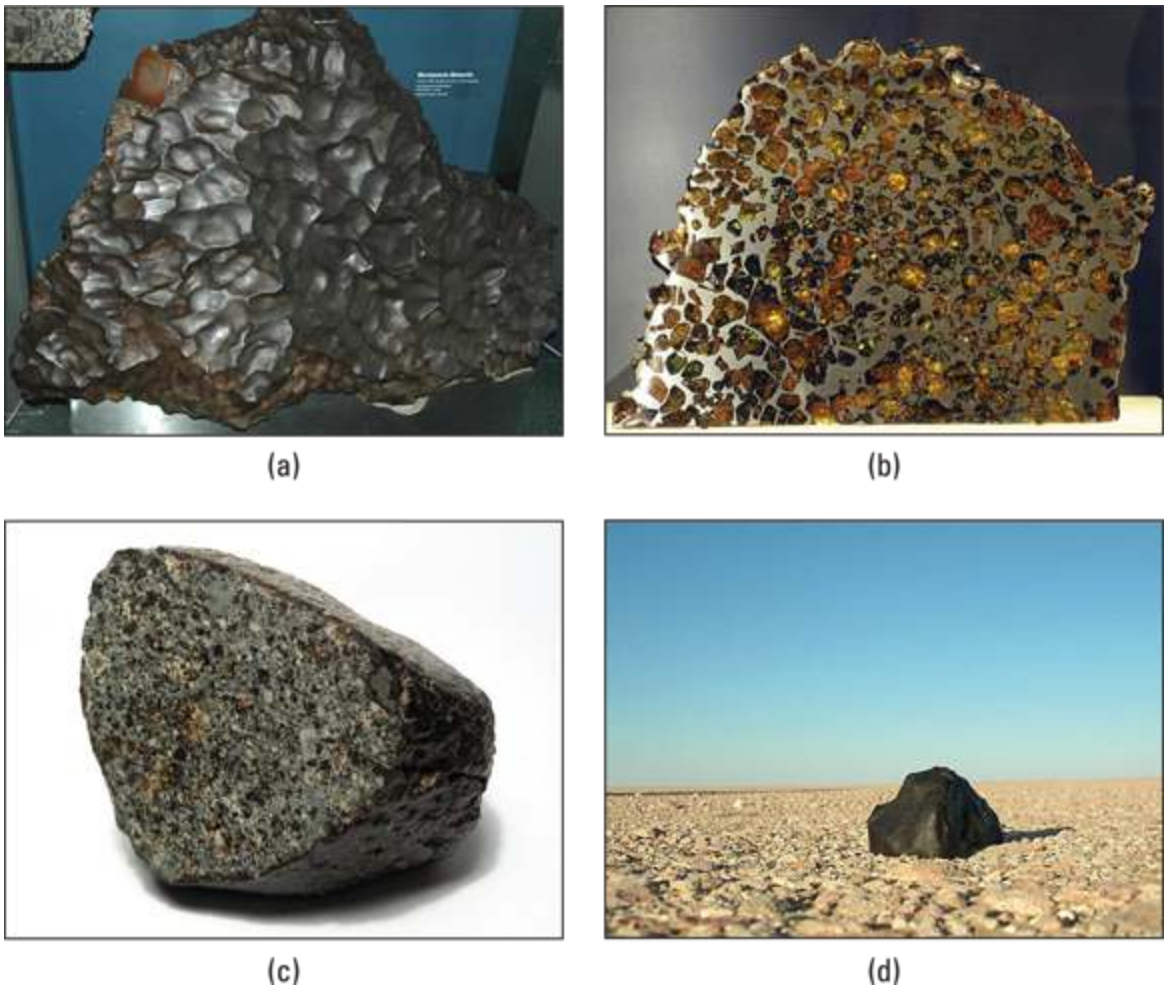


TIP In 1999, the *Torino scale* was adopted by scientists to rate the danger of asteroids spotted in space that might potentially impact the Earth. The scale ranges from 1 to 10, and is weighted by both the size of the potentially hazardous object (PHO) and the likelihood of collision. A worldwide network of monitoring organizations keeps a close watch for any such dangers.

Searching for space rocks



TIP Meteorites are sometimes found by chance, especially in desert areas. Meteorite finds tend to favor metallic meteorites, which are easier to distinguish from terrestrial rocks, and are resistant to erosion. However, fallen meteoritic stones are also recovered, often recognizable by their blackened exterior *fusion crust.* Some examples are shown in Figure 11-4.



Credit: (a) James St. John/Flickr/CC BY 2.0 (b) Captmondo/Wikimedia Commons/CC BY-SA 3.0 (c) H. Raab/Wikimedia Commons/CC BY-SA 3.0 (d) Meteorite Recon/Wikimedia Commons/CC BY-SA 3.0

FIGURE 11-4: (a) The 2520-lb Murnpeowie iron meteorite found in the Australian Outback in 1909. (b) Polished section of the beautiful Esquel pallasite meteorite, found in 1951 in Argentina. (c) A small stony meteorite found near Tindouf, Algeria, showing chondrules (grains). (d) A desert meteorite find at Rub' al Khali, Saudi Arabia, weighing just under 1 lb.

REMEMBER Beginning in the mid-twentieth century, organized searches began to be mounted to systematically search for meteorites, especially in areas of desert, prairie, or snowfields — where they are more easily distinguished. A few important searches include:

- **H. H. Nininger:** In the 1930s and 1940s, meteorite enthusiast Harvey Nininger traveled across the plains states of the US, educating local residents how to spot meteorites on the largely bland, well-tilled farmlands. This campaign resulted in the collection of more than 200 new meteorites. Nininger was also vocal in advocating for the extra-terrestrial origin of Meteor Crater (then called Barringer Crater) in Arizona, a small, recent and therefore recognizable crater dating from 50,000 years ago.
- **Australia:** Beginning in 1971, multiple campaigns across the Australian desert in the Nullarbor Plain region have resulted in more than 500 meteorites. Dark meteorites are readily recognized against the lighter limestone rock of the region.
- **Antarctica:** From 1976, the ANSMET program (Antarctic Search for Meteorites) has been an annual campaign mounted by a consortium of US universities funded by the US National Science Foundation (NSF). The search is undertaken by small teams of scientists who roam the ice sheet for weeks, focusing on regions where implanted meteorites are transported by ice movements and then exposed by wind — often close to the Transantarctic Mountains. The search has returned a trove of more than 20,000 samples to date, including some especially important ones (see later).
- **Arabia and north Africa:** Highly publicized finds of meteorites across the Arabian and Saharan region in the 1980s and 1990s spawned a "gold rush" of many private searches, with the meteorites often sold for large sums to private collectors, although some also purchased by museums.



TIP These searches have been important in vastly increasing the numbers of meteorites available for study, compared to those witnessed to fall directly. This has led to a huge expansion in our understanding of the types and varieties of meteorites, which is the topic of the next section.

Meteorite Types and Origins



TIP Recovered meteorites are classified depending on their material:

- **Stony:** Rocks known as stony meteorites comprise more than 90 percent of recovered *falls*. They are further divided into *chondrites*, which have prominent grains (chondrules) and *achondrites,* which lack the large grains. Chondrites are usually less processed by heat than the achondrites, since heat tends to melt grains.
- **Irons:** "Irons" are metallic meteorites, although the name is not quite accurate since they contain a mixture of metals blended together. Iron meteorites account for around half of all meteorite *finds*, and an estimated 80–90 percent of all recovered meteorite mass.
- **Stony-Irons:** The rarest type of meteorites (0.5 percent), these are made of green or amber olivine rock enclosed in iron and metal. These are often quite beautiful when cut and polished (see Figure 11-4b).

This is a high-level overview of meteorite types, and there are as many sub-types as there are rocks. Some meteorites have very similar compositions to Earth rocks, whereas others are wildly different.

Carbon wonderland



REMEMBER Among the most scientifically important meteorites are rare carbon-rich types.



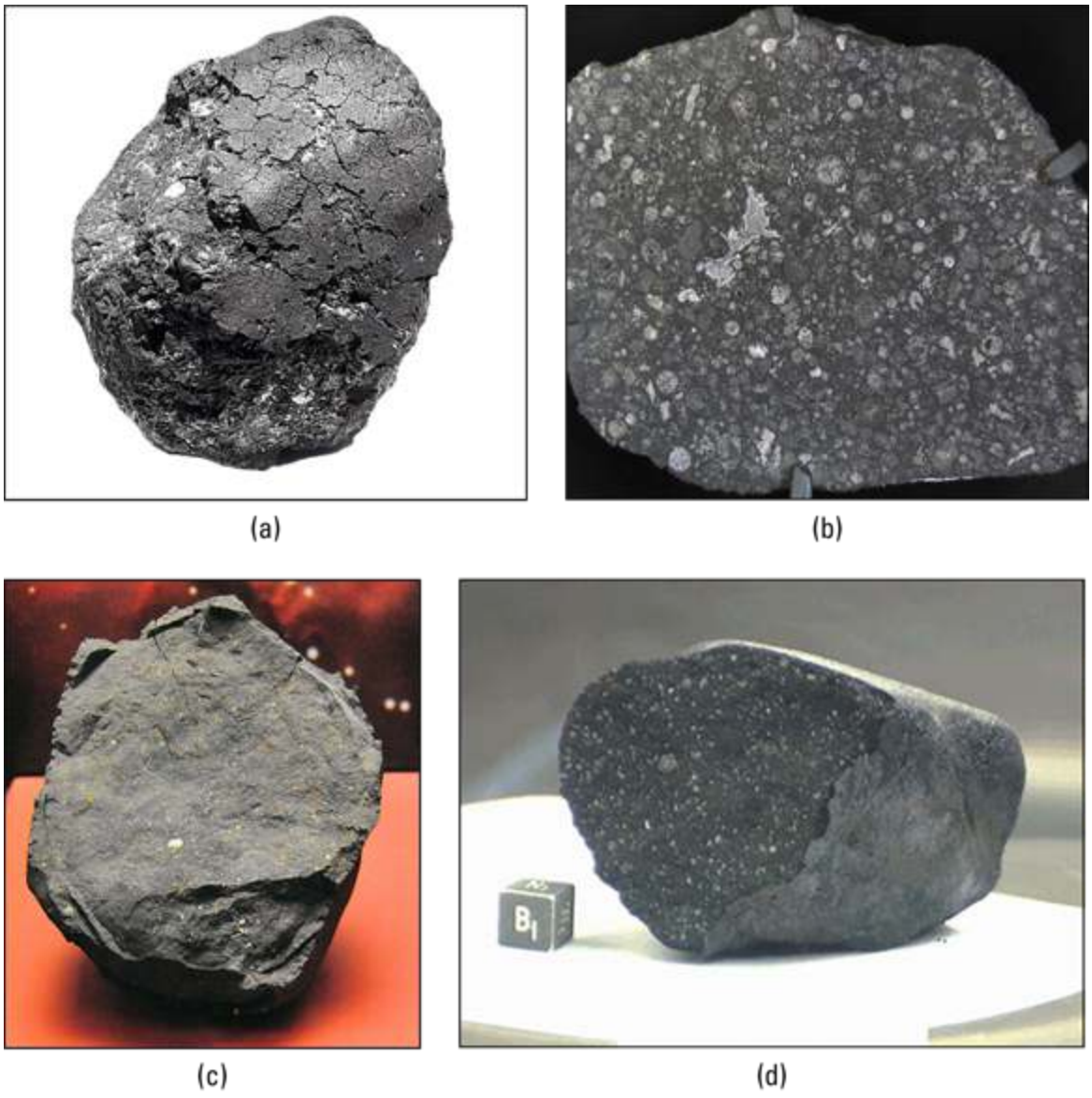
TECHNICAL STUFF Although most of the carbon material is a plain, sooty substance known as "insoluble organic matter" (IOM), a fraction of the

material is much more interesting. This soluble part ("complex organic matter" — COM) has been found to contain many of the chemicals used by life, including many of the common amino acids that comprise proteins (refer to Chapter 7).

Some of the key carbonaceous meteorites that enabled these discoveries include (see Figure 11-5):

- **Orgueil (1864):** Following the L'Aigle event, another fall in France near the commune of Orgueil ignited another debate — this time about meteorites and life. The meteorite was rich in carbon, appearing to its early investigators to be similar to peat from the Somme Valley, leading to speculation that it was evidence of life in space. The meteorite also contained diamond grains that are older than the solar system.
- **Allende (1969):** In February 1969, a very large carbonaceous meteorite broke up over the Mexican state of Chihuahua, raining down dark rocks near the village of Allende. Over subsequent decades, more than two tons of sample from Allende have been collected, making it the largest carbonaceous meteorite ever found on Earth — and one of the best studied. Coming during the Apollo Program to place astronauts on the moon, Allende arrived just as interest in space was peaking, drawing many new geologists into the field of meteoritics.
- **Murchison (1969):** The year 1969 was a bumper year for meteorites, with a second important fall being recorded near the town of Murchison in Australia. Over 100 kg (220 lb) of carbonaceous material was recovered. Murchison is renowned for yielding the oldest materials ever analyzed: pre-solar grains that formed around 7 billion years ago, or 2.5 billion years older than the solar system itself. Analysis also showed at least 15 amino acids that are important for life (refer to Chapter 6).
- **Tagish Lake (2000):** On January 18, 2000, a large bolide exploded over Tagish Lake in western Canada. Later calculations estimated that the explosion occurred at 30–50 km altitude of a rock weighing

around 1.3 tons. Around 10 kg (22 lbs) of material was subsequently collected from the surface of the frozen lake. Tagish is another carbon-rich meteorite containing pyridine and purine nucleobases that are used by terrestrial life in DNA (refer to Chapter 6), along with tiny "nanodiamonds." The Tagish Lake meteorite has been dated to 4.5 billion years in age, and is presumed to have formed at the same time as the solar system.



Credit: (a) Eunostos/Wikimedia Commons/CC BY-SA 4.0 (b) Shiny Things/Wikimedia Commons/CC BY 2.0 (c) Basilicofresco/Wikimedia Commons/CC BY-SA 3.0 (d) Mike Zolensky/NASA JSC/Wikimedia Commons/Public domain

FIGURE 11-5: Carbonaceous meteorites: (a) Orgueil. (b) Allende section, showing chondrules. (c) Murchison. (d) Tagish Lake.

From this small list, you can clearly see the importance of these primitive meteorites, containing clues to the formation of the solar system, and ingredients of life. But does this tell us about whether life was in fact seeded from space (the *panspermia* hypothesis — refer to Chapter 10)?



TECHNICAL STUFF An interesting finding from carbonaceous meteorites is an excess of left-handed over right-handed amino acids, in some molecules where both types are possible (known as an *enantiomeric excess*). In Tagish Lake, for example, there is a 60 percent excess of L-type aspartic acid. This is significant because we know that life on Earth uses entirely L-type amino acids. So, is this evidence for life in these samples?

Scientists believe that — rather than evidence for life — these findings show that enantiomeric excesses can be produced by a range of means. One of the leading culprits is thought to be polarized starlight, which can selectively destroy one type of enantiomer (such as R-type) and preserve the other (L-type).



REMEMBER In summary, so far there is no evidence of actual life in these rocks, although they certainly contain the ingredients that we believe were also needed on Earth for *abiogenesis* — the formation of life from nonliving matter (refer to Chapter 6). This gives us reassurance that the chemical precursors to life are not rare or difficult to produce, and that we don't need to invoke a set of rare or unusual circumstances for these conditions to have arisen on Earth.

However, as you'll see in the next section, the debate about evidence for life in space rocks was not limited to only amino acids.

Parent of pieces



TIP Many meteorites appear to be pieces of asteroids. Remarkably, our science has advanced to the point where we can even identify in some cases *which* asteroid.



TECHNICAL STUFF A particular example is the set of "HED" meteorites (named for three types of minerals comprising them). These meteorites are thought to have originated from the large asteroid Vesta. The theory goes that Vesta suffered a large impact — evidenced by a large crater on its southern hemisphere — which gave rise to a set of smaller "child" asteroids, so-called "V-types." These later ended up in orbits which intersected that of the Earth and — *wham* — HED meteorites.



TIP However, some rare meteorites have even been traced to larger bodies. Perhaps unsurprisingly, one group appears to have come from our nearest neighbor, the Moon.



TECHNICAL STUFF An unusual meteorite was found by the ANSMET survey (see earlier) in 1982 (ALH 81005, see Figure 11-6a), by which time lunar rocks had already been returned to Earth by the Apollo missions. Subsequently, ALH 81005 was recognized as potentially lunar due to a close match of the chemical isotopes to the Apollo samples, and soon other finds were also identified as lunar rocks.

Today, almost 400 lunar meteorites have been collected on Earth totaling more than 1,000 kg (2,200 lbs) (see Figure 11-6b). However, to date no definitive source crater on the Moon has been confirmed for any of these.



TIP Even rarer are meteorites from Mars. By the 1980s three unusual groups of meteorites known as "SNCs" (named after their three original class members) were recognized to have similarities to each other that indicated a planetary origin, but not from Earth. Key clues included younger ages than most meteorites, along with evidence of mineralogical alteration in the presence of liquid water. The definitive proof came in 1983 when analysis of trapped gases in one of these rocks showed that it had an identical composition to the atmosphere of Mars, as measured by the Viking landers in 1976 (see Chapter 12). Around 300 Martian meteorites have now been identified — see example in Figure 11-6c.



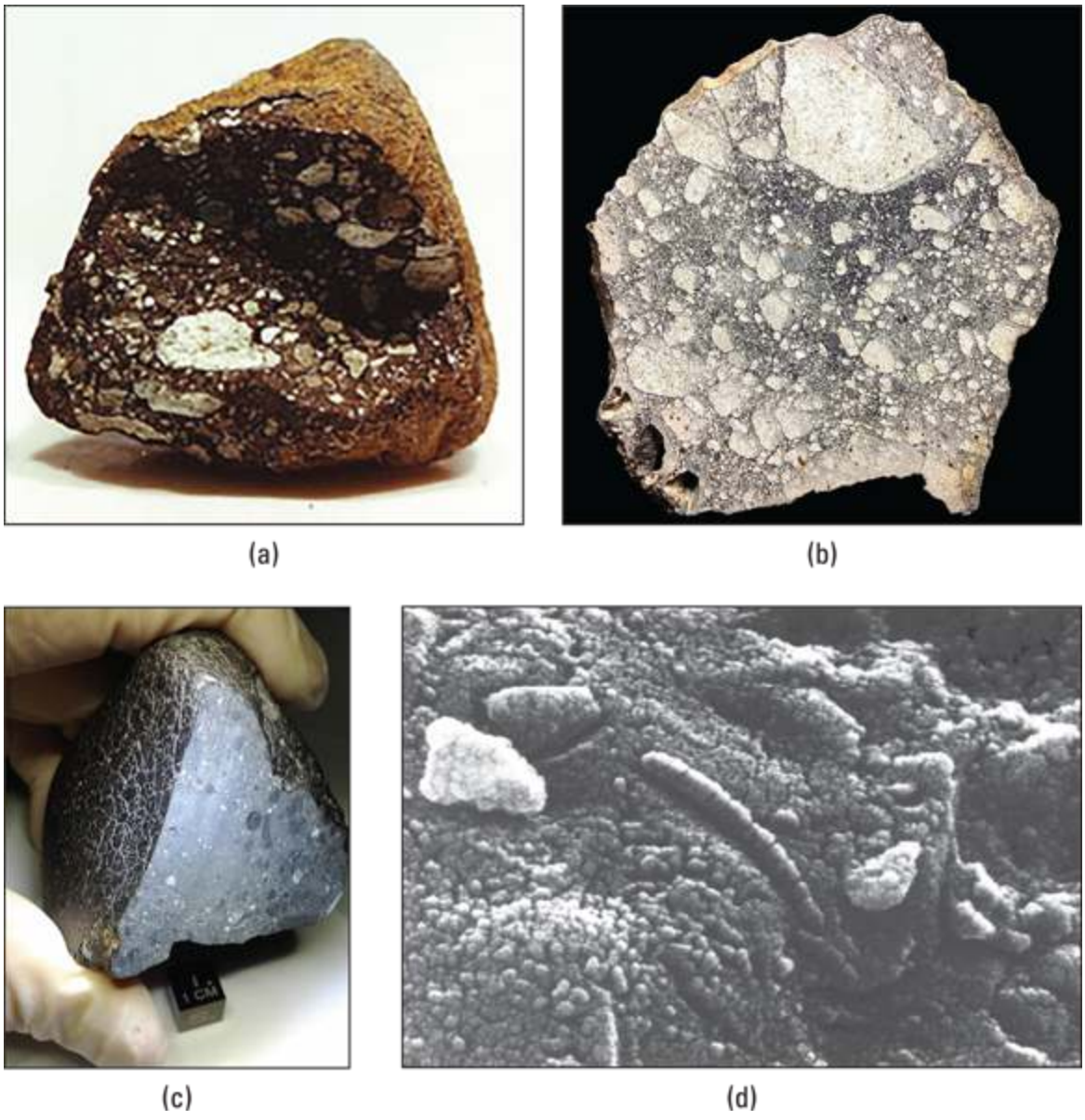
REMEMBER You are probably wondering already whether any of these pieces of Mars showed evidence of life — as many scientists did. A dramatic announcement was made in 1996 when scientists from NASA's Johnson Space Center in Houston, Texas, showed pictures of curious, worm-like structures in the ANSMET-collected rock "ALH84001" (meaning "Allan Hills, Antarctica, 1984, sample 001," see Figure 11-7d). These structures, they proposed, along with some other mineralogical clues, showed evidence of ancient life.

A veritable storm of scientific controversy immediately erupted. In the ensuing decades, this unassuming 1.9 kg (4.3 lb) piece of blackened rock has generated more debate than perhaps any other rock in history.



TECHNICAL STUFF One of the major foci of the debate was whether bacteria could realistically be so small — the thread-like traces being typically only 20–100 nanometers in diameter — much smaller than any known lifeforms on Earth. This seemed a major argument against life. However, lead scientist David McKay and his team maintained that theoretical (yet unobserved) nanobacteria could potentially be so miniscule.

When the dust settled, the consensus opinion of most geologists (not including the original team) was that the miniature structures, remarkable as they were, could be explained by abiotic geology and did not need a living organism to create. However, the debate served to kickstart the field of astrobiology in the late 1990s (which is why you are holding this book) and the subsequent program of Mars rover exploration in the early 2000s, and like so many scientific debates has served a very productive purpose.



Credit: (a) Silvanius/https://commons.wikimedia.org/wiki/File:ALH81005(2).jpg/CC BY-SA 4.0/last accessed Oct. 10, 2026. (b) Steve Jurvetson/Flickr/CC BY 2.0 (c) NASA/Public domain (d) NASA/Wikimedia Commons/Public domain

FIGURE 11-6: Lunar and Martian meteorites. (a) The first known lunar meteorite, Allan Hills 81005. (b) Slice of NWA 5000, the largest known lunar meteorite, found in the Sahara Desert in 2007. (c) Martian meteorite NWA ("North West Africa") 7034, nicknamed "Black Beauty." (d) Microscope images of structures inside Martian meteorite ALH 84001 originally proposed to be evidence of life.

Bringing Home the Bounty

Despite the growing bounty of meteorites found on Earth, this is not enough to answer all our questions about solar system geology. Meteorites suffer from several drawbacks limiting their scientific usefulness:

- **Contamination:** Meteorites are inevitably contaminated with Earthly material by the time they are collected — even snow is laden with microbes and dirt. Although the interior of meteorites is less likely to be contaminated than the exterior, water can still find its way inside via microscopic cracks. Therefore, the presence of any interesting substances in meteorites can always be questioned as terrestrial contamination.
- **Provenance:** The origin of meteorites is never known exactly, even when the parent body is known, as is the case for the HED (Vesta), lunar, and Martian (SNC) rocks. We cannot be quite sure what part of the planet or moon that the rock came from, limiting its geological value.
- **Processing:** Meteorites are heated by their passage through the Earth's atmosphere, which may cause changes such as loss of volatiles or changes in structure, relative to their original condition.
- **Diversity:** Meteorites don't cover all the places we wish to have samples of. They sample certain asteroids, and some sites on the Moon and Mars that were impacted, but not many others.

The solution therefore can only be to send missions to collect the sample and bring them back to Earth — cleanly.

A taxing return: Hayabusa



TIP The first asteroid sample return mission was the JAXA (Japanese Aerospace Exploration Agency) spacecraft *Hayabusa* (aptly meaning "peregrine falcon"). *Hayabusa* (see Figure 11-7a) rendezvoused with small near-Earth asteroid Itokawa (see Figure 11-7b, about 300 m, or 1,100 ft in length) in 2005, making several

touch-and-go sampling attempts that were complex, chaotic, and of unknown success.



REMEMBER Nevertheless, in 2010 the sample capsule was returned successfully to Earth, and by 2011, mission scientists could announce that around 1,500 dust grains from Itokawa had been successfully collected. The analysis confirmed that Itokawa was composed of materials similar to many common meteorites found on Earth. Moreover, the mission was the first successful sample return from an asteroid, paving the way for more ambitious follow-on missions.

Diamond in the rough: Ryugu and Hayabusa 2



TIP *Hayabusa 2* (see Figure 11-7c) was launched in 2014 and sampled asteroid Ryugu in 2018, benefiting from the experience JAXA had accumulated with *Hayabusa*. Samples were successfully collected and returned to Earth for analysis in 2020.

The samples showed Ryugu (see Figure 11-7d) to be a very different body from Itokawa — dark, carbonaceous, and with a very young surface of around 9 million years in age. Ryugu's density is barely greater than water. Most likely it was created as the product of an earlier asteroid collision and breakup, and appears to be about 50 percent empty space, with an average density barely greater than water. Ryugu quite literally is a pile of rubble!

For astrobiology, Ryugu proved to be a rich target, and like many carbonaceous meteorites, it was rich in organic molecules. Sample analysis has so far shown the presence of all five key nucleobases needed to construct DNA and RNA (refer to Chapter 7).

Bounteous Bennu and OSIRIS-REx

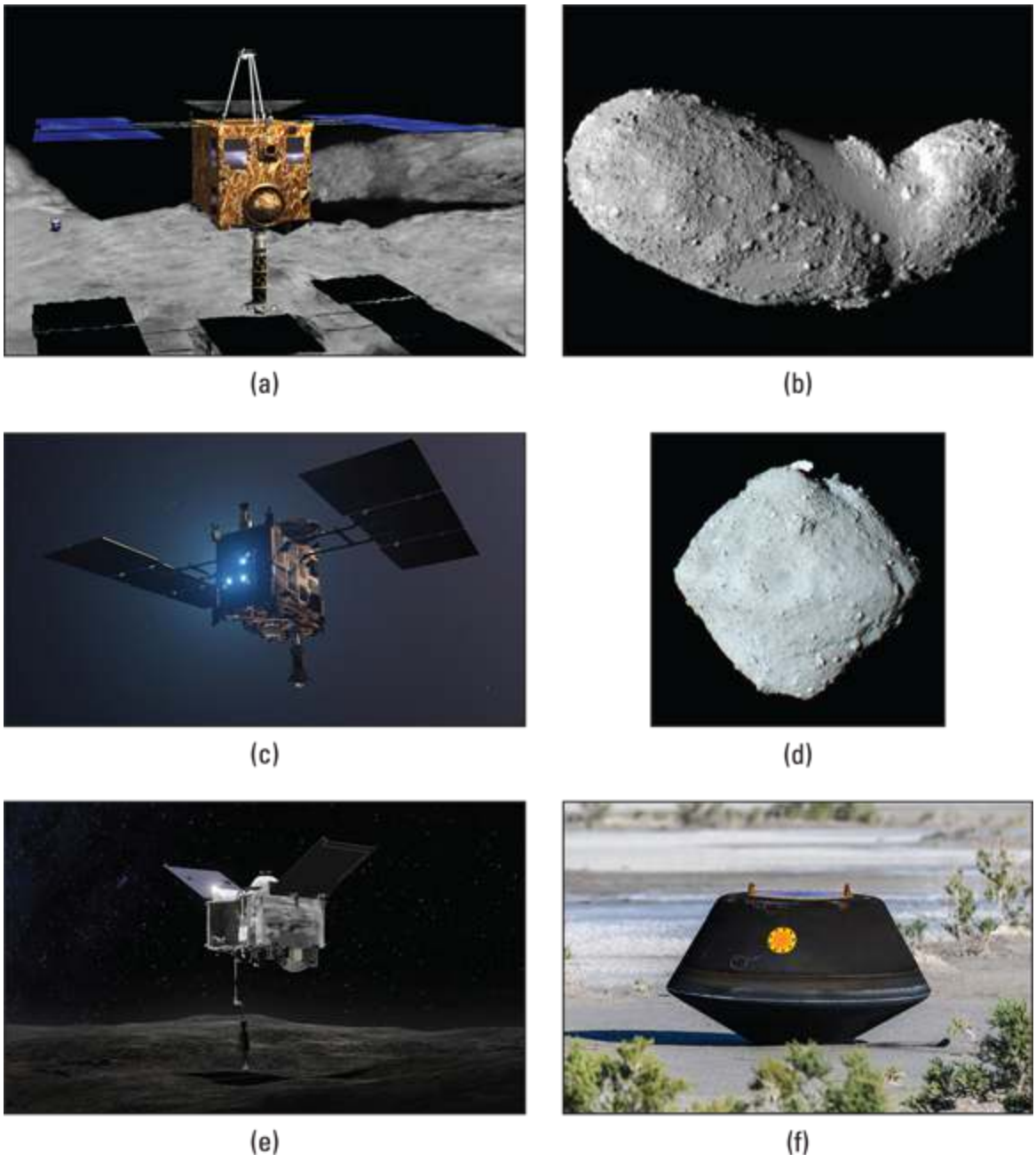
NASA's first foray into the asteroid sample return business came with the launch of *OSIRIS-REx* (see Figure 11-7e) in 2016. The spacecraft rendezvoused with near-Earth asteroid Bennu in 2018, and spent two years making a detailed survey of the little world, and reconnoitering a site to perform a safe "touch and go" (TAG) sample collection. Samples were collected in 2020 and returned to Earth in 2023 (see Figure 11-7f).



REMEMBER Like Ryugu, Bennu also proved to be a dark, primitive carbonaceous body that originated from the breakup of a larger parent body — perhaps the same parent body of Ryugu. Pre-solar grains found in samples from Bennu date to before the formation of the solar system, and once again all five key nucleobase molecules of DNA and RNA were found.



TIP The *OSIRIS-REx* spacecraft has now been targeted to visit a second asteroid, Apophis, which will pass very close to the Earth (20,000 miles) in 2029. This extended mission will return valuable information useful for planetary defense — future redirection of potentially hazardous objects such asteroids like Apophis.



Credit: (a) Jgarry/Wikimedia Commons/Public domain (b) JAXA/Wikimedia Commons/CC BY 2.0 (c) DLR German Aerospace Center/Flickr/CC BY 2.0 (d) ISAS/JAXA/https://commons.wikimedia.org/wiki/File:162173_Ryugu_brightened.png/CC BY 4.0/last accessed 08, 2026 (e) NASA/Goddard Space Flight Center/Wikimedia Commons/Public domain (f) NASA/Keegan Barber/Wikimedia Commons/Public domain

FIGURE 11-7: Asteroid sample return missions and targets: (a) *Hayabusa*; (b) Itokawa; (c) *Hayabusa 2*; (d) Ryugu; (e) *OSIRIS-REx*; (f) the *OSIRIS-REx* sample capsule landed back on Earth.

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Chapter 12

Mars

IN THIS CHAPTER

- **Learning how astronomers mistook geology for signs of an inhabited planet**
- **Discovering how space missions gradually unveiled the mysteries of the red planet**
- **Understanding NASA's attempts to find microbial life on Mars**
- **Finding out about the quest today to search for Martian life**

Mars: The Red Planet. Subject of endless fascination to Earthlings, ranging from the religious to the literary. In one form or another, Mars has featured prominently in our culture for all of recorded history.

In this chapter, I cut through the hype to reveal the *real* Mars. Not the dying home world of the alien invaders in H. G. Wells's *The War of the Worlds*, nor the spear-toting God of War of Greek mythology. Instead, you get acquainted with Mars as we know it today — a dusty, rusty, cratered-strewn planet — seemingly dull and lifeless, but teeming with clues of a rich, watery past. A Mars that is both known and unknown, and that may yet be hiding buried secrets, including perhaps hardy subsurface life.

Romancing the Red Planet

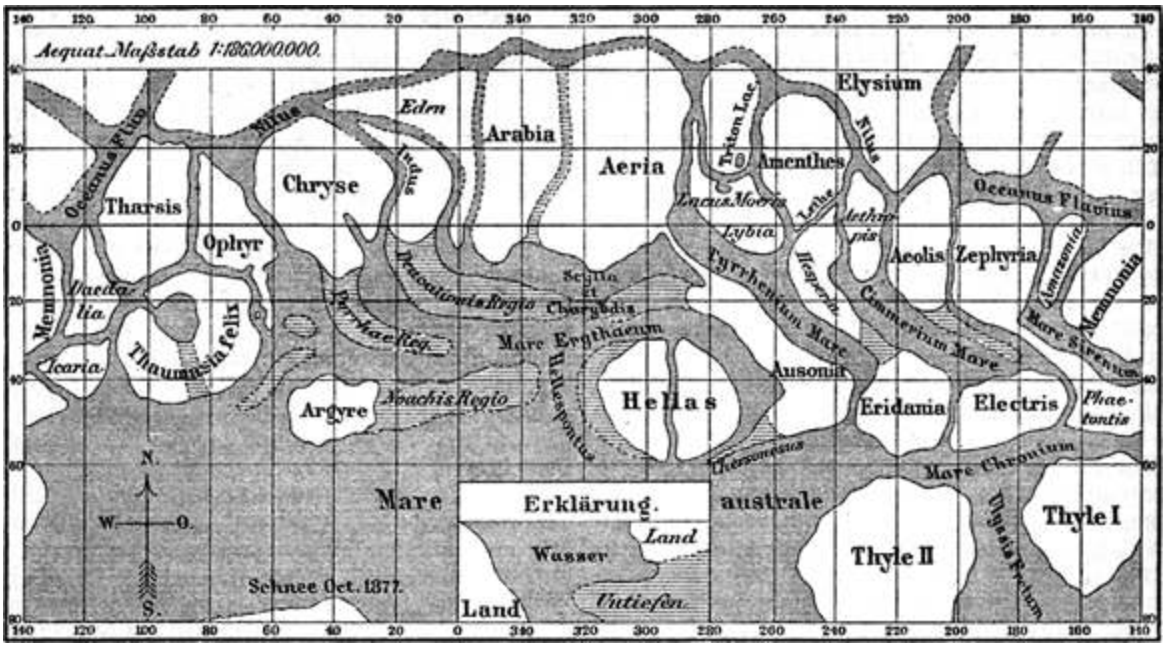
Let us start our Martian odyssey of discovery in the recent past, when telescopes began to reveal Mars as more than the enigmatic red dot known to ancient observers (refer to Chapter 2), and the first hints of landforms emerged.

Schiaparelli's canals

In 1877, Mars reached its "Great Opposition" — being both closer than usual to the Earth and on the opposite side of Earth to the Sun. This meant that it was also fully illuminated, like a full Moon, although much farther away and smaller in the sky. These two coincidences created a golden opportunity for a burst of new observations.

In Turin, Italy, astronomer Giovanni Schiaparelli turned his telescope to view the Red Planet, and over a period of weeks patiently sketched maps of its light and dark areas when the night sky viewing was clear. Schiaparelli's captivating map (see Figure 12-1) provided new, classical monikers for the most prominent terrains, naming the brighter areas after lands and islands of antiquity and the darker areas for seas and rivers. As for the "seas" on the Moon (lunar mare), Martian seas eventually proved not watery at all, but rather to be darker regions of the dry surface. But the names stuck.

The most significant outcome of Schiaparelli's naming spree was due to a famous example of "lost in translation." With his limited telescope technology, glimpsing Mars through the Earth's twinkling atmosphere, Schiaparelli had succumbed to a trick of the mind, joining up dark features on the surface with imaginary lines. He called these *canali* — meaning *channels* in Italian, intended to convey a river-like meaning.



Credit: Unknown author/Wikimedia Commons/Public domain

FIGURE 12-1: Schiaparelli's 1877 map of Mars where many terrains received their modern names.



REMEMBER However, English-speaking astronomers soon misinterpreted these "canali" as literal *canals*, imbuing them with a wholly different character and artificial origin, imagined due to a water-irrigating Martian civilization. This was the source of much of the subsequent science-fiction frenzy over "Martians" that continues to the present day (see Chapter 19).

Lowell's observatory

One of the new crop of Martian canal-enthusiasts was the American Percival Lowell. After a successful business career, Lowell became entranced by the allure of Mars, and decided to spend the remainder of his years in astronomical study. One of his first acts in 1893 was to found an observatory in Flagstaff, AZ (the Lowell Observatory, see Figure 12-2) at a high-altitude site specifically chosen for a clear view of the heavens.



REMEMBER At Flagstaff, Lowell embarked on a dedicated effort to map the Martian "canals," gradually expanding his maps and in tandem his increasingly fanciful theories about a thirsty, water-irrigating Martian civilization. Lowell's maps and associated musings were published in three books from 1895 to 1908 to great public interest and spurring on the Martian novel craze — but receiving a much less enthusiastic response from academic astronomers.



(a) (b)

Credit: (a) James E. Purdy/Wikimedia Commons/Public domain (b) Pretzelpaws/Wikimedia Commons/CC BY-SA 3.0

FIGURE 12-2: (a) Percival Lowell (March 13, 1855 — November 12, 1916), an influential American astronomer who popularized the idea of canals on Mars. (b) The dome of the Clark Telescope (1896) installed at Lowell Observatory, Mars Hill, Flagstaff, Arizona, used by Percival Lowell to make his studies of Mars.

In 1909, Lowell's work received a significant setback when the new 60-inch telescope at Mount Wilson, California more clearly showed the surface of Mars, with no evidence of anything but natural landforms. Yet, the talk of Martian civilizations persisted.

The Space Age Arrives

Through the first half of the twentieth century, astronomical evidence continued to pile up that Lowell's romantic vision of a populated Mars was mistaken. But from the viewpoint of distant Earth, Mars remained a trembling orange orb to even the largest telescopes, and many scientists remained open-minded that Mars might still harbor life, if perhaps not entire civilizations.



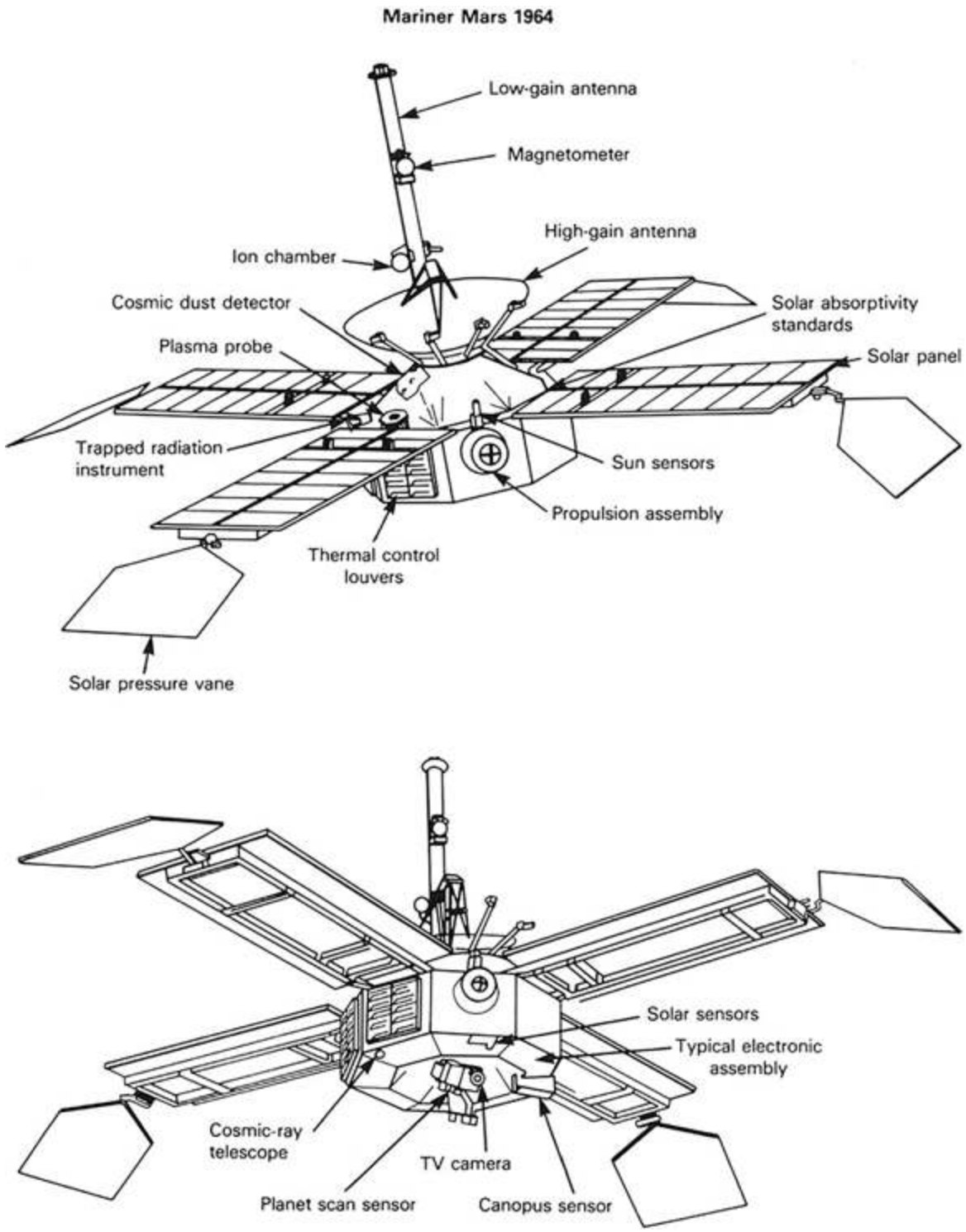
REMEMBER Some scientists noticed that the dark patches on Mars varied in shape and size, growing larger and smaller with an apparent annual cycle. This led to a belief among some astronomers that the darker areas were vegetation, expanding and contracting with the seasons. Could Mars be covered in plant life, perhaps even used for agriculture by salad-munching Martians? Only close-up images would finally settle the debate — and that would come soon.

Taking the first photos: Mariners 4 to 7

In July 1965, humanity's first successful mission to Mars, NASA's *Mariner 4* (see Figure 12-3), whizzed past the red planet and snapped the first close-up images of the surface. These revealed an old, heavily cratered terrain (see Figure 12-4) similar to that of the Moon, much to the chagrin of those hoping for an inhabited Mars. Although later spacecraft missions showed a more complex picture of Mars's surface with dried-up riverbeds and flood plains, the idea of a global Martian civilization was largely dispelled.

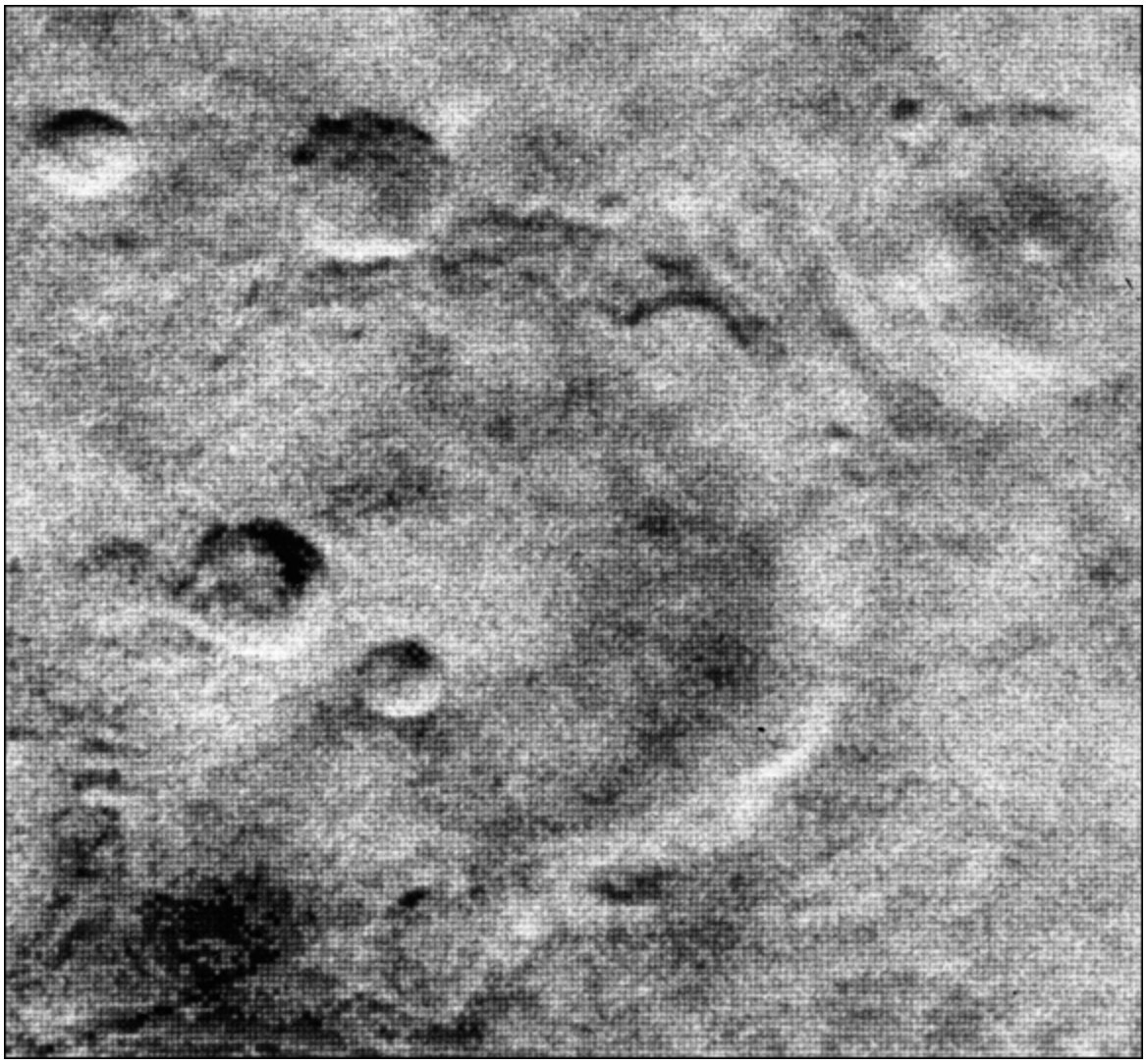


TECHNICAL STUFF The images of cratered landscapes from *Mariner 4* were shocking to many: After so many years of speculation about Martian civilizations, could it really be true that Mars was just Earth's Moon 2.0? Despite the disappointment, further NASA missions to Mars had already been planned, and in the summer of 1969, Mariner 6 and 7 were next to reach Mars (see Figure 12-5) flying over the equator and south pole and making important atmospheric measurements — but again by chance missing Mars's most spectacular geological features.



Credit: NASA/JPL-Caltech/Public domain

FIGURE 12-3: The NASA *Mariner 4* spacecraft that took the first photographs of Mars in 1965. The spacecraft body measures 50 in (1.27 m) in width and 18 in (46 cm) high, whereas the full span, including solar panels and vanes, was 22.6 ft (6.88 m).



Credit: NASA/JPL-Caltech/Public domain

FIGURE 12-4: Image of Mars from *Mariner 4* showing cratered landscape, taken from a distance of 9,846 km (6,118 mi) on July 14th, 1965. The large crater (150 km, 93 mi) was later named “Mariner”; the full image width is 250 km (155 mi).

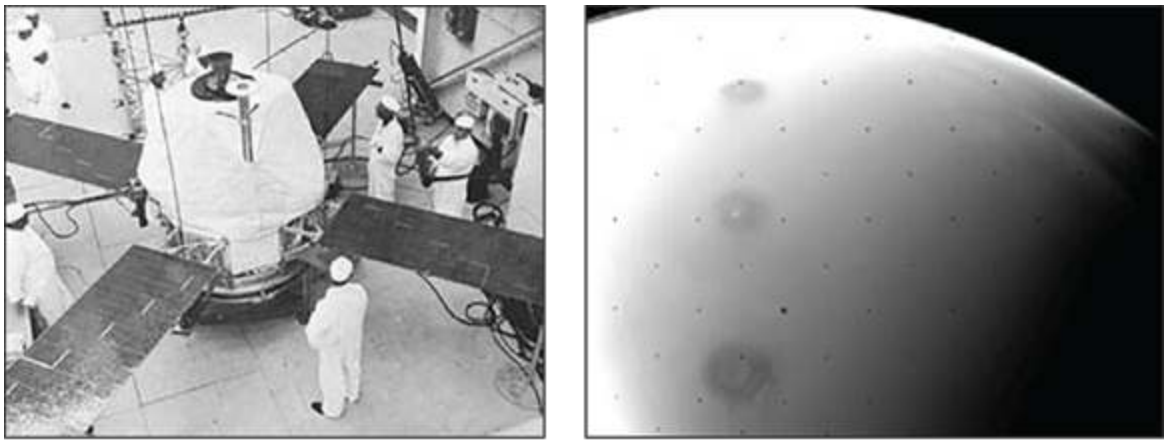


Credit: 4throck/Wikimedia Commons/CC0 1.0

FIGURE 12-5: Distant view of Mars from *Mariner 7*, showing polar caps.

The grandest canal: Mariner 9

REMEMBER Following three previous fly-by missions, NASA's next Mars mission would finally orbit the planet, enabling it to make a global map for the first time, and ensuring that no lurking Martian cities were missed. *Mariner 9* (see Figure 12-6a) arrived in Mars orbit on November 14th, 1971 (sadly, its sister craft, *Mariner 8* was destroyed in a launch failure) — while the planet was enveloped in a global dust storm. With the surface invisible for weeks after arrival, the spacecraft waited and waited, and was finally rewarded with a spectacular view of the summits of giant volcanoes emerging from the dusty atmosphere as the storm abated (see Figure 12-6b).



Credit: (a) NASA/Public domain (b) NASA/Public domain

FIGURE 12-6: (a) *Mariner 9* being prepared for launch. (b) Three volcanoes of the Tharsis plateau became visible as the dust settled (*note:* black dots are added by the camera).

TECHNICAL STUFF Further discoveries awaited. The biggest mountain in the solar system — Olympus Mons, reaching 21 km (69,000 ft) in height and covering a land area the size of Italy — was first recognized as a volcano from *Mariner 9* images. However, the largest discovery (quite literally) was the Valles Marineris (see Figure 12-7), the largest canyon in the solar system, wide enough to stretch across

the entire continental United States (4,000 km, 2,500 miles). Together these landforms began to tell a story about the past of Mars, one shaped by volcanism, and also by flowing water.

Scientists now struggled to fit all the puzzle pieces together. While the "canals" of Mars envisaged by Lowell and others had proven to be mistaken, Mars indeed did have natural channels, rivers, arroyos and gullies clearly carved by water — although seemingly in the distant past. In this respect, Mars was much more likely to have once harbored life than the Moon, which never had any flowing water at all. Was there still a chance that microbial life could be sheltering below the surface, out of reach of solar radiation and nourished by subsurface water?

Clearly there was only one way to find out: A landing craft was now needed.

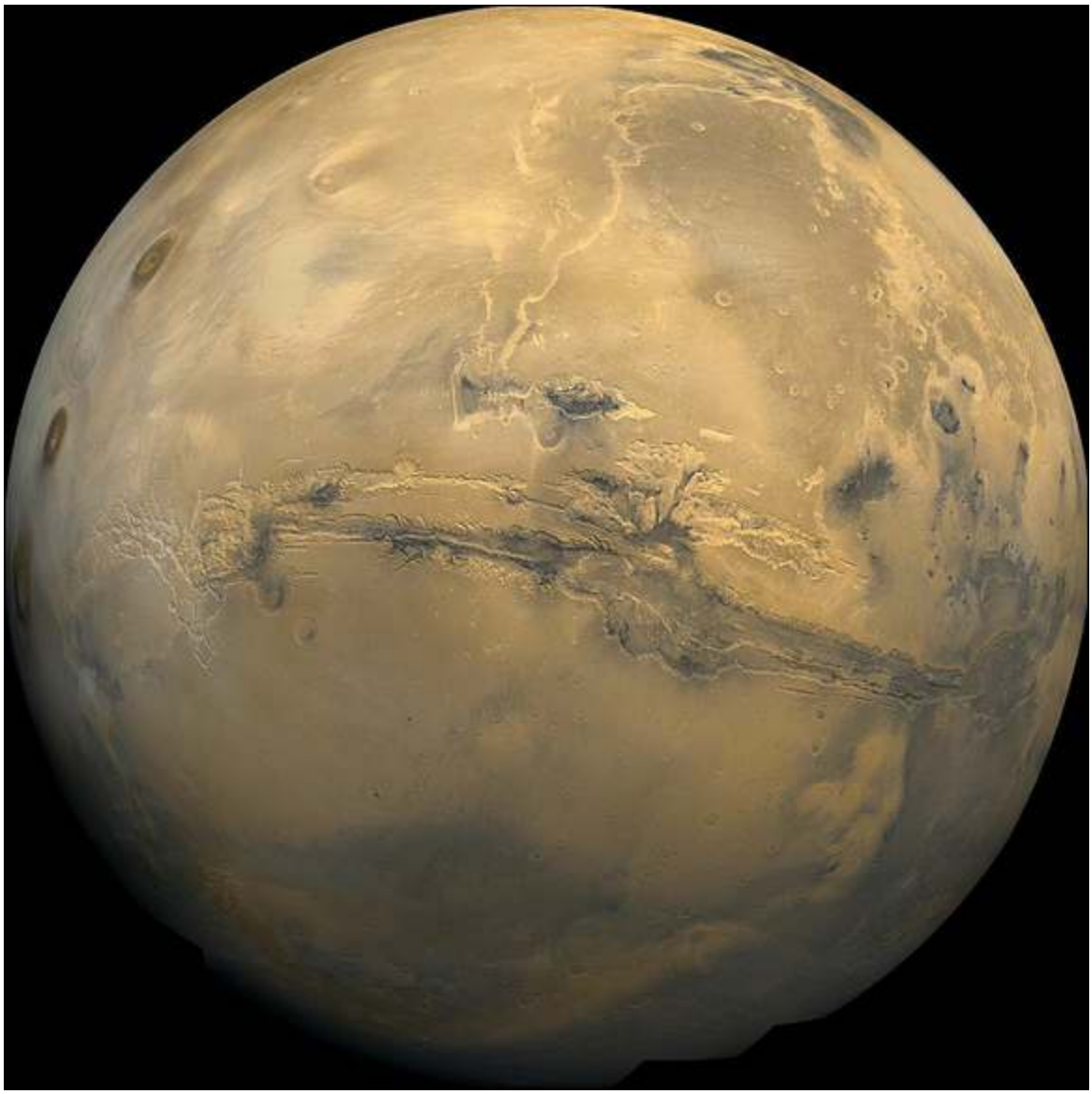
Probing for life: The Vikings arrive

In 1976, barely a decade after the first successful space flyby of Mars by *Mariner 4*, two landers — *Viking 1* and *2* — touched down safely on the Martian surface. Although the earlier Soviet probe Mars 3 had also landed, it did so during the dust storm of 1971 and returned no useful data.



REMEMBER The two *Viking* landers (and accompanying orbiters) were NASA's most sophisticated robotic probes to date, and the first interplanetary missions to directly search for life on another world. They were — in later terminology — the first astrobiology missions on Mars.

To cast a wide net, the landers set down on two widely spaced locations on Mars: *Viking 1* on the smooth "Golden Plain" (Chryse Planitia), and *Viking 2* on the more northerly plains of Utopia Planitia. Meanwhile, the two orbiters stayed above making surveys of Mars's surface and atmosphere, including the spectacular global view of Mars (see Figure 12-7).



Credit: Viking Project/USGS/NASA/Public domain

FIGURE 12-7: Global picture of Mars assembled from images from the *Viking 1* orbiter, February 22, 1980. Note the Valles Marineris stretching across the center, and the three Tharsis volcanoes on the left.



Each of the *Viking* landers carried four distinct experiments designed to find evidence of life using different techniques:

- **Gas chromatograph — mass spectrometer (GC-MS):** This instrument measured the mass of different gas molecules that evaporated from the soil when heated, enabling the composition to be determined. A key finding of the GC–MS was that carbon-bearing molecules associated with life (refer to Chapter 5) appeared to be largely absent — a finding that made it hard to entertain notions of any living matter in the soil. Note, however, the later discovery of *perchlorates* — chemicals that can destroy organic molecules when they are heated together — in Martian soil by the *Phoenix* lander led to the revised assessment of the GC–MS results on carbon molecules as "inconclusive."
- **Gas exchange (GEX):** This experiment was designed to "feed" any Martian microbes and check whether respiration occurred, detectable through changes to the gases above the sample. Nutrients were added to a soil sample, and later, to water, too. The GEX experiment noticed that oxygen (O_2) disappeared and carbon dioxide (CO_2) appeared, providing some initial excitement since these are characteristics of respiration on Earth.
- **Labeled release (LR):** The LR was intended to be the most sensitive test of microbial metabolism. Small droplets of nutrient-containing water were again added to Martian soil, but with a twist: The nutrients had been "tagged" with the rare, radioactive carbon isotope C14. This meant that any carbon dioxide given off by the sample could be checked to see whether it also contained C14 — intended to be an unambiguous indication that microbes had eaten the food and given off the carbon dioxide, rather than it arising from CO_2 frost evaporating from the Martian soil. The result of the LR experiment appeared at first positive: C14-containing gas was indeed detected! However, later reevaluation has shown that this could happen through abiotic (non-biological) mechanisms instead.
- **Pyrolytic release (PR):** Rather than checking for C14 incorporation into gases, this experiment checked whether radioactive C14-labeled CO and CO_2 were incorporated into solid material, intended to see if Martian life had used the gases to "grow." After some days of

exposure to the gases, the gases were removed and the remaining solid material vaporized and checked for C14 radioactivity. The results of this experiment are perhaps best described as "inconclusive" — some small amounts of radioactivity were detected that could be interpreted as a positive result, but non-biological mechanisms have been suggested to explain the results.



REMEMBER Summing up: Did the Vikings find evidence for life or not? After some initial enthusiasm, scientists quickly realized that the onboard experiments were not as definitive as they had thought, and that nonbiological mechanisms — chemical reactions of the Viking-supplied nutrients with inorganic chemicals in the soil — could give rise to "false positive" results.

To this day, the debate about the interpretation of the Viking results rages on among scientists, without enough evidence to close out the matter one way or the other. Although this might seem frustrating to those wanting a simple answer, it's important to realize that this is how the scientific process is intended to work. Any time there is the tiniest hint of uncertainty or doubt, that means that more work and experimentation is needed to be certain.



TIP For questions as important as "did we discover life on Mars?" we must recall an adage often attributed to Carl Sagan — that "extraordinary claims require extraordinary evidence" (sometimes given by the acronym "ECREE"). We must seek the *truth*, and not slip into the trap of *confirmation bias* — giving weight only to evidence that supports the hypothesis we set out to test.

In the next section, I dig deeper into the types of inorganic substances later found in the Martian soils that may be responsible for false positives in the Viking results, and the new experiments underway to provide more definitive answers.

Roving and roaming on Mars

In the wake of Viking, NASA took an extended break from further Mars-landed investigations for two decades. However, intriguing evidence of possible microfossils in the Martian meteorite ALH84001 (refer to Chapter 11) returned Mars to the forefront of the quest for life. This excitement led to new missions designed to traverse the Martian surface to "follow the water" — to get a better understanding of the environment before trying again to detect life directly.

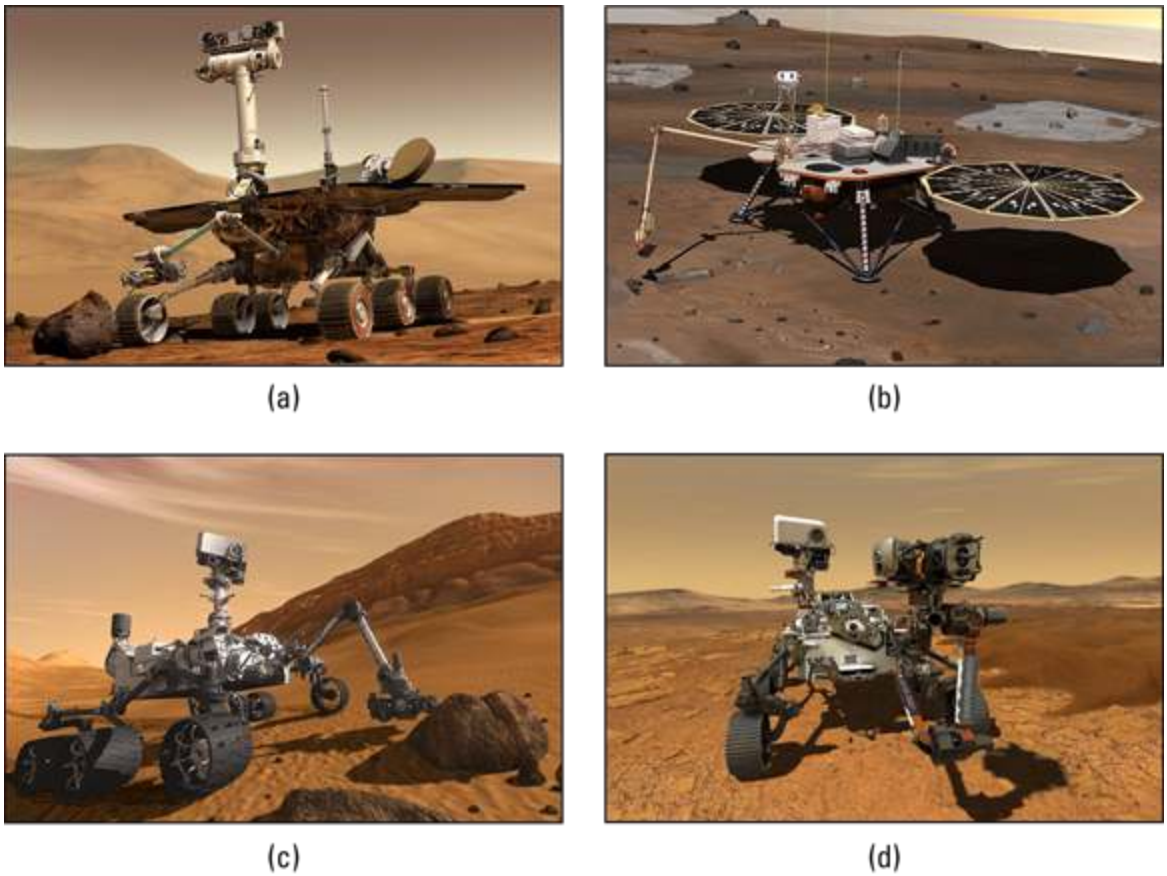


TIP For a thorough description of all the many successful (and unsuccessful) missions to Mars, check out *Space Exploration For Dummies* by Cynthia Phillips and Shana Priwer (Wiley). Here I focus on just the most important recent missions that shed light on the question of Martian astrobiology.

- **Mars exploration rovers (MERs, see Figure 12-8a):** The twin MER rovers — named *Spirit* and *Opportunity* — launched in 2003 and successfully landed on Mars in 2004. These were the first elements of the new NASA initiative to "follow the water," tracing the aqueous history of the Martian surface. The golf cart-sized rovers were designed to be "robotic geologists," each equipped with a brace of cameras and several instruments designed to probe the composition of rocks. Both rovers were wildly successful, lasting far beyond their intended 90-sol (90 Martian days) lifetime, and both found evidence of minerals that are often formed by contact with water, such as the iron-containing hematite and the sulfur-rich mineral jarosite.
- ***Phoenix* (see Figure 12-8b):** *Phoenix* was NASA's second attempt to land near to one of Mars's poles and landed successfully on the northern polar plain Vastitas Borealis in 2008. *Phoenix*'s task was to search for water in the less-sunny, polar regions, which were expected to preserve water closer to the surface than at the lower latitudes explored by the MERs. In one of the most iconic

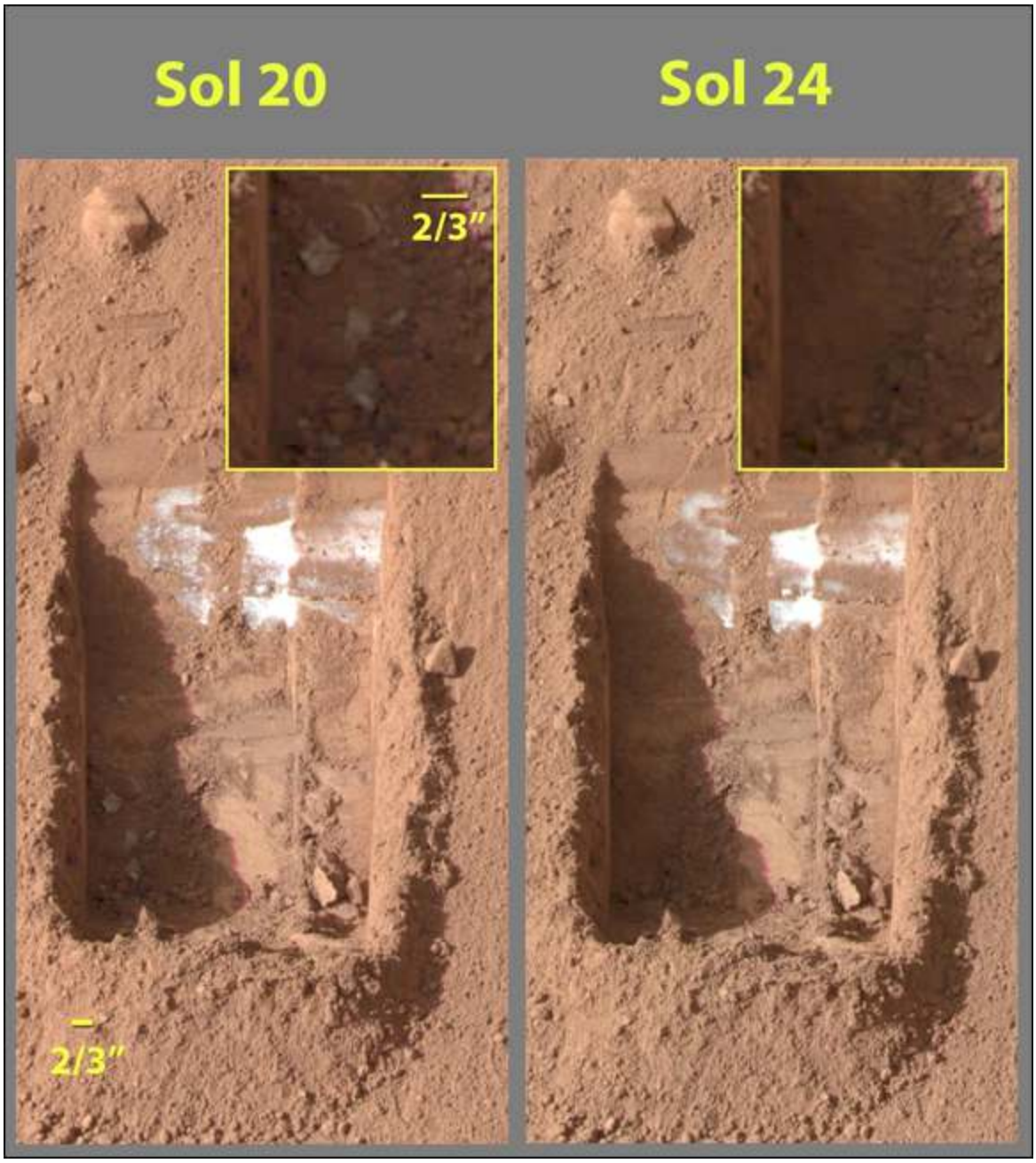
photographs in Mars exploration, Phoenix scraped back the red dirt with a digger arm revealing bright white patches of ice (see Figure 12-9) that evaporated over the course of 4 sols. More surprises lay in store. The LIDAR instrument (laser reflection) detected nighttime clouds, and even snow falling! The soil was also found to contain high levels of perchlorate (ClO_4), a potent oxidizer discussed in detail later.

- **Mars Science Laboratory (MSL, see Figure 12-8c):** The Mars Science Laboratory rover (aka *Curiosity*) is a much bigger rover than the MERs, sized closer to a compact car. MSL also has much more reliable power source — nuclear energy — than the solar panels of the previous missions. Since 2012 MSL has been roaming the 154 km (96 mi) wide Gale Crater, making measurements of the rock strata, atmosphere, and more. Some of MSL's most significant findings include layered mudstones, showing that the crater was once filled with water. In addition, MSL detected carbon-rich organic molecules for the first time on the surface, leading to speculation that life may still be waiting to be found somewhere in the subsurface.
- **Mars 2020 rover (M2020, see Figure 12-8d):** The most recent Mars rover, similarly sized to *Curiosity*, is the M2020 rover *Perseverance*. Like *Curiosity*, *Perseverance* (or "Percy") is nuclear powered and highly capable, but its primary mission is to select samples for return to Earth rather than to accomplish scientific investigations on Mars. To that end, Percy has been drilling, extracting, and stashing (caching) small samples of interesting rocks as it traverses Jezero Crater. *Perseverance* has confirmed suspicions that Jezero was once flooded and has a floor rich in clay minerals. Percy's most intriguing finding for astrobiology so far is the unusual rock named "Chevaya Falls" (see Figure 12-10), which shows black-and-white patches dubbed "leopard spots." The spots contain iron and phosphate, often associated with microbial life, leading some scientists to speculate that these could be preserved signatures of life from 3.5 billion years ago.



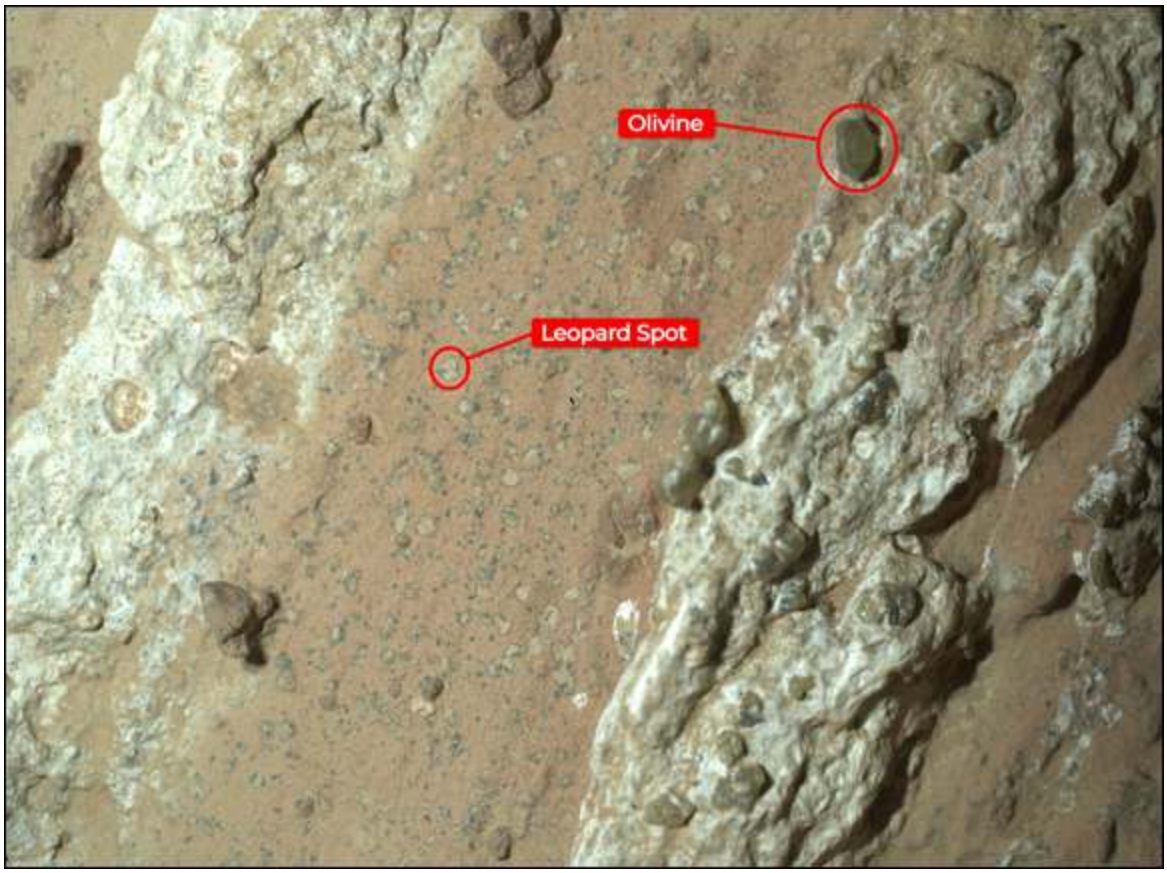
Credit: (a) NASA/Public domain (b) NASA/Public domain (c) NASA/JPL-Caltech/Public domain (d) NASA/JPL-Caltech/Public domain

FIGURE 12-8: (a) Mars exploration rover *Spirit*. (b) Mars *Phoenix*. (c) Mars Science Laboratory *Curiosity*. (d) Mars 2020 rover *Perseverance*.



Credit: NASA/JPL-Caltech/University of Arizona/Texas A&M University/Public domain

FIGURE 12-9: Bright water ice showing up near to the *Phoenix* lander when the surface dust was clawed away; several days later the water had begun to evaporate.



Credit: NASA/JPL-Caltech/Public domain

FIGURE 12-10: The “leopard spots” at Chevaya Falls, a sedimentary deposit of mudstones in Jezero Crater investigated by the *Perseverance* rover. These bright spots with dark rings several mm in size have been suggested to be potential biosignatures.

The History of Mars

From the data returned from the many Mars orbiters, landers and rovers to date, a picture emerges about the watery past of Mars and how its habitability may have changed over time.

The four ages of Mars



REMEMBER Similar to the geochronology of the Earth, the geologic history of Mars has been divided into periods. On Mars, these are:

- **Pre-Noachian (earlier than 4,100 *Mya*, or million years ago):** A very early, violent period on Mars when the planet was forming and undergoing major impacts, when no true geological record is preserved. However, it is assumed that the *hemispheric dichotomy* occurred in this period, when Mars was walloped by a large planetesimal, which shaved off a large part of the northern hemisphere, leaving it permanently lower than the southern hemisphere by 5 km (3 mi).
- **Noachian (4,100–3,700 Mya):** This is where things get interesting for life. In this period, major impacts were still occurring, but their scars in the form of giant impact craters are preserved on the Martian surface - primarily in the older, southern hemisphere where they appear highly eroded. Due to the crustal fracturing from impacts and the ongoing volcanic activity which created the Tharsis bulge, large amounts of CO_2 and H_2O in the form of steam were released into the atmosphere, and Mars was overall quite warm and wet. We see the evidence for this in the valley networks that breach crater walls and leave traces of flows in the forms of fan-like alluvial deltas. If life arose on Mars, it was likely to have happened in the Noachian.
- **Hesperian (3,700–3,000 Mya):** After the end of the LHB (around 3,700 Mya), Mars became less pummeled from outside. However, the Hesperian was a time of major volcanism, when the Tharsis volcanoes were formed. Volcanic activity released the gases H_2S and SO_2 into the atmosphere, where they combined with water to form sulfuric acid. New sulfate minerals began to accumulate on the surface. By the end of the Hesperian, the atmosphere had thinned considerably, and water in the crust began to freeze. Only episodically did water melt thereafter due to volcanic or tectonic activity, forming large “outflow” channels and leading to periodic but short-lived pooling on the surface.
- **Amazonian (3,000 Mya–present):** The Amazonian period runs from about 3 billion years ago to the present. Major processes in the Amazonian included ongoing but slow accumulation of craters, and apparently still some volcanism, with Olympus Mons having been

active in the past few 10s of Mya. The Amazonian is the time period we witness today.

Now you have an overview of Mars's life story, let's look in more detail at what changed the atmosphere and with it, the habitability of the surface.

The tragedy of the Martian atmosphere

Evidence points to Mars having lost a lot of its original atmosphere, especially water. There are several effects at work here. Mars is smaller and has a lower gravity than the Earth (about 38 percent) which allows gases to escape to space more easily, all else being equal. However, Mars has larger problems to worry about, the most significant of which is the solar wind.



REMEMBER The *solar wind* is a constant stream of lightweight particles emitted from the Sun. Over time, this can destroy planetary atmospheres in several ways: either by breaking up their gas molecules, or by knocking them away into space.

The Earth is largely protected by its magnetic field, which deflects the mostly charged particles (and causes the brilliant displays of the polar aurorae). Mars, however, is a smaller planet than Earth and so cooled down much faster. This caused its originally molten metallic core to stop moving, which is required to generate a magnetic field, leaving the Martian atmosphere defenseless to the solar wind. Without its magnetic shield, much of the original water vapor (H_2O) was broken up, with the hydrogen lost to space and the oxygen becoming locked up in rocks.



TECHNICAL STUFF Today, we see evidence of this past atmospheric loss in the isotopic ratio of light elements, especially the *hydrogen* measured in Martian water. Hydrogen comes in two stable forms, a lighter

version (H) and a heavier one (D). When water is broken up, the lighter H escapes to space more easily than the heavier D. So, over time, any remaining water tends to have less H and more D. This effect has been measured, and indeed Martian water has about six times the proportion of D compared to water on Earth, indicating that as much as 90 percent of the original water may have been lost.



REMEMBER As the Martian atmosphere became eroded by the solar wind, it provided less *greenhouse warming* (refer to Chapter 5), and the planet cooled off. This meant that water no longer flowed on the surface, and remaining water became frozen out into polar caps and sub-surface permafrost, as seen by *Phoenix*.

Habitability of Mars Today

It appears, therefore, that Mars *could* have been habitable in the past, especially during the post-apocalyptic, balmy years of the Noachian period, when water ran in rivers and pooled inside craters to form lakes. So much we know from the persistent investigations of our little robotic geologists, the rovers I discussed earlier.

But what about Mars today, could it be potentially inhabited by hardy extremophiles (refer to Chapter 9)?

Gasping for air: The Martian atmosphere

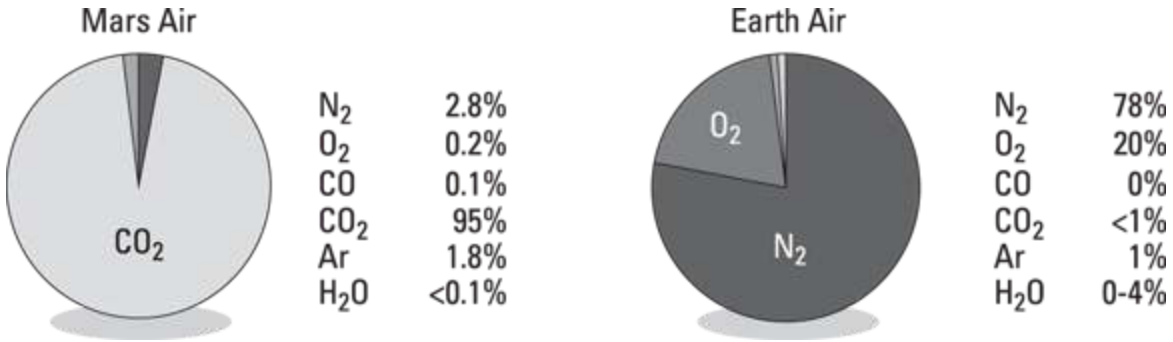
Mars is not a place where you'd want to stroll today without a spacesuit. First, the atmosphere is *thin* (low pressure). Although it varies across the surface and with time of year, it averages around 6-7 millibars, or 0.6-0.7 percent of the Earth's surface pressure.



TIP For comparison, you'd need to reach 110,000 ft (34 km) above the Earth to find air this thin, well above the altitudes where commercial jet liners roam (39,000 ft, 12 km) and thinner than the air at the top of Mount Everest (8.8 km) which is around 33 percent of the air pressure at sea level.



REMEMBER Second, the atmosphere is not breathable by humans, composed of more than 95 percent carbon dioxide (CO_2) — the gas we exhale — and very little of the oxygen (O_2) we need to inhale — about 100 times less than in Earth's air. (See Figure 12-11.) Lastly there's a lot of dust (but you knew that already) to gum up your spacesuit joints and obscure your camera lens.



Credit: Author

FIGURE 12-11: Gaseous composition of Mars vs Earth air (percentages by volume).

Quenching a thirst: Water

NASA's search for life on Mars from around 2000-2020 focused heavily on the theme of "follow the water" — since on Earth where there is water, there is usually life. Our spacecraft explorers have shown us that Mars still has significant water today, but it's locked up in the colder polar caps and below the surface, as the *Phoenix* lander importantly proved.

However, there is speculation that Martian water may melt in places, such as far beneath the polar caps, or even on warmer days as salty brines which can stay liquid at colder temperatures than pure water. Even periodic melting may allow extremophile organisms to briefly flourish.

Getting salty with Martian soil

During its experiments, the *Phoenix* lander found that the Martian soil, or *regolith*, is heavily impregnated with perchlorates. These chlorine-rich minerals dissolve in water to form brines, which can be both a good and bad thing for life. Although salt may help to stop water from freezing, very salty water is toxic to most lifeforms.



TECHNICAL STUFF Combined with solar UV radiation, and other chemicals in the Martian soil such as hydrogen peroxide (hair bleach), perchlorate would be an effective sterilizer, or bug-killing "bactericide." All is not quite lost here — halotolerant extremophiles ("halophiles," refer to Chapter 9), such as the yeast *Debaryomyces hansenii* found in cheeses and beer as well as salt flats, are able to adapt to high levels of perchlorate.

Methane and microbes

Perhaps the most intriguing clue in recent years about Martian habitability was the announcement of the discovery of methane (CH_4) in its atmosphere. This was first reported in 2004 by observations from telescopes on the Earth, and simultaneously from data from a European Space Agency (ESA) orbiter, Mars Express.



REMEMBER The presence of methane is highly surprising, since it would react quickly with the oxidizing Mars atmosphere to form water and carbon dioxide. So, if the methane is really there, it must be

continuously replenished: and speculation led quickly to the idea of life in the form of *methanogens* (methane-producing bacteria).

Later searches for the methane have proved confusing. An ESA mission sent to map the methane — the *ExoMars Trace Gas Orbiter (TGO)* — found no evidence of the earlier atmospheric methane. However, on the surface, the SAM (Sample Analysis on Mars) instrument on the *Curiosity* rover did detect occasional puffs of methane. A genuine mystery that persists to this day.

Future Missions

To wrap up this roller-coaster ride that is the search for life on Mars: Your takeaway message should be that Martian life today, or in the past, remains possible but not proven.

Returning samples

At the time of writing, MSL and M2020 continue to rove the Martian surface making new measurements. However, many scientists believe that the question of Martian life, either past or present, will not be settled until we can return samples from Mars to analyze in a terrestrial laboratory, where we have access to much more sophisticated instruments.



REMEMBER The main goal of the M2020 rover (*Perseverance*) is to collect samples that will later be returned to Earth for full laboratory analysis. This is the "holy grail" for many Mars scientists — access to a varied trove of high-quality samples to really search for evidence of life in that warm, Noachian period.

Protecting the home world

An important consideration arises when samples are transferred either from Mars to Earth, or from Earth to Mars (on our rovers and the like)

— *contamination*, known to the space community as *planetary protection.*



REMEMBER Contamination is bad for science, since we may detect life on Mars in the form of microorganisms brought from Earth! This would indeed be a giant waste of time and effort, so exquisite care is taken to make sure that any spacecraft sent to Mars are as sterile as possible.



TIP The reverse is also true: We don't want any samples brought from Mars (or another planet or moon) to escape our laboratories until we are sure they don't contain anything harmful to life on Earth, such as bacteria that we don't have defenses against.

Planetary protection is therefore a key topic taken into consideration by space agencies around the world when designing missions to Mars or other potentially habitable worlds. At the same time, it provides endless fodder for science fiction novels, TV shows, and movies (see Chapter 19).

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Chapter 13
Ocean Worlds

IN THIS CHAPTER

- **Learning about the exploration of the outer planets**
- **Understanding how tidal heating melts moon interiors**
- **Meeting the archetypal ocean worlds**
- **Discovering how life could exist inside hidden oceans**

For many years NASA focused its attention on "following the water" — mostly to Mars (see Chapter 12). However, in the early years of the 21st century, it became apparent that the rusty red planet was not the only — or even the best — place to look for a watery habitat.

In this chapter, you see how many of the moons and other small worlds of the outer system were discovered to be sneakily smuggling vast oceans beneath their scarred, icy crusts — abodes that could harbor life.



TIP I'll use the term *ocean worlds* to refer to the moons and other small worlds of the outer solar system that harbor water layers. But you'll see that these oceans are miles below the surface, unlike the Earth's oceans on the surface.

Missions of Discovery

Following success with robotic missions to the inner planets in the 1960s, NASA began to plan missions to visit the then-unexplored planets of the outer solar system in the 1970s. By 1989, NASA had made spacecraft flybys of all four giant planets, and the former planet Pluto (see *Astronomy For Dummies* by Stephen P. Maran and Richard

Tresch Fienberg (Wiley) for the full sorry saga) was finally reached in 2015.



TIP Table 13-1 summarizes all the missions to the outer planets to date, including flyby missions, orbiters, probes, and landers (refer to Chapter 12). I've included the New Horizons mission to Pluto, which was considered a planet when the spacecraft was launched, but later demoted to a dwarf planet (the flame war about this continues to rage but doesn't alter its scientific interest).



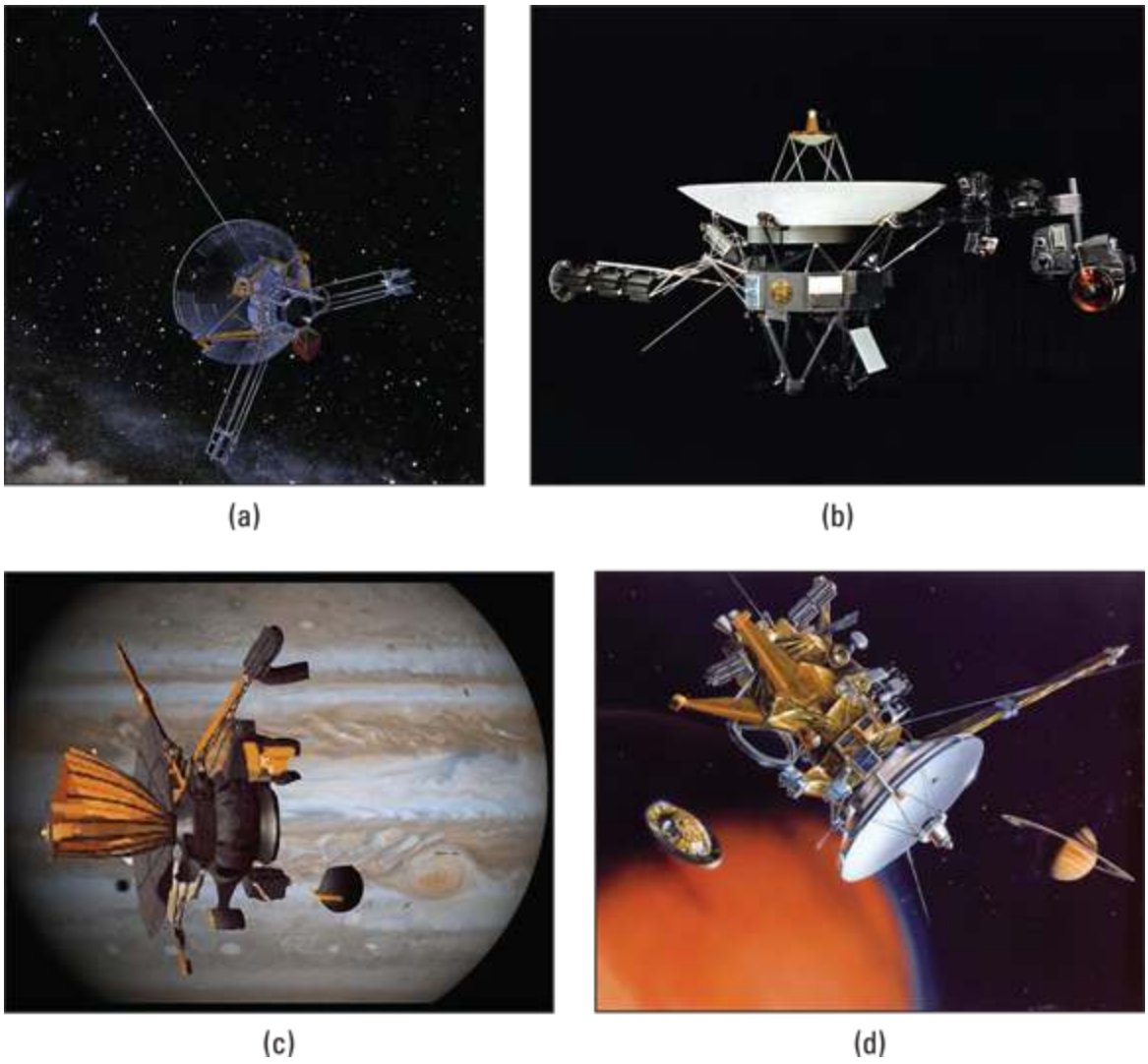
REMEMBER Some missions in Table 13-1 are currently in flight to their eventual destinations or being built at the time of publication, whereas others are old and may no longer be active (I'm looking at you, Voyager 1 and 2). Be sure to check online for the latest information. There are no repairs in deep space.

TABLE 13-1 Missions to the Outer Planets

Spacecraft	*Launch*	*Targets Visited*	*Status*
Pioneer 10	March 1972	Jupiter (November 1973)	Leaving the solar system. Last contact 2003.
Pioneer 11	April 1973	Jupiter (December 1974); Saturn (September 1979)	Leaving the solar system. Last contact 1995.
Voyager 1	September 1977	Jupiter (March 1979); Saturn (November 1980)	Active. Entered interstellar space August 2012.
Voyager 2	August 1977	Jupiter (July 1979); Saturn (August 1981); Uranus (January 1986); Neptune (August 1989)	Active. Entered interstellar space November 2018.
Galileo	October 1989	Jupiter system (December 1995-September 2003)	Intentionally destroyed in Jupiter's atmosphere.

Spacecraft	***Launch***	***Targets Visited***	***Status***
Cassini-Huygens (NASA-ESA)	October 1997	Saturn system (July 2004–September 2017). Titan landing by Huygens January 2005	*Cassini* was intentionally destroyed in Saturn's atmosphere at end of mission.
New Horizons	January 2006	Jupiter (February 2007); Pluto–Charon (July 2016); Arrokoth (January 2019)	Active. Passing through the Kuiper Belt.
Juno	August 2011	Jupiter (July 2016–)	Active in Jovian system as of 2026.
JUICE (ESA)	April 2023	Reaching Jupiter July 2031	Active.
Europa Clipper	October 2024	Entering Jupiter orbit April 2030	Active.
Dragonfly	Launch planned for July 2028	Arrival scheduled for late 2034	Under construction.

Let's now take a look at some of these missions in more detail, since they proved pivotal in expanding our ideas of habitable worlds (see Figure 13-1).



Credit: (a) NASA Ames/Public domain (b) NASA/JPL-Caltech/Public domain (c) NASA/Public domain (d) NASA/Public domain

FIGURE 13-1: Artists' renditions of (a) *Pioneer 10* and *11*; (b) *Voyager 1* and *2*; (c) *Galileo*; (d) *Cassini-Huygens*.

Pioneering the space frontier

First up for exploration of the outer planets were the aptly named *Pioneer 10* and *11* spacecraft, launched in 1972 and 1973 as pathfinders for the more ambitious *Voyager* mission that was to follow.



REMEMBER *Pioneer 10* was the first spacecraft from Earth to cross the asteroid belt, and soon reached Jupiter in November 1973, just 20

months after launch. The flyby gave us the first closeup color pictures of Jupiter and the moons Ganymede and Europa, as well as important measurements of the planet's intense magnetic field and particle environment. *Pioneer 10* also tried out a special type of slingshot maneuver that accelerated the spacecraft and changed its trajectory, a trick that was vital for the later missions.

Pioneer 11 reached Jupiter in 1974, taking close-up pictures of its famous Red Spot and hitherto unseen polar regions. The spacecraft then used a gravity assist to redirect it to Saturn, becoming our first visitor to the sixth planet in 1979. At Saturn, *Pioneer 11* had a wild ride, venturing close to the rings and nearly hitting the small moon Epimetheus (to be fair, mission planners didn't know it was there) and discovering other small moons and rings. *Pioneer 11* was also the first spacecraft to take close-up pictures of Saturn's largest moon, Titan, which you hear more about later in the chapter.

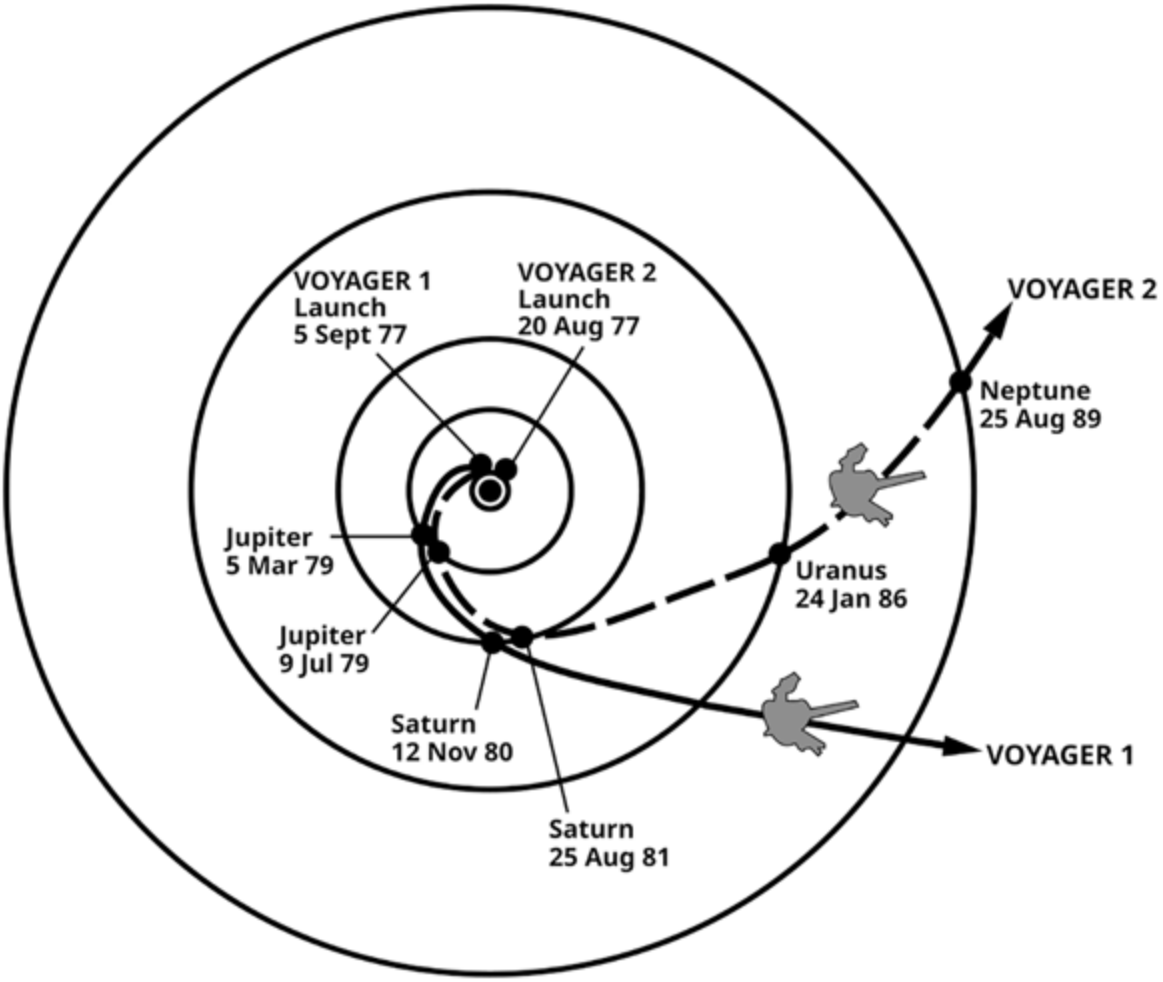


TIP The *Pioneer* missions also carried a carved message to any alien races that might one day find either spacecraft as they wander far out among the stars. For more, look in Chapter 17.

Voyaging farther and deeper



REMEMBER For many, the *Voyager* missions are the epitome of deep space exploration. Together, the *Voyager 1* and *2* spacecraft duo reached all four giant planets (see Figure 13-2), including Uranus and Neptune for the first time (*Voyager 2* only). Both spacecraft have now entered interstellar space and, incredibly, are still sending back data. They will celebrate their 50th birthdays in 2027.



Credit: NASA/Wikimedia Commons/Public domain

FIGURE 13-2: The Grand Tour of the outer solar system, undertaken by the *Voyager 1* and *2* spacecraft between 1977 and 1989.

Voyager 1 launched two weeks after its sibling, *Voyager 2*, but on a faster trajectory and so reached Jupiter and Saturn first. At Jupiter, *Voyager 1* made the surprising discovery that the innermost large moon, Io, was volcanically active. It also returned the first clear photographs of another moon, Europa, showing that its bright icy surface was crisscrossed in mysterious dark cracks.

As it passed close to Jupiter, *Voyager 1* then emulated the trick of *Pioneer 11*, using the giant planet's gravity to redirect toward its next encounter, with Saturn. There, *Voyager 1* made a close flyby of the giant moon Titan, using radio waves to penetrate through the atmosphere and reveal its true size.



TIP Using an infrared spectrometer (refer to Chapter 3) to measure gases, *Voyager 1* found that Titan is rich in chemicals that could be ingredients or "building blocks" for life. (More on that topic later in this chapter.)

Voyager 2 also flew by Jupiter and on to Saturn, confirming the earlier findings of *Voyager 1*. Making a second gravity-assist at Saturn, *Voyager 2* became the first terrestrial spacecraft to reach Uranus, 19 times farther from the Sun than the Earth. Little was known about the planet and its moons until *Voyager 2* returned the first close-up pictures and data, and it remains the only spacecraft to have visited the Uranian system.

Following a third heroic gravity slingshot at Uranus, *Voyager 2* finally reached the outermost gas planet Neptune in 1989. Neptune's system proved to be different yet again from Jupiter, Saturn, and Uranus; encircled with dark dusty rings unlike the bright, icy rings of Saturn. Neptune's largest moon, Triton, also yielded surprises, including geysers of nitrogen.



REMEMBER It's easy to get Saturn's moon *Titan* mixed up with Neptune's moon *Triton*. *Titan* is an unusual name, since it refers to a race of 12 giants (confusingly, including Saturn) rather than to a single mythological being. *Triton* is easier — a mythological merman and son of Neptune, the sea god. Triton also sounds like "trident," the three-pointed spear that Neptune carried.

Orbiting Jupiter: Galileo

The *Pioneer* and *Voyager* missions had opened our eyes to the wonders of the outer solar system, flying quickly through and snapping tantalizing glimpses of the planets, rings, and moons (see *Astronomy For Dummies* by Stephen P. Maran and Richard Tresch Fienberg or *Space*

Exploration For Dummies by Cynthia Phillips and Shana Priwer (both Wiley) for more). However, scientists wanted to know more.

Jupiter is the closest and biggest gas planet, with four large but very different moons. Questions quickly arose: What was erupting on Io? Why was the surface of Europa so young? How deep do the colorful atmospheric bands on Jupiter extend? A new mission — named *Galileo* after the discoverer of the four large moons — was sent to find answers.



REMEMBER In 1995, *Galileo* (Figure 13-1c) became the first spacecraft to orbit Jupiter, dropping a probe into the giant planet's atmosphere that successfully measured the composition. Despite a raft of technical problems, *Galileo* survived for eight years, before being intentionally destroyed by a final plunge into the gas giant's atmosphere. During its mission, *Galileo* made stunning discoveries about the planet and its moons. For astrobiology, the most significant of these were the findings that both Europa and Ganymede have water oceans inside (see later in this chapter).

Running rings around Saturn: Cassini–Huygens

Just as *Galileo* was the first spacecraft to orbit Jupiter, *Cassini* (Figure 13-1d) became the first to orbit Saturn, in 2004. Saturn's radiation environment is less intense than Jupiter's, so *Cassini* worked well until finally running low on fuel in 2017, and was guided to a fiery death, burning up in Saturn's atmosphere.



REMEMBER Like *Galileo*, *Cassini* carried a parachuting probe onboard, this one named *Huygens* after the Dutch astronomer who discovered the moon Titan in 1655. Unlike the *Galileo* probe that plunged into Jupiter, *Huygens* was not dropped into Saturn itself, but rather onto the surface of Titan.

Galileo's Moons

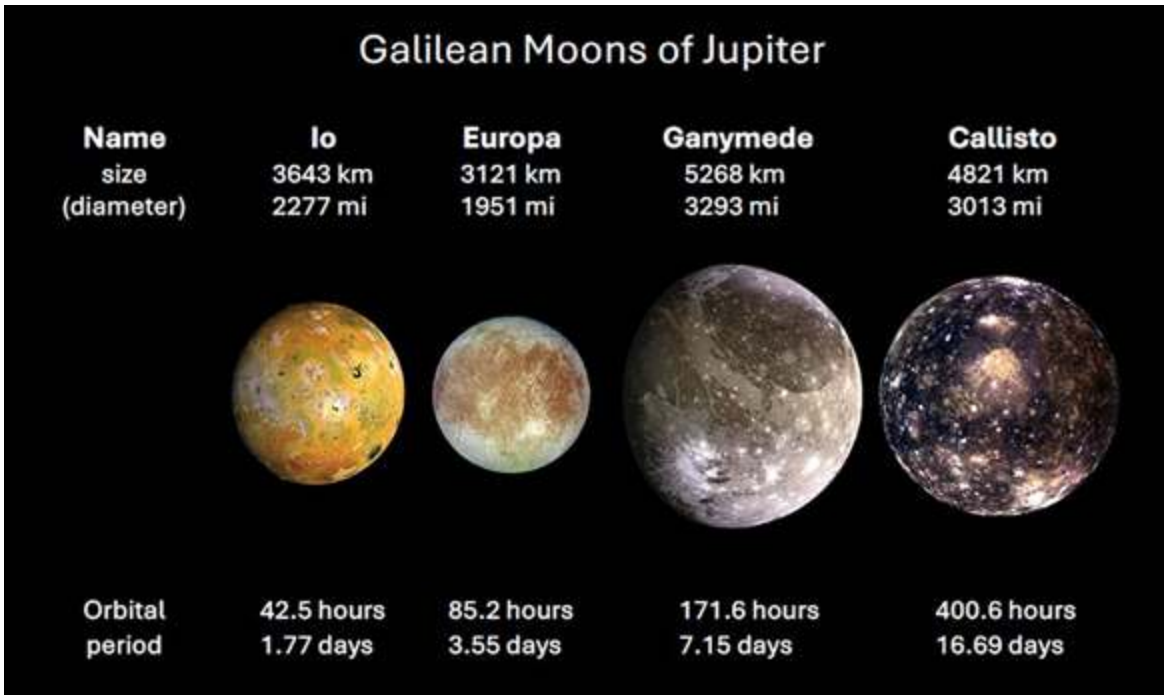
The missions to the outer solar system were truly eye opening, revealing the giant planets and their moons in never-before-seen levels of detail. Scientists were amazed at just how different the various moons were.



TIP Figure 13-3 shows the four large moons of Jupiter side-by-side (in reality they are very far apart). These are also known as the *Galilean satellites*, after their discoverer (refer to Chapter 2). You can see right away how different they appear:

- **Io:** Closest to Jupiter. Surface colored with vibrant reds, browns, and black rings with strong evidence of volcanic eruptions.
- **Europa:** Second from Jupiter and smallest of the "big four." Bright icy surface with few craters, overlaid with rusty-colored patches and lines.
- **Ganymede:** Largest of the Galilean moons. Darker, older surface than Europa with evidence of both substantial cratering and geophysical activity.
- **Callisto:** Farthest from Jupiter. Mostly very dark surface with abundant cratering that has ejected fresher, bright icy material.

How then can we interpret the huge differences between members of the same "family," which presumably formed at the same time and from the same materials? To answer that, you need to understand how heating affects their histories. There are two important sources of internal heat: (i) radioactivity and (ii) tides, and I'll look at each in turn.



Credit: NASA/Public domain

FIGURE 13-3: Galilean moons of Jupiter (to scale).

Heating the mixture: Radioactivity

During the initial formation of a planet or moon, a mixture of rocks, ices, and metals binds together under gravity in a process known as *accretion* — think of throwing cake ingredients into a mixing bowl. This undifferentiated ball of stuff is known as a *protoplanet*, and includes traces of some radioactive substances — forms of chemical elements that are unstable and partially disintegrate over time, releasing heat energy. Although this energy source slowly wanes, it can still be very important in heating the interiors of bodies that don't get a lot of tidal heating (see the next section). If the bodies are also large, they will take a long time — millions to billions of years — for all the heat to escape.

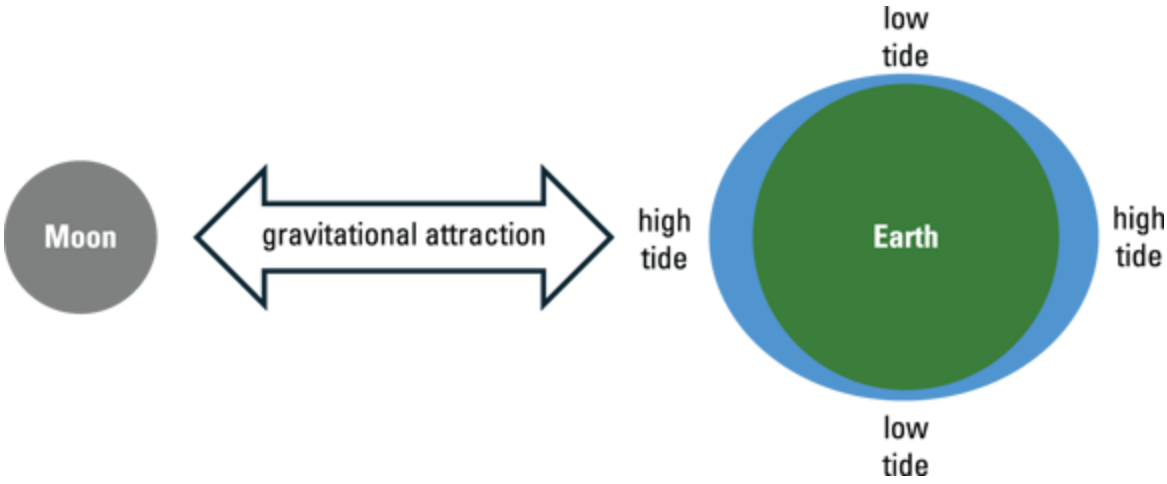
Kneading the dough: Tidal forces

On the Earth, we think of tides as the twice-daily pattern of rising and falling sea or lake levels experienced in coastal areas. You may also remember that tides are caused by the tug of our Moon (and Sun) on the Earth's water (see Figure 13-4), which causes the water to bulge toward and away from the Moon as the Earth spins on its axis.

But what about on other planets and moons that have no water on the surface? In fact, tides are experienced everywhere in the solar system where two bodies interact by gravity. Some tides are stronger and some are weaker, depending on the sizes and separations between the two bodies.



REMEMBER Tidal forces on the moons close to giant Jupiter and Saturn are extremely strong — enough that the solid rock and water ice comprising them is kneaded like bread dough. This causes them to warm up inside in a process known as *tidal heating*.



Credit: Author

FIGURE 13-4: Schematic diagram of tidal forces between the Earth and Moon.



TIP At Io, Jupiter's innermost large satellite, tidal forces are 20,000 times stronger than the tidal forces of the Moon on the Earth. These are thought to be able to lift the entire surface by up to 100 m (330 ft)!

Baking the cake: How heated moons change

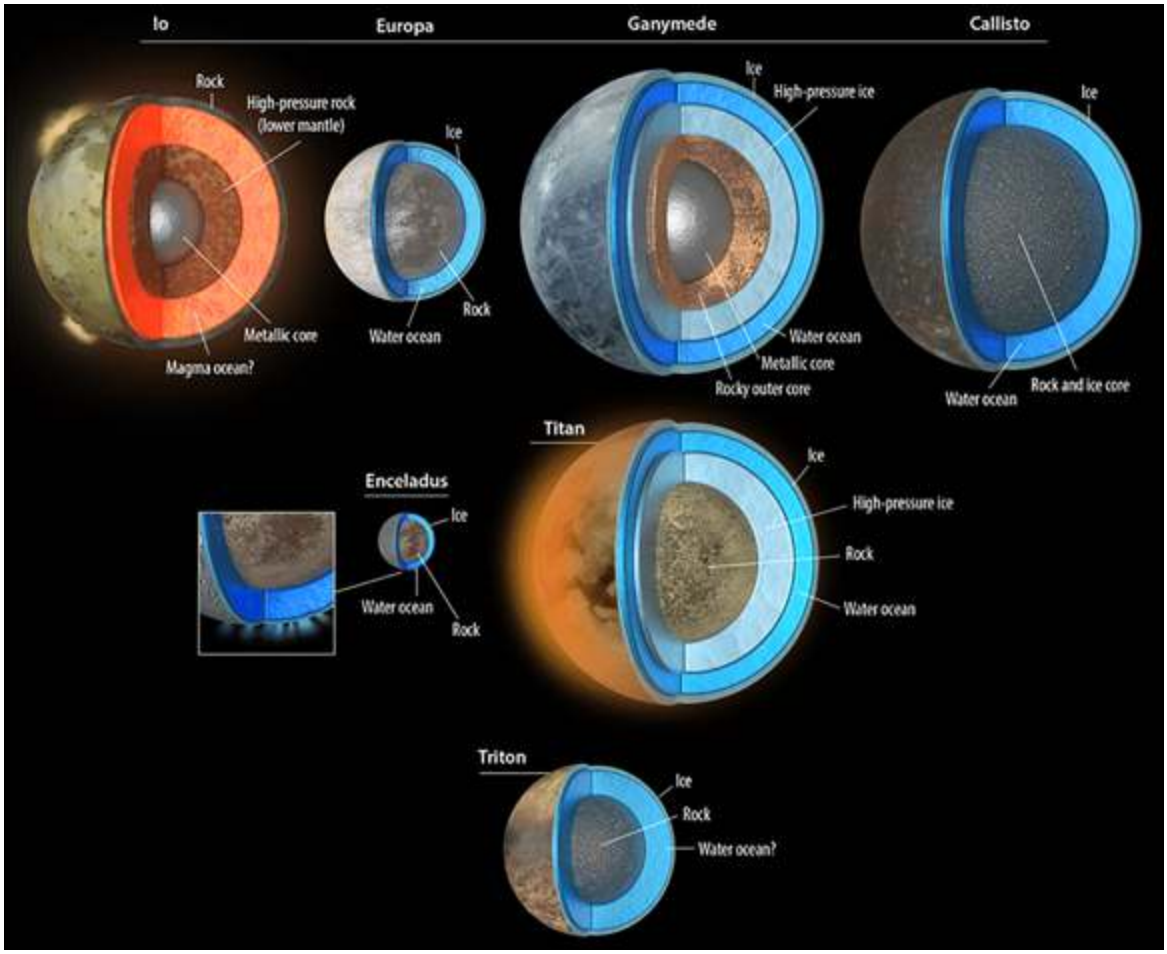
Now that you've seen how the initial cake-batter of planets and moons comes together and gets heated up by radioactivity and tidal forces, let's

see what the result is. Heating causes several things to happen, which I'll use to explain the differences among the four Galilean moons:

- **Devolatilization:** Lighter elements and molecules (*volatiles*), such as water, can be vaporized if the heating is extreme enough. They evaporate from the surface and escape into space — bad news for water-based lifeforms. This is the fate of poor Io, the most tortured of Jupiter's companions. Virtually all of Io's water and light elements escaped long ago, and now it continues to erupt with heavier sulfur-rich substances, creating the colorful reds and yellows on the surface. If you imagine an over-cooked, dried out pizza — that's Io.
- **Differentiation:** When the heating is less extreme, the rocky and icy materials melt rather than vaporize, and different materials separate into layers depending on their density. Denser substances sink downwards as the moon becomes molten inside, forming a heavy core of iron at the center surrounded by rock. The less dense water ice melts, and a watery or slushy mantle results, overlaid on top with a solid crust — picture a frozen lake in winter with an icy crust, watery interior, and rocky bottom — this is the second satellite, Europa (see Figure 13-5). Ganymede is also differentiated, but its greater size and gravity leads to ice both above and below the ice, due to high pressures. Callisto, the furthest of the four, is only partially melted with a layer of ice and water, but mostly undifferentiated toward the core, like an icy snowball chock full of rocks.
- **Magnetic fields:** It's no surprise that a watery ocean can have some salt dissolved, which comes from the rocks that the water is in contact with. A salty ocean can conduct electricity well, so as the moon circles Jupiter and feels Jupiter's strong magnetic field, a process called *induction* causes electric current to flow in the ocean, and a weak magnetic field results. This is important because if we can detect the "induced field," it's strong evidence that there's an ocean. This is how the internal ocean on Europa was first discovered. Note that Ganymede also has a magnetic field, but a permanent

rather than an induced one, caused by circulation of liquid iron in its core (as on Earth).

So far in this chapter, you've seen how the outer solar system was explored and data gathered, followed by the theory, modeling, and understanding that evolved to explain the observations. Now you're ready to see what that implies for life in some of these "ocean worlds" in the next sections.



Credit: Chuck Carter and James Tuttle Keane/Keck Institute for Space Studies

FIGURE 13-5: Interiors of "ocean worlds" in our solar system.

Europa

REMEMBER In 1999, the new field of astrobiology was rocked by results from the *Galileo* spacecraft showing evidence for a water ocean inside Europa. Although this had been suspected since at least the *Voyager* era, the finding of an induced magnetic field, due to a salty ocean sloshing around inside the moon, provided confirmation and changed the course of astrobiology. While continuing to search for life on Mars, NASA also began to plan new missions to the "ocean world" moons.

After a sustained campaign by planetary scientists, the *Europa Clipper* spacecraft (see Chapter 21) was launched in 2024 to answer many of the questions left by *Galileo* when its mission ended in 2003. Let's look at some of those high-level questions that *Clipper* is set to answer.

Cracking up

As you saw earlier, Europa is covered in dark, rust-colored wavy lines that meander across its surface like the crayon scribblings of a preschooler (see Figure 13-6a). On closer examination, those colored bands — and many thousands of narrower ones — appear to be deep trenches or fractures in the crust, sometimes with clearly raised edges like dikes around a levee on Earth.



(a) (b)

Credit: (a) NASA/JPL-Caltech/SETI Institute/Public domain (b) NASA/JPL/University of Arizona/Public domain

FIGURE 13-6: Close up of the surface of Jupiter's moon Europa showing geological features: (a) red-colored cracks; (b) plate-like slabs of ice, known as *chaos*.



TECHNICAL STUFF The culprit for this cracking is thought to be the tidal forces I discussed earlier. As Europa orbits Jupiter, it is squeezed first in one direction, then another, with the net effect of opening and then closing cracks in the surface. When the cracks are open, slushy water erupts out onto the surface but instantly freezes. Over time, this builds up the distinctive cracks, surrounded by the raised dikes where the water "lava" has oozed out and then frozen.



TIP These cracks are important, not just for understanding the geophysics of Europa's surface, but also — you guessed it — for astrobiology. The cracks may be places where liquid water has penetrated the solid crust and lurks very close to the surface, ready to erupt. That means we could drill just a short distance and access water from the deep ocean to look for traces of life.

Even if it's too far to drill, the dikes of frozen water surrounding the cracks may also be excellent places to search for life. Here, microorganisms may be preserved and not long exposed to the radiation of space, providing a good chance of detecting intact biological material. There may even be photosynthetic organisms inhabiting the near surface ice, living in watery pores. For a sci-fi glimpse at what could be living in Europa's cracks, see Chapter 19.

Chaos



REMEMBER In your house, *chaos* may mean that the living room is in need of a good tidying up. However, c*haos* on the surfaces of planets and moons — especially Mars and Europa — are regions of giant,

jumbled-up blocks of rock (Mars) or ice (Europa). The scattered blocks near to each other on the surface of Europa seem to have similarly shaped edges, looking as if the original surface was broken up into huge chunks like pieces of a giant jigsaw puzzle (but not an easy one to reassemble).

Several dozen chaos regions, or potential chaos regions, have been identified on Europa in images from the *Galileo* spacecraft (see Figure 13-6b). Their defining characteristic is a landscape of wide, tall ice blocks surrounded by lower-lying, smoother ice. Think of a floating ice sheet on Earth that has broken up, the pieces have floated around in the ocean, and then become refrozen again into an ice pack, towering above the newer ice layer.



The formation of chaos regions is not well understood at present. One possibility is that a subsurface lake of liquid water formed due to heating from below, and then a portion of the crust collapsed into the lake. The pieces of ice crust then floated around and refroze back into a solid surface.

You may now have an idea why astrobiologists are so excited about the messy chaos regions on Europa. Along with the cracks mentioned above, chaos terrains are places where liquid water may be hidden just under the surface, providing a great place to drill into to search for ocean-loving organisms. The scientific excitement over the cracks and chaos has led to plans for a future lander, *Europa Lander*, with sensitive, life-detecting instruments — see Chapter 21.

Enceladus

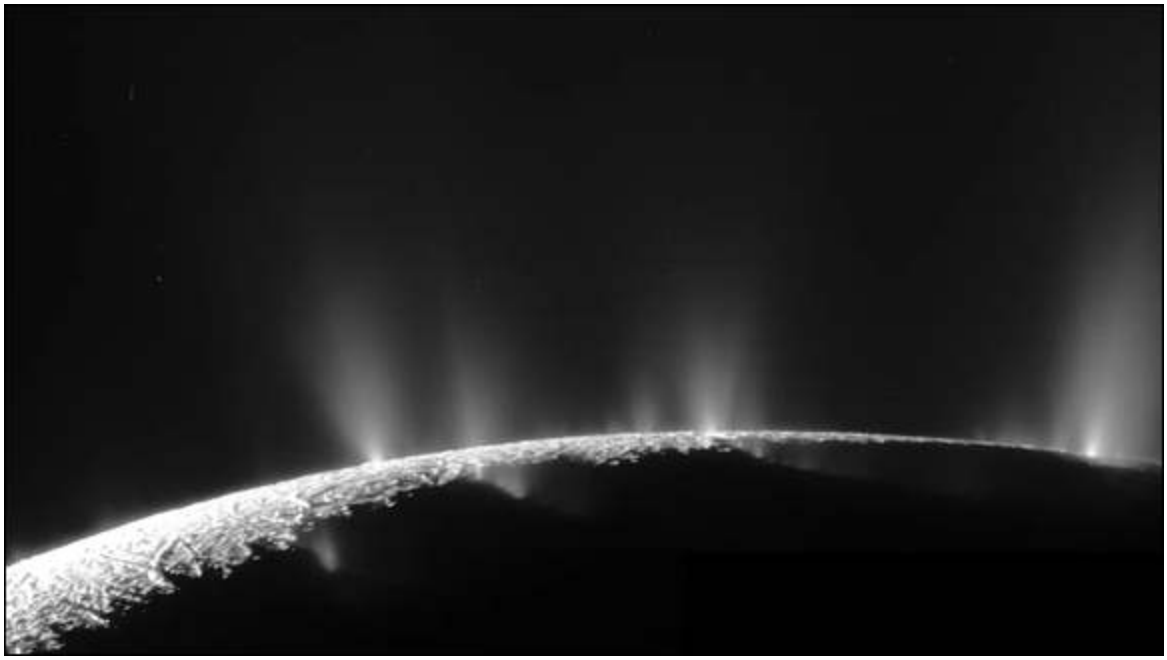
Saturn's moon Enceladus is only 504 km (314 miles) in diameter but has had an outsize impact on the field of astrobiology. As far back as the *Voyager* flybys of Saturn in 1980-1981, Enceladus was flagged as a curious character. Instead of orbiting Saturn through an airless vacuum

of empty space, Enceladus trails a mist of water droplets, that spread out into a vast donut around Saturn almost 1 million km (600,000 miles) wide. By the time *Cassini* reached Saturn in 2004, this "E-ring" was already a prime target for investigation.



REMEMBER During close flybys of Enceladus in 2005, instruments on the *Cassini* spacecraft detected strange activity near the moon, including distortions in the magnetic field near the south pole. By November that year, the cameras had spied plumes of water erupting from cracks near the south pole and shooting hundreds of kilometers into space (see Figure 13-7).

This dramatic discovery led to changes in the planning of the mission, as *Cassini* was subsequently targeted to make more flybys of the "little moon that could" at different distances, some passing as low as 48 km (30 mi) above the surface — a quite spectacular feat of astro-navigation.



Credit: NASA/JPL/Space Science Institute/Public domain

FIGURE 13-7: Plumes of water seen erupting from the south pole of Enceladus into space.



TECHNICAL STUFF During these flybys, *Cassini* sampled the spray of water, "tasting" it with various instruments (imagine opening your mouth as you pass under a water sprinkler) and found they contain some salt, some sand grains, and some soot, as well as frozen water and other condensed gases and minerals. The various minerals and sand detected also indicate that the ocean has a rocky floor, and isn't sandwiched between two pure water ice layers that could keep it sterile.



TIP These discoveries clearly categorize Enceladus alongside Europa as a second "ocean world" with a warm ocean inside that could be great habitat for life — if it is able to develop there in the first place (refer to Chapter 5). There are already plans being made for a trip back to visit Enceladus — see Chapter 21.

Titan



REMEMBER Whereas Enceladus is diminutive, Titan is the opposite — the second-largest moon in the solar system, barely 74 mi (118 km) smaller than Ganymede. Titan is also remarkable for being the only moon in the solar system with a dense atmosphere, with a weather system similar to Earth, having rainfall, wind, rivers, and lakes.

However, on Titan — almost ten times farther than Earth from the Sun — the surface temperatures are much colder than Earth (-180°C, -292°F). Therefore, water on Titan's surface is frozen as hard as rock on Earth. Likewise, its rainfall, rivers, and lakes are not water but liquified methane — the gas used for home heating and cooking on Earth —

falling from the atmosphere. Like antifreeze, methane can stay liquid at temperatures where water is already frozen solid.



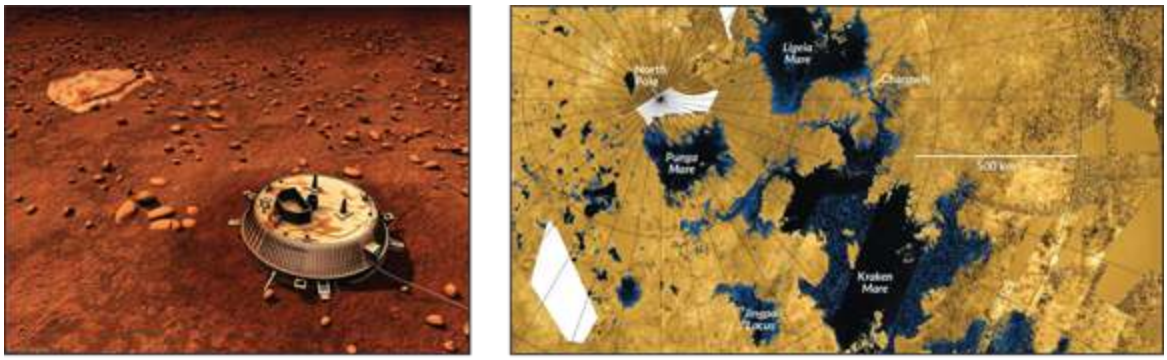
Methane is a *hydrocarbon* chemical, a compound containing atoms of the elements *carbon* and *hydrogen*. In fact, methane is the simplest possible stable hydrocarbon, with one carbon atom surrounded by four hydrogen atoms (chemical formula: CH_4).

Hydrocarbons are incredibly important in biology, with all the key molecules of life — amino acids, lipids, nucleobases, sugars — all largely composed of carbon and hydrogen. Therefore, the presence of methane is very significant, since it can be a building block for making those larger biomolecules — like a Lego brick used to build a Lego house.

Lakes and seas

Due to the cold atmosphere — with plentiful liquified methane along with ethane (methane's chunkier cousin) — scientists predicted that lakes, seas, and even oceans of these substances would be seen blanketing Titan's surface when *Cassini* and *Huygens* arrived in 2004.

However, when *Huygens* landed near to Titan's equator in January 2005 (see Figure 13-8a), it didn't splash down on a chilly methane sea or lake, but rather onto a cold icy plain that may be a dried-up methane seabed. This finally provided clarity that Titan was not, after all, a world awash in a global methane ocean at the present day.



Credit: (a) ESA/C. Carreau/https://science.nasa.gov/mission/cassini-huygens//Public domain/last accessed Oct. 11, 2026 (b) NASA/JPL-Caltech/ASI/USGS/Public domain

FIGURE 13-8: (a) Artist's impression of the *Huygens* probe on Titan's surface. (b) Lakes and seas near Titan's north pole mapped by *Cassini*'s radar instrument.

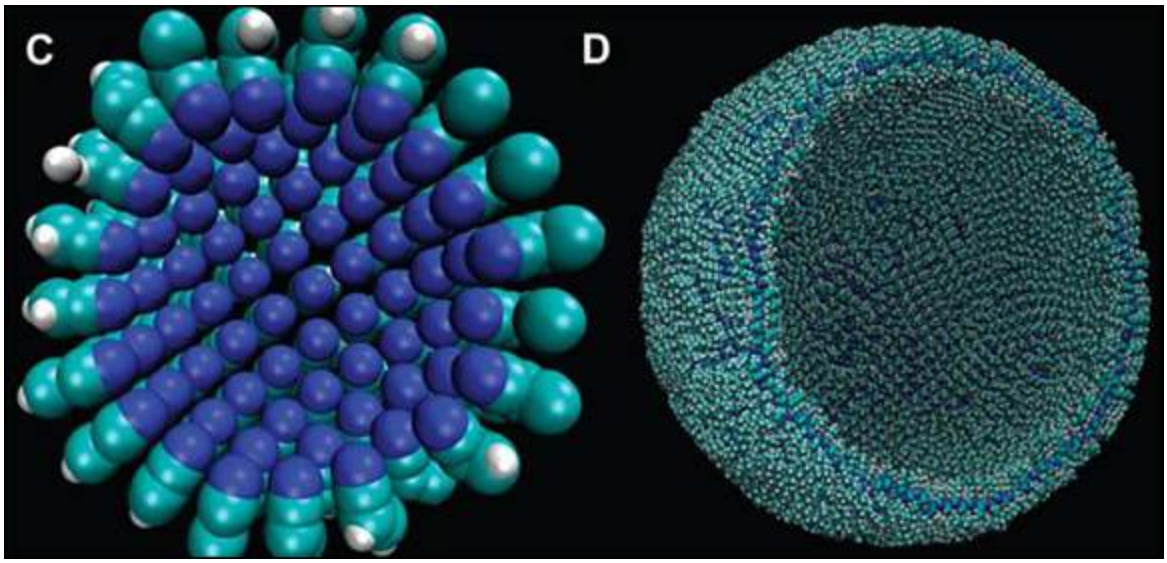
It didn't seem possible that there was not even a puddle of methane on Titan's surface — after all, the atmosphere was raining the stuff. The mystery was finally solved later in 2006 when *Cassini* flew over Titan's north pole and finally began to glimpse the smooth surfaces of methane seas (see Figure 13-8b) using its radar-mapping instrument.



For astrobiology, the methane seas provide a possible habitat for exotic life, life that would be very different from life in Earth's seas. For starters, any lifeforms would need to cope with extreme cold (–180°C, –292°F), so even the hardiest psychrophiles (refer to Chapter 9) found on Earth — with their watery cells — would freeze solid. The whole process of osmosis — moving key chemicals into and out of the cell through pores (refer to Chapter 4) would need to work in an entirely different way.

But what if it could? A group of Cornell University scientists have proposed that Titan sea life might be able to construct cell walls by reversing the usual structure found on Earth, with the hydrophilic ends of the lipids (cell wall bricks) sandwiched in the middle instead of on the outside as in terrestrial cells. If you can imagine wearing your waterproof rain jacket inside out, then you get the idea. They dubbed

these novel cells *azotosomes* — meaning cells made of nitrogen-containing compounds (see Figure 13-9).



Credit: Stevenson et al. 2015/with permission of American Association for the Advancement of Science - AAAS

FIGURE 13-9: Titan azotosomes proposed by Cornell University, composed of nitrogen-containing molecules of acrylonitrile. Left: a single-layered structure (*micelle*). Right, a double-layered structure (*vesicle*).

Could these "azotosomes" really exist to encapsulate life in methane seas? A key first step would be to try to make these in a laboratory — but no one has (yet) tried to do that. Or instead, we can go to Titan and see if nature has solved the problem, sending a boat or submarine to Titan's seas with a package of life-detecting instruments (see Chapter 21).

Interior ocean

On Titan's surface water is frozen solid. But deep inside Titan, things warm up (remember the tidal heating?) and scientists wondered if Titan — like Enceladus and Europa — could also have a deep watery ocean inside.



TECHNICAL STUFF As the *Cassini* mission progressed, it gathered data about how the moon's shape was changing as it orbited Saturn. If Titan was even a little slushy inside, it would show deformations as it moved closer and farther from Saturn — like a water balloon rolling on a table top. Eventually these shape changes were found, so Titan joined the exclusive club of "ocean worlds."



REMEMBER So — like Europa and Enceladus — Titan has the potential to host an ocean biosphere, with aquatic life swimming inside, oblivious to the far-distant Sun. The fact that Titan has both surface methane seas *and* an internal water ocean makes it the only world we know of with *two* different types of seas — even the Earth can't make that claim. How cool is that?

Other Moons and Dwarf Planets

Although Europa, Enceladus, and Titan are currently the best-known ocean worlds aside from Earth, other bodies may also harbor internal oceans. If confirmed, these would further expand the potential for aquatic life in the solar system. Let's look at a few of these possibilities.

Getting salty: Ceres

Ceres may be the closest ocean world to the Sun (other than Earth). When discovered in 1801, Ceres was the only known object orbiting the Sun in the gap between Mars and Jupiter — a region we now call the *main asteroid belt*. It was initially classified as a new planet, but after the later discovery of many more small objects in similar orbits, they were all demoted to *minor planets*, or *asteroids*. Today, Ceres is categorized as a *dwarf planet,* but don't expect that this won't change again — science is always on the move.



REMEMBER The *Dawn* spacecraft mission orbited and explored Ceres from 2015 to 2018, greatly revealing this small (960 km, 550 mi) and relatively unknown world. Its measurements are compatible with Ceres being mostly solid, but perhaps having a dense layer of muddy brine inside, and who knows? Maybe some organism might find it a perfect home.

Sibling rivalries: Ganymede and Callisto



REMEMBER Ganymede — the largest moon in the solar system, and one of the four large moons of Jupiter— is also host to an internal water ocean (see Figure 13-5). Modeling suggests that Ganymede's ocean is probably the largest body of liquid water in the entire solar system — and yes that includes even the Earth!



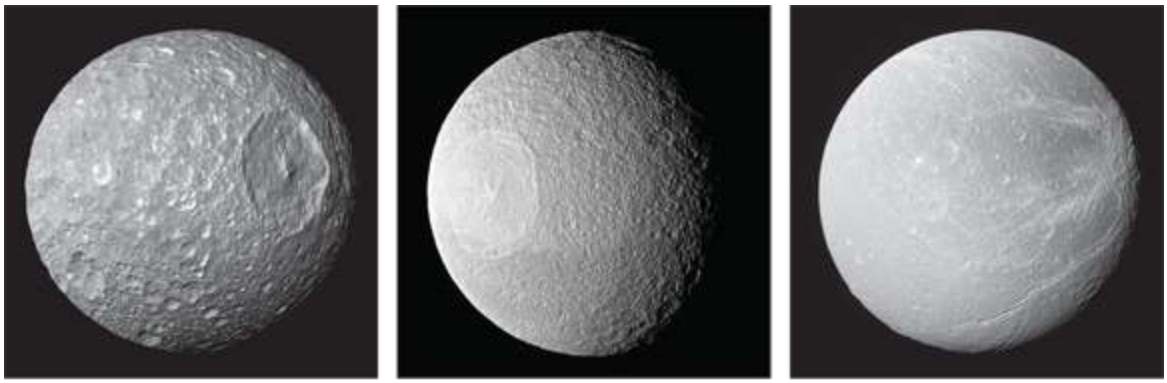
TIP Some calculations indicate that Jupiter's fourth and farthest large moon, Callisto, also hosts a water ocean inside (as depicted in Figure 13-5). However, the evidence for a Callistan ocean is much less solid (pun intended) than for Ganymede, since Jupiter's heating may not be enough to prevent poor Callisto from freezing solid, from core to crust. Further measurements of Callisto's gravity and magnetic field from ESA's upcoming JUICE mission (see Chapter 21) should help to settle the question.

Warm-hearted: Mimas, Dione, and Tethys

Saturn's moons Mimas (396 km, 246 mi), Tethys (1,060 km, 660 mi), and Dione (1,123 km, 697 mi) — see Figure 13-10 — are all much smaller than their big brother, Titan. Therefore, heat can escape much more easily, and after billions of years since their formation they should

have had plenty of time to cool off and freeze solid like a homemade juice pop.

However, they are all closer to Saturn than Titan and have orbits that incur some tidal heating. Mimas (whose giant crater Herschel makes it resemble the fictional Death Star in the Star Wars movies) is especially susceptible to this, orbiting just outside the main rings and even closer to Saturn than Enceladus. Tethys and Dione, although further out, are also larger, meaning that any heat is retained more easily. All have curious orbital wobbles or structural deformations that mean that their interiors are not easy to know for sure, so for now they remain "candidate ocean worlds" as well.



Credit: (a) NASA/JPL-Caltech/Space Science Institute/Public domain (b) NASA/JPL-Caltech/Space Science Institute/Public domain (c) NASA/JPL/Space Science Institute/Public domain

FIGURE 13-10: Moons of Saturn: (a) Mimas; (b) Tethys; (c) Dione.

The furthest fountains: Triton

Neptune's moon Triton (not to be confused with Saturn's moon Titan) is an oddball (see Figure 13-11a). Triton is by far the largest (1,353 km, 851 mi) irregular moon in the solar system, meaning that its orbit is not aligned with the equator of its host planet (Neptune), and it also doesn't orbit in the same direction that the planet spins. This is a good clue that Triton was captured into orbit by Neptune, rather than having formed with the planet like the Galilean moons of Jupiter, for example.



REMEMBER Triton is also thought to be another closest ocean world, with a watery layer about 150 km (90 mi) deep buried beneath a similar thickness of water ice crust. Although Triton's orbit is now circular, and hence without any tidal heating, other mechanisms such as the heat from radioactive elements could maintain its warmth. Sadly, we don't know much about Triton or the Neptune system, being only visited by *Voyager 2* in 1989. Let's hope that another mission to Neptune is just over the horizon.

Life at the edge: Pluto, Charon, and the KBO crowd

Pluto, the famously demoted ninth planet (now categorized as a dwarf planet, like Ceres), along with sibling Charon (see Figure 13-11b), was visited in 2015 by the *New Horizons* spacecraft. As with Triton, some models show that these distant worlds may be large enough to hold onto internal heat from radioactivity and have internal water layers. Their potential for life is even less well known.



TIP Larger Kuiper Belt Objects (KBOs) such as Eris and Makemake may also have internal water oceans. Clearly, there is plenty of potential for life far beyond the inner solar system, and it will take many more missions to check out all these exciting leads.



Credit: (a) NASA/NASA-JPL/USGS/Public domain (b) NASA/APL/SwRI/Public domain

FIGURE 13-11: (a) Neptune's moon Triton photographed by *Voyager 2* in 1989. (b) Pluto (lower right) and Charon imaged by the *New Horizons* spacecraft in 2015.

Stevenson, J., Lunine, J. I., & Clancy, P. (2015). Membrane alternatives in worlds without oxygen: Creation of an azotosome. Science Advances, 1(1), e1400067. DOI: 10.1126/sciadv.1400067.

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Chapter 14

Life in the Clouds

IN THIS CHAPTER

- **Learning how life on Earth uses the aerial environment**
- **Probing for exotic life on Venus**
- **Envisaging a floating ecosystem on Jupiter**

We think of life as being at home in the sea, on land, and underground: but what about in the air? Some planets in our solar system either have inhospitable surfaces (I'm looking at you, Venus) or no surfaces at all (Jupiter and the gas giants), but this hasn't deterred suggestions that life could literally be blowing in the wind.

In this chapter, you learn about some of these ideas in more detail and can make up your mind for yourself whether they are realistic. But I begin with some supporting evidence from life on Earth that lives mostly up in the air.

Surfin' the Breeze: Aeroplankton

You might think that living is a breeze some of the time, but for lifeforms known as *aeroplankton* that's a way of life.

So, what is aeroplankton exactly? The term encompasses a number of different types of microscopic life that use the aerial environment in different ways:

- **Spiders and worms:** Properly known as *arthropods* (insects and spiders) and *nematodes* (worms), smaller creatures of these species use the wind as a means of colonizing new habitats and reaching new food sources. Spiders are particularly adept, with some specializing in spinning their spider silk into kite-like structures enabling them to

float miles high into the air. (If this makes you queasy, make sure to wear a mask outdoors).

- **Unicellular microorganisms:** Thousands of species of marine microorganisms, including cyanobacteria and microalgae, are swept up into the atmosphere from sea spray, as well as land bacteria from drying environments. Some of these species have adapted to include the free transportation opportunity into their lifecycles, but many details of the *aerobiome* remain to be understood.
- **Viruses:** Viruses (refer to Chapter 4), being very small, are inevitably transported in the air and make great use of this opportunity to spread — think of cold and flu viruses inhabiting the nasal passages and throat as a great place to be coughed and sneezed to the next victim. However, since it's still debatable whether viruses are truly alive (they cannot survive without a host), it seems unlikely that viruses would be found living airborne on another planet without a larger host organism.

To sum up: research is still needed to determine whether there are truly any forms of life that exist entirely in the air, as opposed to spending some fraction of their life cycles there.

Venus

Despite being named in many cultures for the goddess of love, life on Venus would be far from friendly to humans. Recall the *greenhouse effect* I discuss back in Chapter 5 — the blanketing effect that the Earth's atmosphere has on the planet, blocking heat (infrared rays) from escaping to space and warming the surface by about 40°C (104°F). Without the "greenhouse," we'd all be frozen solid.

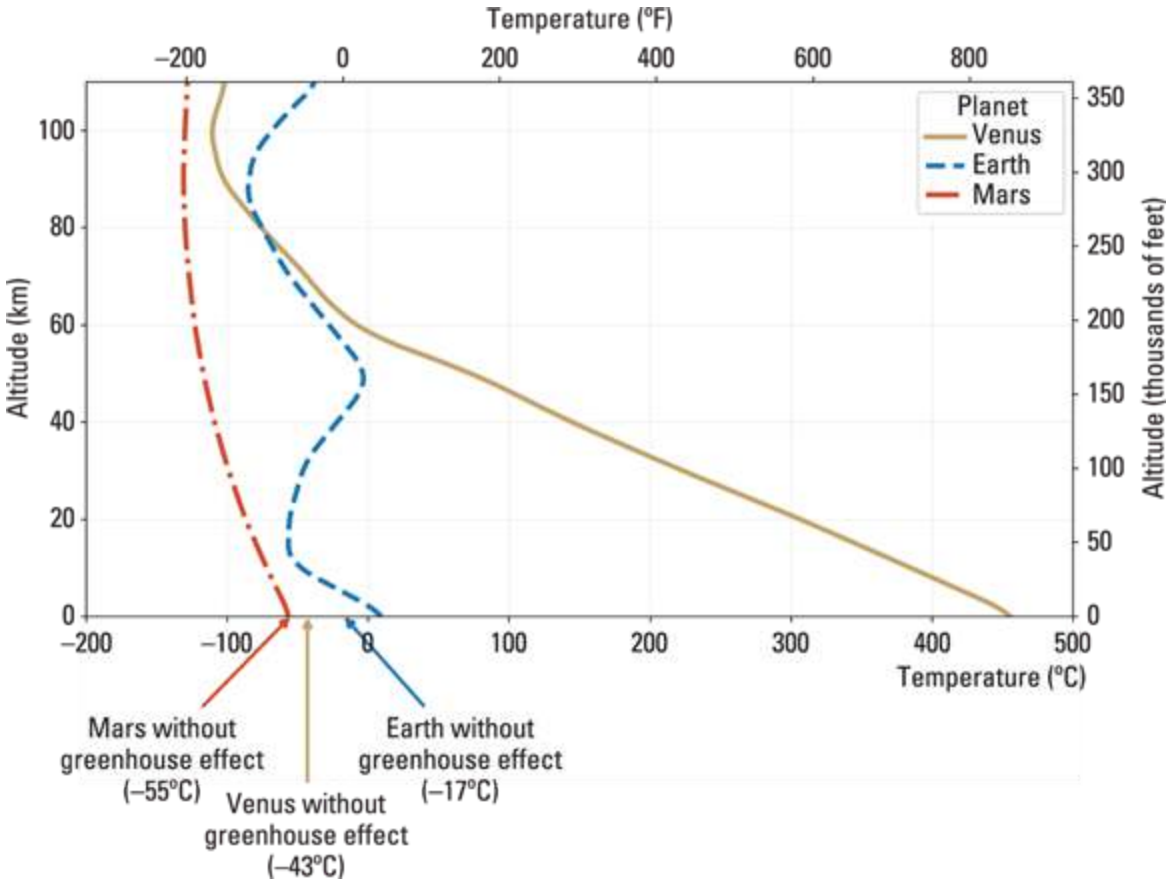


On Venus, however, a much denser atmosphere takes the greenhouse warming to another level — warming the surface by up to 500°C (932°F) and reaching a temperature that would melt lead

(see Figure 14-1). With such an extreme surface environment, reaching the Venusian surface with a surviving spacecraft took many attempts by the Soviet Union in the 1960s through 1980s until finally successful with *Venera 7* in 1970.

Livin' the high life

Not long after the true nature of Venus's oven-like surface became known during the early years of the space age, scientists began to speculate that more congenial conditions for life might exist above the surface.



credit: Author

FIGURE 14-1: Atmospheric temperature profiles of Venus, Earth, and Mars compared.



Temperatures above 50 km altitude (30 miles) begin to cool off into a more copacetic range, reaching 30 to 80°C (86 and 176°F). Despite also being a region where sulfur dioxide (SO_2) combines with carbon dioxide and water to form clouds of sulfuric acid (H_2SO_4), these conditions are similar to those in the hot springs of Yellowstone National Park (see Chapter 9) where *thermoacidophiles* are happily thriving.

This led Harold Morowitz and Carl Sagan to propose in 1967 that Venus's high atmosphere might be a home for floating, balloon-like organisms several inches in size or larger. These would live by capturing trace water from the clouds, and absorbing nutrients wafted up as ash from the surface.

In one scenario, life could have evolved on the surface of Venus in the far distant past, before the entire planet became overheated. Then, as the planet warmed up over many millennia, life would have had time to evolve and adapt to living off the surface, in the temperature clouds. Another possibility is that life was seeded into Venus's clouds from elsewhere in the solar system — an example of the panspermia hypothesis (refer to Chapter 10).



A possible clue to the presence of airborne life in Venus's clouds is the mysterious *UV absorber*. This is a currently unknown ingredient of the atmosphere that absorbs UV sunlight (see Figure 14-2a) — exactly as might be expected for certain forms of life using UV as an energy source, although there are also other plausible explanations that don't involve life. One of the goals of the upcoming *DAVINCI* mission (see Chapter 21) is to better understand this curious phenomenon, and maybe even tell us whether it is due to floating Venusian life.



(a) (b)

Credit: (a) JAXA/ISAS/DARTS/Kevin M. Gill/Flickr/CC BY 2.0 (b) Mike Peel/https://commons.wikimedia.org/wiki/File:Model_of_James_Clerk_Maxwell_Telescope_(JCMT).jpg/CC BY-SA 4.0/last accessed Oct. 11, 2026

FIGURE 14-2: (a) Appearance of Venus in the ultraviolet (UV) seen by the *Akatsuki* spacecraft in 2016. (b) Scale model of the James Clerk Maxwell Telescope (JCMT) located on Maunakea, Hawaii.

Phosphine and ammonia

A more recent frenzy of speculation regarding Venusian life erupted in 2020 when a team led by UK astronomer Jane Greaves announced the discovery of phosphine gas (PH_3) on Venus. Phosphine would be highly unstable in Venus's acidic atmosphere and is present in small amounts in Earth's atmosphere only from the decay of dead organic matter, leading to suggestions that decaying Venusian life could be producing the phosphine there as well.



Greaves's team used two telescopes to make the claimed discovery: the James Clerk Maxwell Telescope (JCMT) on Hawaii (see Figure 14-2b), and the Atacama Large Millimeter-submillimeter Array (ALMA, see Figure 15-8a) in Chile. JCMT is a "single-dish"-type telescope 15 m (50 ft) in diameter; however, ALMA is a much larger array of 66 separate "radio dishes," whose data can be added together to mimic a single large telescope several miles across.

Several problems soon arose with the purported phosphine discovery. The most serious being that other astronomers disputed that the data even showed the presence of phosphine at all, with some claiming that other gases or the complex ALMA data processing were producing spurious signals instead (the debate continues to this day). There is also the problem that phosphine is itself quite toxic to life.



REMEMBER Finally, phosphine is quite abundant in nonbiological settings, such as the atmospheres of the giant planets, where it is understood to be a naturally occurring gas in their hydrogen-rich atmospheres and not a "biosignature."

Floating, Sinking, and Hunting on Jupiter

Speaking of giant planets and life … surely, we can rule out those swirling gas giants Jupiter and Saturn as potential habitats? With their cold, oxygen-less atmospheres replete with racing winds and heaving storms, not to mention a complete lack of solid surfaces, these must not be environments where life could flourish.

Not so fast. In a breathtaking leap of imagination, Carl Sagan and Edwin Salpeter of Cornell University speculated in a 1976 paper that an entire ecosystem could exist in Jupiter's temperate middle atmosphere. They argued that here could be found many of the key ingredients needed for life:

- **Redox pairs:** Chemicals that can react together.
- **Energy:** In the form of lightning and sunlight.
- **Convection:** Air movements to allow mixing of gases and nutrients.

Sagan and Salpeter proposed that Jovian creatures could come in three types (see Figure 14-3):

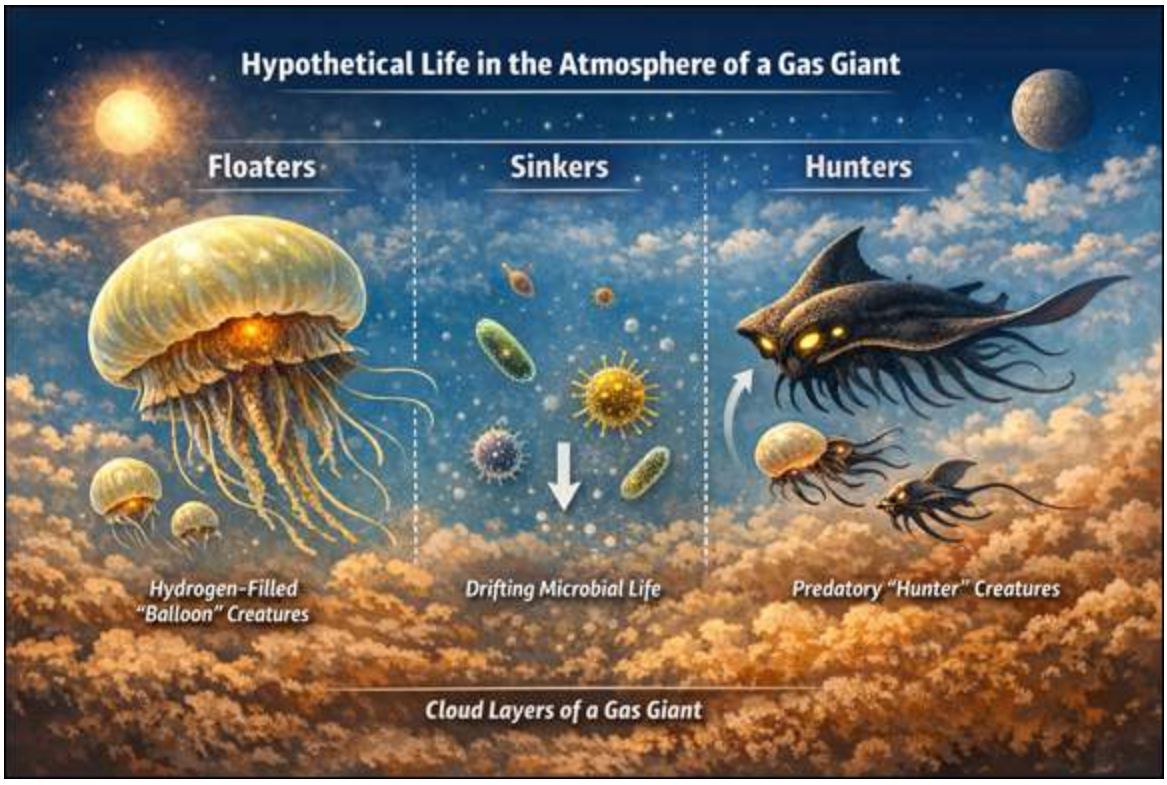
- **Sinkers:** These small creatures would be the base of the food pyramid. Similar to marine plankton on Earth, they would use photosynthesis (energy from sunlight) and chemosynthesis (energy from chemicals) to grow and reproduce.
- **Floaters:** Envisaged as vast (up to a mile in size) floating gas-bag creatures, these jellyfish-like or whale-like creatures would graze on the sinkers through tendrils or baleen filters, modifying their internal pressures to follow the densest food currents.
- **Hunters:** At the top of the food web, hunters are predators that feed on the floaters.



REMEMBER It's worth placing these ideas in context: the publication came at a particular moment when Jupiter had just been first imaged close-up by the *Pioneer 10* and *11* spacecraft (refer to Chapter 13), but before the arrival of the more sophisticated *Voyager 1* and *2* spacecraft several years later. At this point in the mid-1970s, excitement and exuberance were high, but information was still low about the giant planets.



TIP Subsequent missions, including the *Galileo* and *Juno* orbiters of Jupiter, provided no further evidence either for or against the Jovian ecosystem hypothesis, so it remains an open question for now. By extension, such a floating ecosystem could hypothetically exist on Saturn and the countless numbers of gaseous exoplanets as well.



Credit: Generated with AI using OpenAI

FIGURE 14-3: Artistic visualization showing the inhabitants of the Jovian ecosystem proposed by Sagan and Salpeter in 1976: sinkers, floaters, and hunters.

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Part 4

Life beyond Our Solar System

IN THIS PART …

Learning how the chemical elements were formed, and how they joined up to form the molecules that led to life.

Discover the increasing diversity of known exoplanets, worlds outside our solar system, some of which may harbor life.

Find out how scientists are searching for alien radio signals and other possible communications from advanced civilizations.

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Chapter 15

Astrochemistry

IN THIS CHAPTER

- **Learning where the chemical elements of the periodic table come from**
- **Discovering how atoms join up to create prebiotic molecules**
- **Finding out how astronomers can detect complex molecules in space**

In this book so far, the focus has been on understanding life close to home: on the Earth, and in our nearby solar system. Now it's time to venture further afield as we embark on a trilogy of chapters about the possibilities for life beyond our solar system.

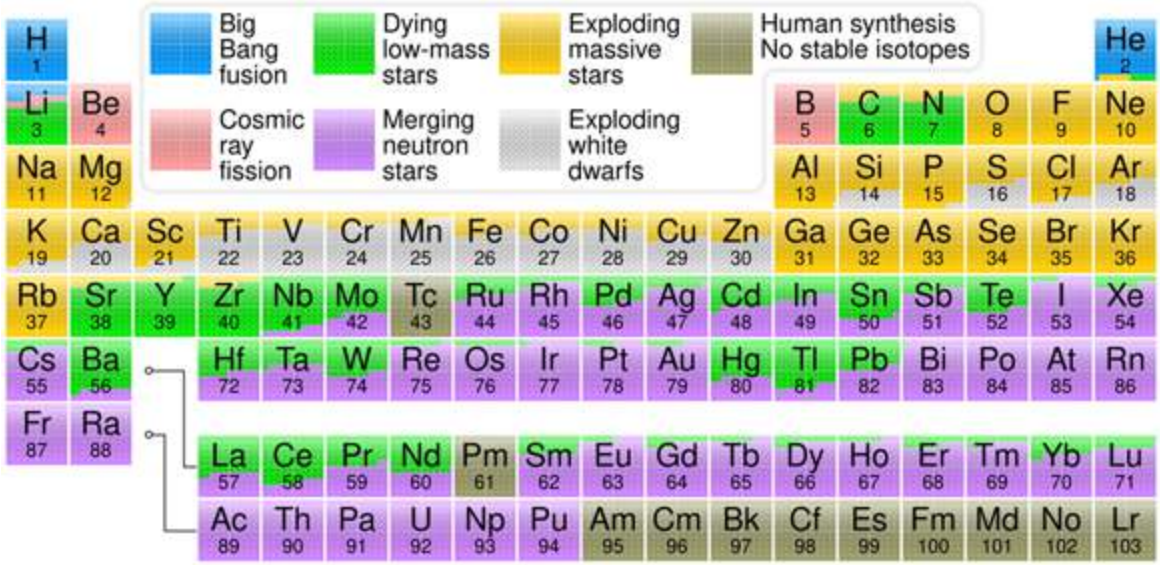
I begin at the beginning: finding out where the elements came from. Next, you learn how the elements combined in space to make molecules, a subject known as astrochemistry. Finally, I discuss the technologies of today and tomorrow astronomers use to investigate the composition of the cosmos.



TIP By the end of this chapter, you'll have learned a lot about the material of the stars and between the stars: material that could be ingredients today for life in our galaxy and across the universe, as we believe it was on Earth.

Building Atoms with Nucleosynthesis

Nucleosynthesis seems like a big, imposing word. But in essence it simply means *making atoms* — the population of the periodic table (see *Chemistry For Dummies* by John T. Moore (Wiley) for more on that topic). I've placed a version of the periodic table below (see Figure 15-1), although with some extra information about where the elements came from.



Credit:Cmglee/Wikimedia Commons/CC BY-SA 3.0

FIGURE 15-1: The periodic table of elements, with added information about their origins.

The Big Bang



REMEMBER Yep, everything started with the Big Bang, the initial explosion that created the cosmos. (For more in-depth insights into cosmology, check out The Origins of the Universe for Dummies by Stephen Pincock and Mark Frary [Wiley].) For our purposes, it's enough to know that all the matter in the universe was once compressed into a very tiny dot, much smaller than a single atom today. Then, for reasons still being worked out, this pinprick of mass and energy exploded around 13.8 billion years ago (see Figure 15-2) to create not only all the matter in the universe, but space itself.

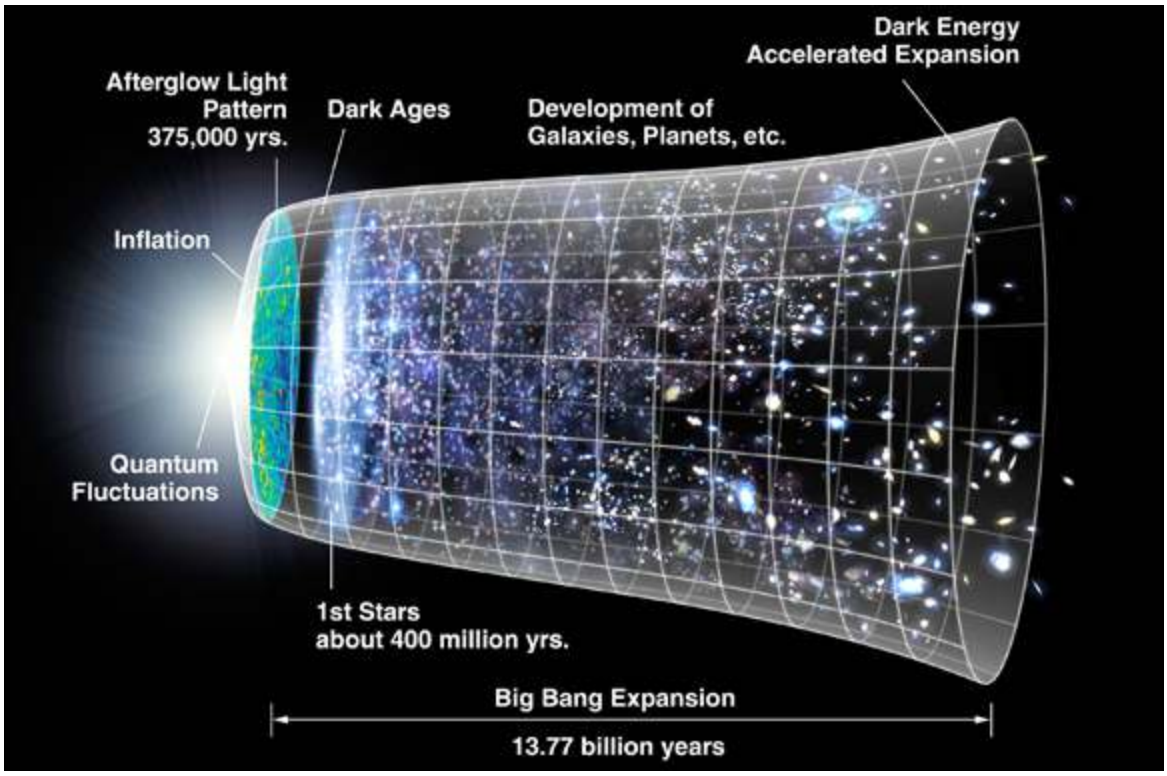


TIP The Big Bang created subatomic particles including protons and electrons, which eventually paired up to create the first atoms — mostly hydrogen, the lightest, and helium, the next up in size. (You can refer back to Figure 15-1 to see where these atoms all fit into the picture as I go along.)

However, you can't do much in the way of building life with just hydrogen and helium: This is a bit like trying to build a cool Lego car using only square and rectangular bricks — there's not much to work with. To add more useful atoms for life's chemistry — carbon, oxygen, and nitrogen especially, something else had to happen. And that something was stars.

Life and death of a star

The life cycle of a star is illustrated in Figure 15-3. Or, I should say *life cycles of stars,* since, depending on their size, stars can have very different lives.



Credit: NASA/WMAP Science Team/Wikimedia Commons/Public domain

FIGURE 15-2: The history of the universe.

For a typical star like our Sun (see Figure 15-3), life begins as a cloud of gas, known as a *protostellar* (or *protosolar* for our solar system) *nebula*. The cloud inevitably has some amount of rotation, and soon begins to collapse, falling inwards due to its own gravity. This creates a rotating, flattened disk, like a spinning record, with a concentration of matter at the center.

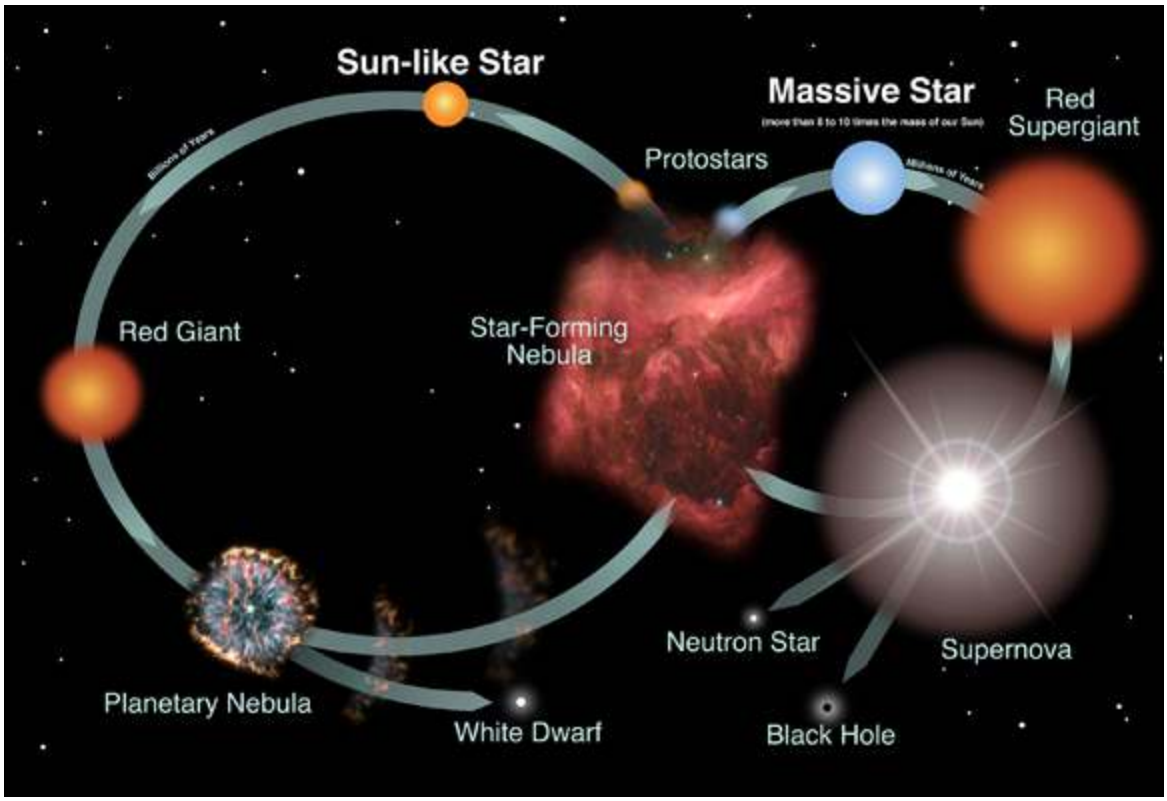
After some time, the central core of the cloud compresses into a dense ball, atoms fuse together under pressure to release nuclear energy, and voila! A new star is shining. The leftover material of the cloud swirls around the newborn star, forming planets, asteroids, and comets.



REMEMBER The first generation of stars after the Big Bang would have been composed almost entirely of the light elements hydrogen and helium. Over the life cycle of the star, these become squeezed together in the process of *nuclear fusion* and become heavier elements, releasing energy in the process. This is one type of *nucleosynthesis* — the formation of new elements.

After the star runs out of energy (about 10 billion years for our Sun) and finally fizzles out and dies (cue the violins), some of its outer envelope is shed into space, replete with heavier atoms from nucleosynthesis during its lifetime.

For much heavier stars than the Sun (right side of Figure 15-3) their life story is quite a bit different. For one thing, they "live fast and die young," like the prototypical Hollywood movie star. Being much larger than the Sun, the pressure at their centers is immense, so they burn through their nuclear fuel much more quickly, in a matter of just a few tens of millions of years.



Credit: NASA/Night Sky Network/Public domain

FIGURE 15-3: Life cycles of stars.

TECHNICAL STUFF Then something even more spectacular happens: After a massive star stops generating heat energy to balance its immense gravity, it collapses abruptly. This causes a final burst of nuclear energy as the remaining light elements are squeezed together into ever-heavier elements such as neon, argon, and potassium — all the way to iron. The infalling material rebounds from the super-heated core, causing a massive explosion that can temporarily outshine the entire rest of the galaxy. Talk about a dramatic death.

REMEMBER These *supernovae* explosions are the main progenitors of the medium-weight elements of the periodic table (see Figure 15-1),

and leave behind a spinning *neutron star,* or even a *black hole* — a mysterious object where time and matter merge together.



TIP Even heavier elements such as gold and lead may also be produced in supernovae explosions, but their main source is now understood to be the mergers of neutron stars, where neutrons are forced onto existing lighter elements under vast pressures to create heavier atoms.

Stellar generations



TECHNICAL STUFF I mentioned that the Big Bang produced mainly the very lightest elements, hydrogen and helium, which would therefore have been the sole possible ingredients of the first generation of stars. But when the first stellar generation had come and gone, the new clouds of leftover matter from stellar deaths and explosions would have been seeded with heavier elements — carbon from low-mass stars, silicon, sodium, and neon from supernovae, and even heavier elements from stellar mergers and other processes.



REMEMBER So, this second generation of stars would have formed from more interesting Lego bricks. This is the story of our solar system: We are composed of heavy elements, including carbon and oxygen, that must have come from an earlier stellar generation. As Carl Sagan aptly put it: “We are all star stuff.”

Obscured by Clouds

After chemical elements form, it isn’t long before they begin to join together to form molecules, the next step on the road toward complexity

and life. Therefore, second-generation and subsequent star systems would have formed from clouds that contained not only heavy elements, but also molecules, greatly accelerating the process of abiogenesis.

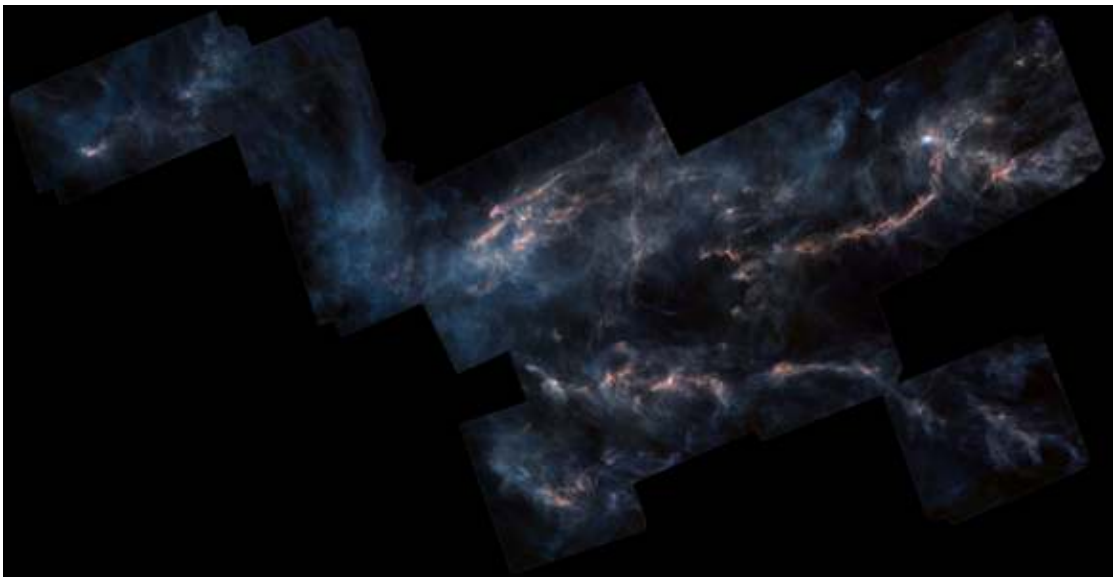


TIP The image in Figure 15-4 shows an example of a dark cloud giving birth to new solar systems: the Taurus Molecular Cloud 1, or TMC-1. TMC-1 is renowned among astronomers due to the incredible complexity of molecules discovered there.



TECHNICAL STUFF Molecules important for life discovered in TMC-1 and other molecular clouds include:

- Simple oxygen-bearing species used by life, such as **water (H_2O), carbon dioxide (CO_2)** and **formaldehyde (H_2CO).**
- Hydrocarbons — molecules containing C and H — ranging from simple **methane (CH_4)** to long chains called **polyynes.**
- Cyanides such as **hydrogen cyanide (HCN), cyanoacetylene (HC_3N)** and even larger variants.
- Amines and imines such as **ammonia (NH_3)** and **methylamine (CH_3NH_2).**

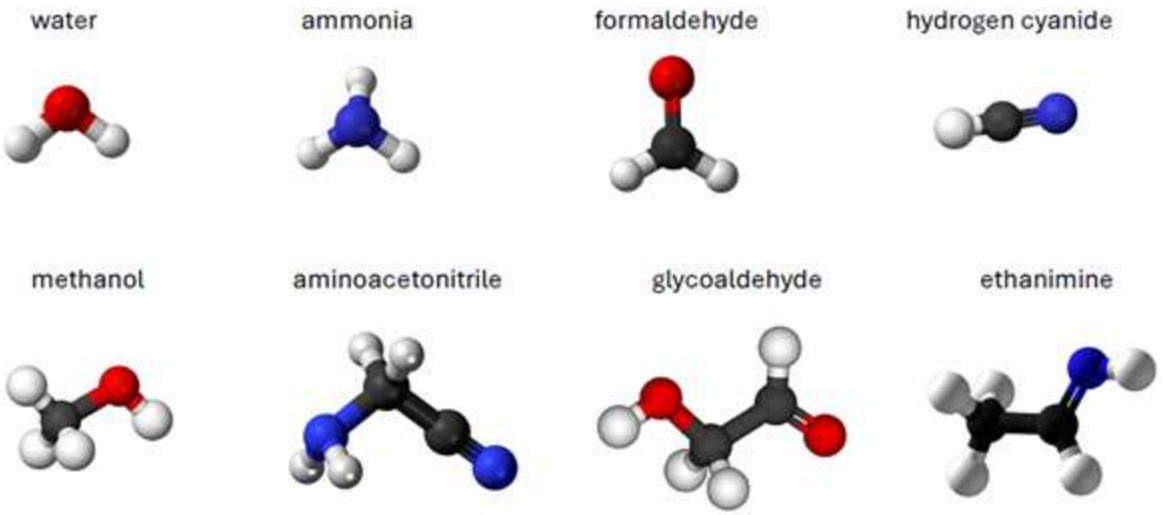


Credit: ESA/Herschel/NASA/JPL-Caltech; acknowledgement: R. Hurt (JPL-Caltech)/CC BY-SA 3.0 IGO

FIGURE 15-4: The Taurus Molecular Cloud (TMC-1) imaged by the Herschel space telescope.

- Complex organics containing oxygen such as **methanol (CH_3OH)** and **acetaldehyde (CH_3CHO).**
- Carbon sheets and rings similar to graphite known as **polycyclic aromatic hydrocarbons (PAHs).**

Figure 15-5 shows some examples of the complex variety.



Credit: Author using elements from Wikimedia

FIGURE 15-5: Examples of complex molecules found in space.



REMEMBER Astrochemists are fascinated by searching for ever more complex molecules in space, since this expands our knowledge of the ingredients that could have helped life get underway. We see these molecules appear again later, after the cloud has collapsed, in the form of comets and carbonaceous asteroids in our own solar system (refer to Chapters 10 and 11).

Now let's take a look at how such molecules are discovered in space by astronomers.

Decoding the Rainbow with Spectroscopy

When we look at an astronomical image, we see many beautiful colors. However, these colors also convey important information, since different atoms and molecules interact differently with different colors of light.



TECHNICAL STUFF Due to their individual electronic structure, atoms and molecules absorb or emit tiny packets of energy, which become transformed into light of different colors. Each atom and molecule has a different electronic structure, so it emits a unique "fingerprint" of energy across the electromagnetic spectrum.

Astronomers can therefore split up starlight into different colors, and by teasing apart the "fingerprints" of different atoms and molecules (like investigating a crime scene), they can decode the individual constituents. This technique is known as *spectroscopy* (see *Astrophysics For Dummies* by Cynthia Phillips and Shana Priwer [Wiley] for more on this topic).

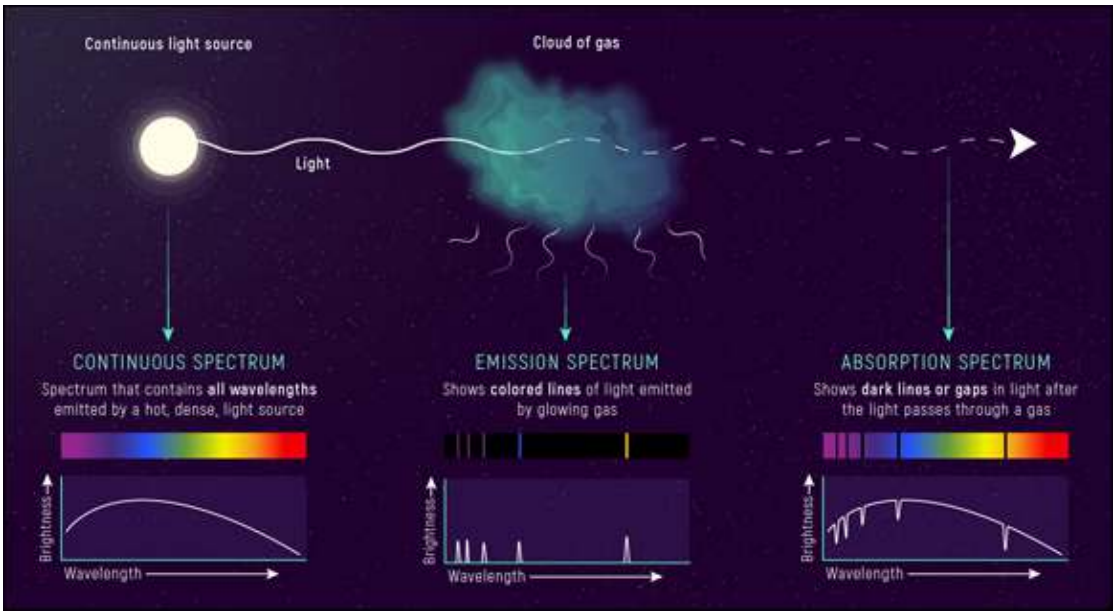


Figure 15-6 shows a graphical depiction of spectroscopy in action. As light from a star passes through a dark cloud, atoms and molecules absorb their "favorite" colors of light, which creates a pattern of dark lines known as an *absorption spectrum* (right). However, the opposite can also occur, where the molecules are heated up to emit packets (*photons*) of light, creating the opposite effect: an emission spectrum.



Although some of these spectral lines are seen in visible light, others occur at longer wavelengths:

- **Ionization lines** occur at the shortest frequencies in the ultraviolet part of the spectrum, when atoms absorb a high energy photon to give up (eject) an electron.
- **Electronic transitions** occur at longer wavelengths in the visible light part of the spectrum, as electrons jump to higher orbits around the atom.



Credit: NASA/ESA/CSA/Leah Hustak (STScI)/Public domain

FIGURE 15-6: Creation of absorption and emission lines in space.

- **Vibrational lines** are found in the longer infrared spectrum, as molecules take up weaker packets of energy to bend and flex.
- **Rotational lines** are found at the longest wavelengths in the radio part of the electronic spectrum, due to molecules taking up energy to spin.

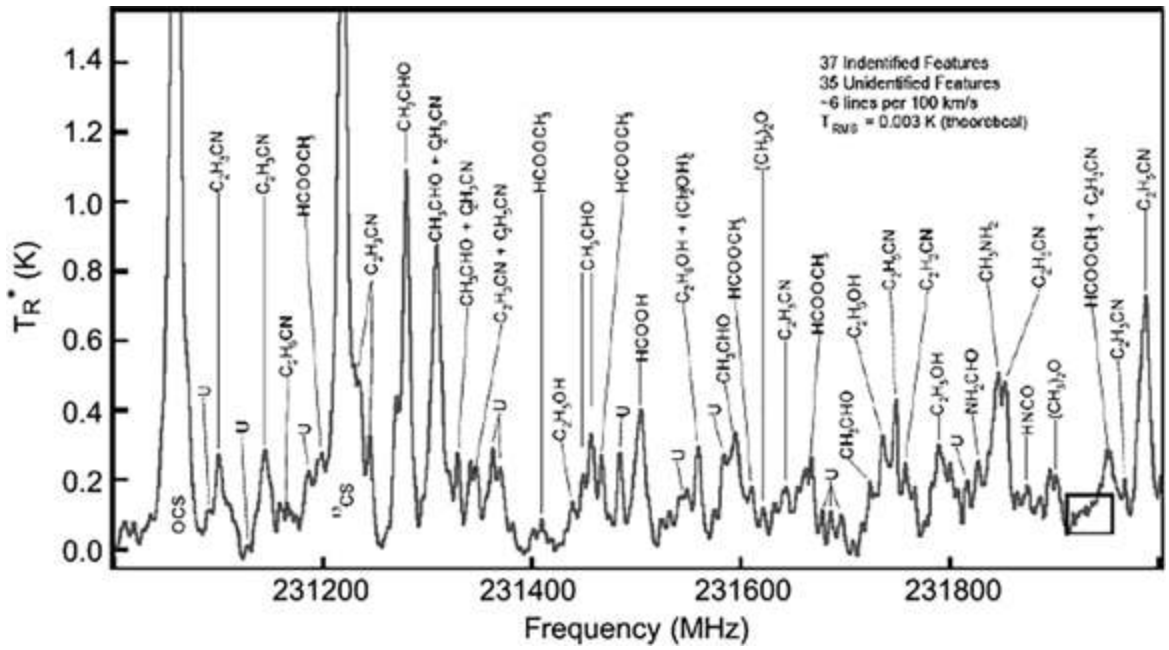


TIP Although all of these spectral lines can be useful to astronomers for decoding interstellar gases, the longest-wavelength rotational lines can be especially useful. This is because radio frequency emissions have the benefit of mostly being unaffected by our atmosphere, and even the intervening dust in space, meaning that we can get a clear view of the sky at radio frequencies, and see the furthest and deepest into space.

Figure 3-2a shows one of the observatories designed to observe the universe at long radio wavelengths: the Karl Jansky VLA telescope array, consisting of 27 antennae (or radio dishes), each 25 m in diameter. These work together as a team, listening in to the weak radio emissions

from dark molecular clouds to discover what molecules are lurking there.

Figure 15-7 shows an example of the radio spectrum data, this one collected from the molecular cloud Sagittarius B2 — SgrB2(N) — near the center of our galaxy. The full spectrum shows emissions from more than 140 different molecules up to 13 atoms in size, including some radio lines that come from as-yet-unidentified molecules (labeled U).



Credit: National Radio Astronomy Observatory/CC BY 4.0

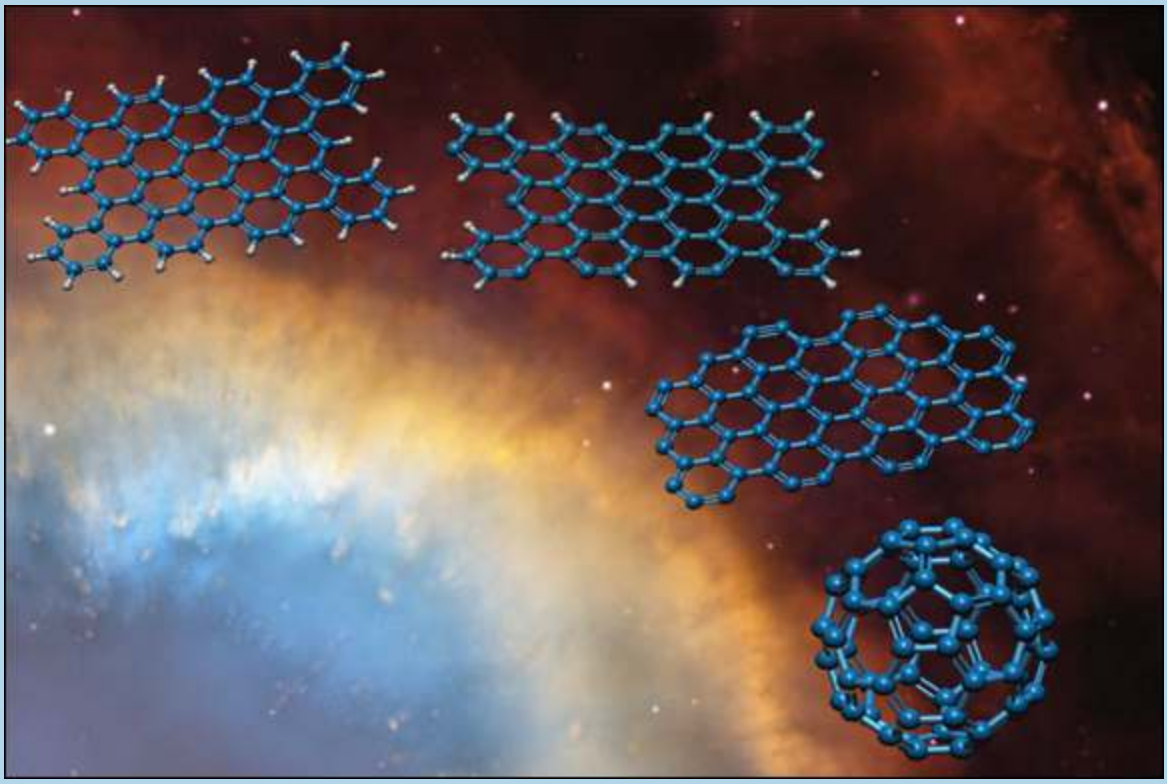
FIGURE 15-7: Radio spectrum from the molecular cloud Sgr-B2(N) showing emissions from different molecules.

Over the past half century or more, astronomers have used radio astronomy to vastly increase our knowledge of molecules in the darkest space. You can read about one unusual example in the sidebar "PAHs and Buckyballs."

PAHs AND BUCKYBALLS

Carbon comes in many forms, including some you already know: graphite (pencil lead) and diamond. Yet another form is graphene, which appears in sheets, where each carbon is linked to three neighbors, forming a hexagonal pattern (see the figure below). In the 1960s and 1970s, several chemists independently predicted that carbon could

theoretically form into a ball with sixty carbon atoms, although the idea was not taken seriously by the wider chemistry community for some time afterwards. That changed in 1985 when a team of scientists discovered how to make C_{60} in the lab, naming the new compound “buckminsterfullerene” after the famous architect Buckminster Fuller, who favored geodesic domes composed of hexagonal shapes. The name is often shortened to “buckyballs,” whereas the larger family of soccer and rugby ball shapes that can be made from pure carbon is now named “fullerenes.” Surprisingly, C_{60} has been found in space, in several types of star and planetary nebulae, making it by far the largest molecule known to exist in space.



NASA/ESA/STScI/IAC/NOAO/NRAO/Public domain

Next-Generation Radio Observatories



Although astronomers have made amazing strides in astrochemistry in the past several decades, further advances always rely on new technology continuously being developed. Figure 15-8 shows some examples of future observatories that will be engines of discovery for astrochemistry:

- **Upgrades to ALMA:** Working at shorter frequencies, the sister of the VLA is the ALMA array in Chile, comprised of up to 66 antennas spread across 16 km (10 miles) of the high Atacama desert (see Figure 15-8a). This remote and dry site makes it one of the best locations in the world for astronomy at microwave frequencies. ALMA is currently undergoing a major upgrade to its receivers that will enable the array to work four times faster than before by the early 2030s.
- **The next-generation VLA (ngVLA):** Following from the success of the VLA, the ngVLA (see Figure 15-8b) will be a much larger radio telescope array with 244 antennas spanning the US states of New Mexico, Texas, and Arizona, as well as northern Mexico. More distant stations will also be located in other states across the continental US, Hawaii, and even in Europe! When the ngVLA begins operations in the 2030s, scientists will have greatly upgraded capability to probe for rare and elusive heavy molecules in dark clouds and stellar envelopes. The ngVLA is expected to be fully operational by 2037.
- **Telescopes on the Moon:** Due to the ever-increasing amount of radio signals on and around the Earth (satellites), it's getter harder every day for astronomers to find a "radio quiet" place to build telescopes and listen to the sky without interference from human radio traffic. The best solution in the long term would be to have a radio telescope on the far side of the Moon, forever blocking the noise from Earth by the bulk of the Moon, and allowing sensitive astronomy to proceed unimpeded. Several designs have been

proposed, including a “Lunar Crater Radio Telescope” (LCRT) and the FARSIDE array. LCRT (see Figure 15-8c) would place a suspended wire mesh framework some 350 m in diameter inside the bowl of a far side lunar crater, in a similar manner to some large radio telescopes on Earth. FARSIDE (see Figure 15-8d) is a different design using an array of 128 antennas distributed over 10 km of the lunar surface to make sensitive measurements of objects at low frequencies, including star-forming nebula, as well as objects on our own solar system.

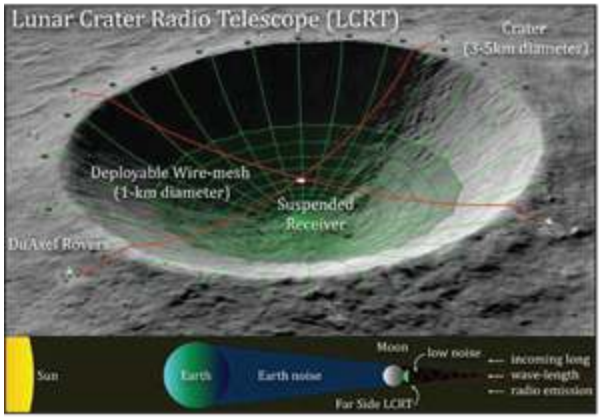
Over the past 30 years one topic has rapidly become the “hottest” growth subject in astronomy: planets around other stars, or exoplanets. In the next chapter, I dive right into this exciting topic and discover what they are.



(a)



(b)



(c)



(d)

Credits: (a) A. Pérez/ALMA Observatory/CC BY 4.0 (b) S. Dagnello, NRAO/AUI/NSF/CC BY 4.0 (c) Saptarshi Bandyopadhyay/NASA/Public domain (d) NASA/Public domain

FIGURE 15-8: (a) The Atacama Large Millimeter-submillimeter Array (ALMA). (b) Drawing of the in-construction next-generation Very Large Array (ngVLA). (c) An artist's impression of the proposed Lunar Crater Radio Telescope (LCRT). (d) The proposed lunar FARSIDE telescope.

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Chapter 16

Habitable Exoplanets

IN THIS CHAPTER

- **Finding out how exoplanets are discovered**
- **Learning the importance of liquid water in the "Goldilocks zone"**
- **Getting to know some of the most Earth-like exoplanets**
- **Discovering atmospheric biosignatures**

Our solar system contains eight major planets, whose names are probably familiar to you, along with a host of minor planets, moons, asteroids, and comets. Until the 1990s, this remained the entire extent of our knowledge of planets in the universe. However, scientists and philosophers had long suspected that there were many other solar systems like our own waiting to be found.

This belief stemmed from the knowledge — beginning during the Copernican Revolution in the 1500s (refer to Chapter 2) — that all the stars in the sky are Suns, and the Sun is just another star. Extrapolating further, if all Suns and stars formed in similar ways from similar materials, why would one out of billions be the only example to have a retinue of planets?



REMEMBER Logically, many, if not most or even all, stars should have planetary systems; however, the ability to detect *exoplanets* (planets orbiting other stars) was extremely challenging and took many advances in astronomical technology to finally become possible.

In this chapter, I begin at the beginning with some philosophical speculations about the "plurality of worlds." I then move on to look at how exoplanets form and the means for their detection, before discussing some notable exoplanets that may even be habitable.



TIP To wrap up, I mention some cutting-edge techniques that astronomers use to find out what their atmospheres are made of.

Dreaming of Many Worlds

On February 17th 1600, the Italian philosopher and polymath Giordano Bruno stood in a town square in Rome, facing a penalty of death. His crime was heresy — speaking out and writing ideas in contradiction to the teachings of the Catholic Church. Among his many "crimes" was the assertion of a "plurality of worlds" — in essence, claiming that the wider universe contained many worlds similar to the Earth.

Reading Bruno's writings today, his words are astonishingly accurate and unambiguous:

> *"There are countless suns and countless earths all rotating round their suns in exactly the same way as the seven planets of our system. We see only the suns because they are the largest bodies and are luminous, but their planets remain invisible to us because they are smaller and non-luminous. The countless worlds in the universe are no worse and no less inhabited than our earth."*
>
> *DE L'INFINITO, UNIVERSO E MONDI (ON THE INFINITE UNIVERSE AND WORLDS)*, GIORDANO BRUNO, 1584

Note that the last statement is a clear endorsement of astrobiology! Although its veracity remains an open question for now.

Although given chances to recant, Bruno refused to change his beliefs, and was burned to death as a consequence. He was perhaps the first to die for (at least in part) a belief in exoplanets, a scientific truth that was unfortunately far ahead of its time, and whose discovery would be

honored four centuries later with a Nobel Prize for two more fortunate scientists.

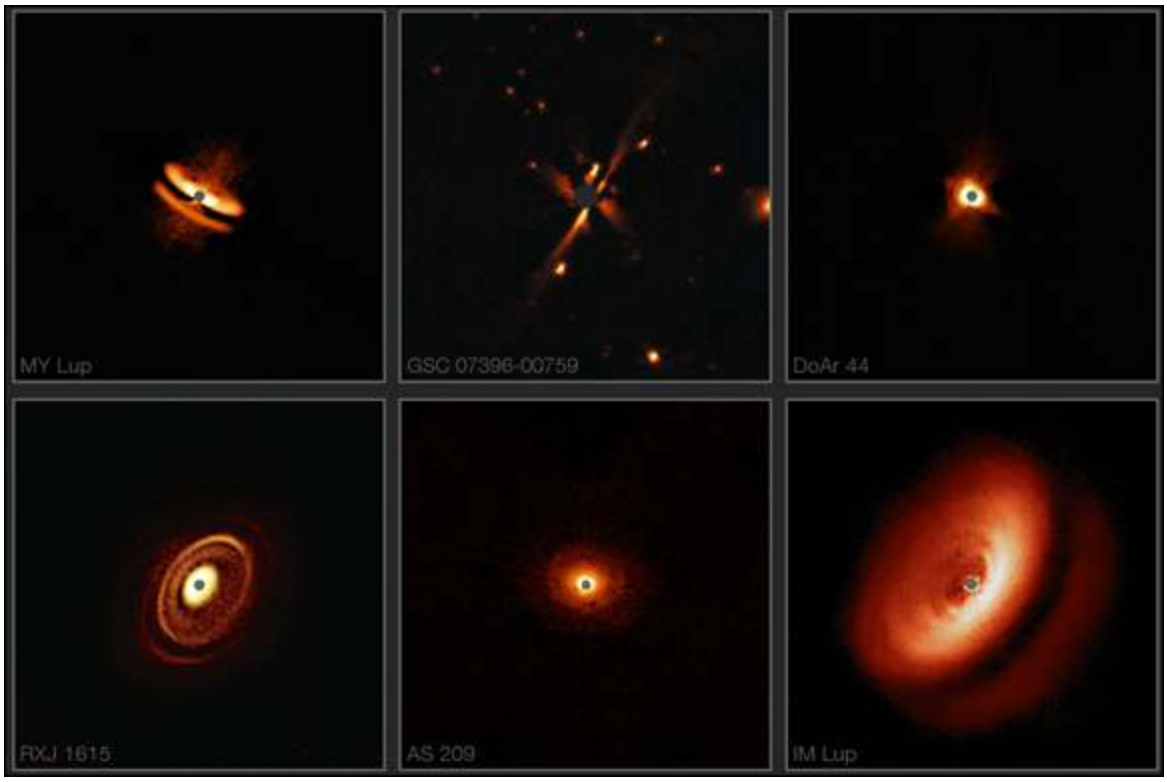
In the next section, I explain how exoplanets are formed.

Spinning Disks into New Worlds



TIP In Chapter 11, you looked at the formation of our solar system, and the formation of other solar systems is expected to take place in a mostly similar way. This begins with the collapse of a gently rotating cloud into a spinning protoplanetary disk, and the subsequent coagulation of material to form a central star (or stars) and retinue of orbiting planets.

Figure 16-1 shows the diversity in appearance of disks at different stages of the process: Less mature disks appear more uniform like a dinner plate, whereas in more evolved disks, the orbiting planets have begun to clear out tracks around the star where they have gobbled up all dust and gas in their path. Some stars also exhibit jets, where material is being blown away along the direction of their magnetic poles.



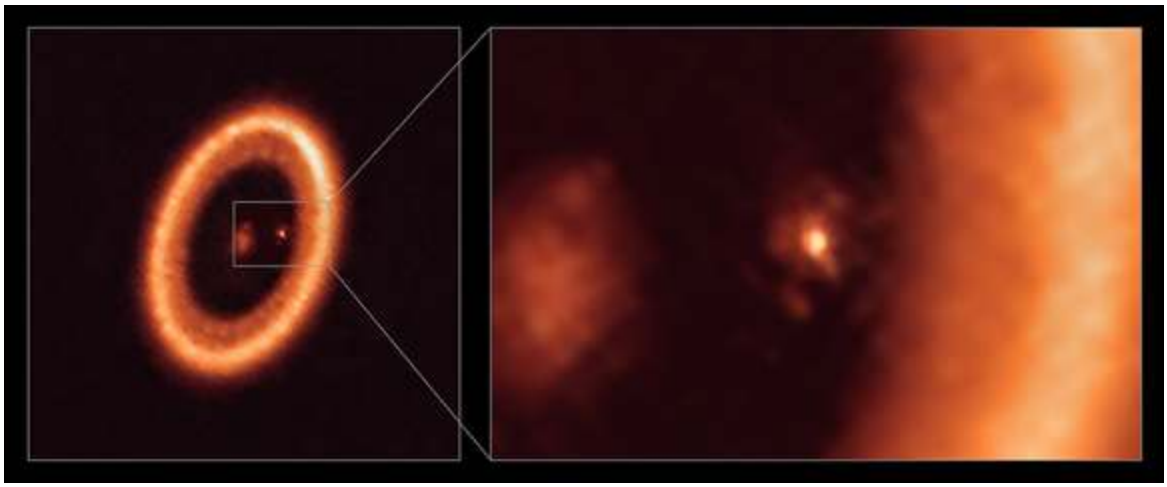
Credit: ESO/H. Avenhaus et al./E. Sissa et al./DARTT-S and SHINE collaborations/CC BY 4.0

FIGURE 16-1: Images of different protoplanetary disks taken with the SPHERE instrument on the European Southern Observatory's Very Large Telescope (VLT).

In some nearby disks, we can even see the planets themselves. An example is shown in Figure 16-2 of the PDS 70 system, which has two distinct nascent planets, and one even shows its own tiny "moon forming" disk.



REMEMBER These incredible images confirm that our theoretical speculations about the formation of our own solar system eons ago are going in the right direction.



Credit: ALMA (ESO/NAOJ/NRAO)/Benisty et al./CC BY 4.0

FIGURE 16-2: Image of the PDS 70 system from ALMA telescope of the ESO.

Detecting Exoplanets



TIP Now that you're acquainted with why and how exoplanets form, I'll explain how they are detected. I begin with recounting the first exoplanet discoveries, and then explain the current methods used for detection.

Unexpected survivors



REMEMBER In 1992, radio astronomers Aleksander Wolszczan and Dale Frail announced the first widely trusted detection of exoplanets, but this "solar system" was vastly different from our own. Rather than sedately orbiting a Sun-like star, the two detected planets were found in the unlikeliest place imaginable: orbiting a pulsar, the spinning core of a dead star that has exploded in a supernova — akin to finding a house still standing near a giant bomb crater.



TIP The method Wolszczan and Frail used was indirect and proved to be groundbreaking, setting the stage for later discoveries. Rather than trying to image planets directly, they instead looked for the influence of the planets on the star, which is an easier problem.



TECHNICAL STUFF Pulsars emit strong beams of radio waves along two directions, their magnetic poles, which are often offset from the north and south poles of their rotation axis (this is also true on Earth). As they spin, the two beams sweep across the sky, much like a lighthouse, except with radio waves rather than visible light. Being massive objects, their rotational period is extremely stable, and the duration between pulses can be as precise as the best atomic clocks on Earth. However, if planets are orbiting nearby, they make the pulsar "wobble," throwing off the timing of the pulses in a regular way.

By precisely analyzing the variations of the pulse interval, Wolszczan and Frail deduced that at least two planets were in orbit. The two planets they discovered (a third was found in 1994), with masses around four times that of Earth, are the hardy survivors of a cataclysmic explosion. They must have been greatly changed as they were blasted by successive waves of material from the exploding star, losing quantities of their own surface material and leaving the cores, which today are cold and almost certainly lifeless.

In contrast, the next exoplanets to be detected were utterly different.

Hot Jupiters!



REMEMBER While astronomers were still reeling from unexpected discovery of the "pulsar planets," yet another surprising exoplanet was announced. Michel Mayor and Didier Queloz of the Geneva

Observatory had used a similar trick of indirect detection on a Sun-like star (51 Pegasi), detecting a near-Jupiter sized planet orbiting the star in a mere 102 hours, or 4.2 Earth days. For comparison, this planet (51 Pegasi b, now officially named *Dimidium*) is seven times closer to 51 Pegasi than Mercury is to the Sun and so has a surface temperature of nearly 1,800°F (977°C) — hot enough to melt lead.

The discovery of Dimidium was followed soon after by the detection of more of these "hot Jupiters" — large, low-density planets orbiting close to their parent stars. After initial calculations confirmed that such objects were indeed resilient to evaporation, the bigger question became — how did they form in the first place? Their very existence seemed to contradict our models of solar-system formation based on our own system, with small, rocky planets made of dense materials (rock and iron) close to the Sun, and large planets replete with lighter elements (hydrogen and helium) further away.



TIP To this day, the debate continues about how these "hot Jupiters" form, including the possibilities that they either formed in their present locations, or else formed much further from their stars and migrated inwards later due to frictional "drag" with the remaining material of the original disk.

Wobbling stars

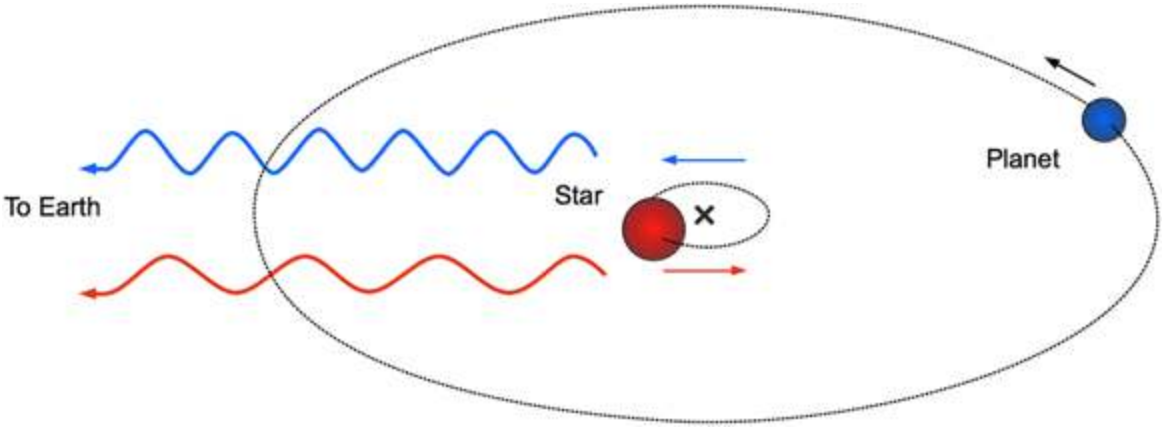


REMEMBER The method that Mayor and Queloz used to detect Dimidium (and previously for the pulsar planets) became a standard workhorse technique for many more exoplanet detections that followed. This *radial velocity* method is illustrated in Figure 16-3. As the planet orbits the star, it also pulls the star to move in a small circle through their mutual gravitational pull. This is like a parent swinging a child around by the arms: The child moves in a large

circle (the planet's orbit) while the parent also rotates in a smaller circle.



Seen from the Earth, the parent star appears to move from side to side as well as back and forth along the line of sight. According to the laws of physics, any light emitted from an object in motion will change its color slightly along the direction of motion: redder as it moves away, and bluer as it approaches. This is the famous "Doppler effect" that causes an ambulance siren to rise in pitch as it approaches and then lower in pitch as it recedes.



Credit: Tenefifi/Wikimedia Commons/CC0 1.0

FIGURE 16-3: Radial velocity (or Doppler) method of exoplanet detection.



Mayor and Queloz used the spectral lines in the starlight — a fingerprint pattern of dark and light lines due to atoms in the star's atmosphere (see Chapter 15) — as a yardstick. The precise wavelengths of the lines are known in a laboratory — any deviations must be due to the Doppler effect of motion. Sure enough, when the starlight was analyzed precisely enough, the spectral lines were seen to be moving rhythmically to higher and

lower frequencies in a steady, periodic fashion. Each complete oscillation of the starlight corresponded to one orbit of the planet.



REMEMBER More than 30 years later, this radial velocity or Doppler technique has now been used to discover over 1,000 exoplanets in a series of increasingly sensitive searches.

Although powerful, the Doppler technique has some inherent limitations. One is that the technique cannot distinguish between a more massive planet orbiting nearly perpendicularly to the line of sight and a less massive planet orbiting in a plane closer to the line of sight. The technique also doesn't give information on the physical dimensions of the planet, meaning that its density (an important clue to composition) is also undetermined.



TIP Therefore, although the Doppler technique is useful for making initial detections and finding orbital periods, we need additional information to learn more about planet's nature.

Game of shadows



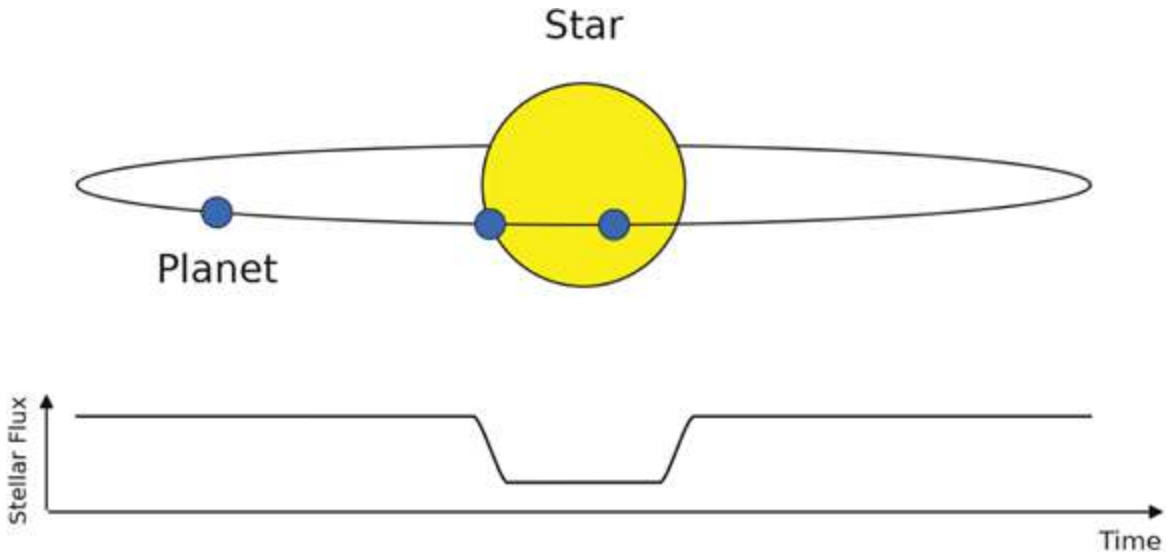
REMEMBER Since 1999, a second method for exoplanet detection has been demonstrated: the *transit method.* This method is easier to understand: As a planet passes in front of the star, some of the starlight is temporarily blocked, leading to a dimming of the star. If that stellar dimming is seen to occur on several occasions at a regular interval it can be strong evidence for an orbiting planet.



WARNING Note, however, that some stars attempt to confound us by pulsating in brightness of their own will, which must be carefully excluded so as not to be fooled by a "false positive."



TECHNICAL STUFF This method is illustrated in Figure 16-4. As the planet begins to cross in front of the star, its light begins to dim, reaching its lowest point when the planet is completely in front of the star. The amount of dimming is known as the *transit depth*, and is greater for larger planets and smaller stars, and lesser for smaller planets passing in front of larger stars. Later, as the planet passes away from the star, the starlight returns to its normal level. Note that multiple dimmings may occur if there are multiple planets in the system.



Credit: Author

FIGURE 16-4: Transit (or eclipse) method of exoplanet detection.



REMEMBER A disadvantage of the transit technique is that many planets will orbit stars perpendicularly to the line of sight to the Earth, and hence never block the starlight as seen by us.



REMEMBER The main advantage of the transit method is that for planets that *do* transit, the size of the planet is determined from the amount of starlight blocked (the transit depth), not the mass. Therefore, the best-characterized planets are those that are detected using both the Doppler and transit techniques. This gives us both the mass and size of the planet, and hence the density — an important clue to the material composition, and hence habitability.

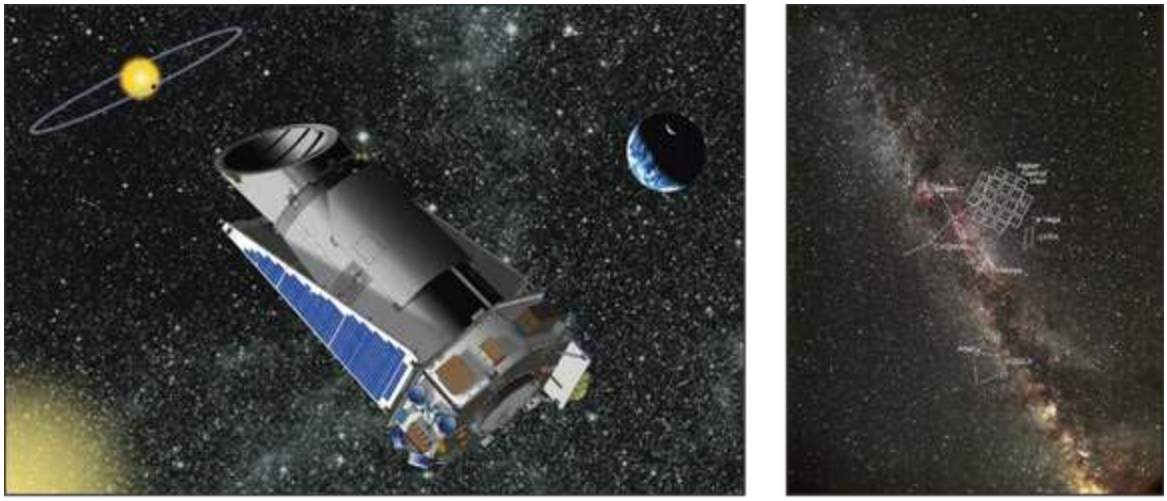
Detecting transits with Kepler



REMEMBER The transit method was used to spectacular success by the Kepler Space Telescope (2009-2018). The concept was simple: put a relatively small, but wide-angle telescope in space where it can measure the amount of arriving starlight incredibly accurately, with no disturbances due to the Earth's atmosphere (no "twinkling" stars).

The Kepler telescope (see Figure 16-5a) was used to stare at a single patch of sky (see Figure 16-5b), dense with thousands of stars, for years on end, keeping a watchful eye on all of them at once. When any one of those stars dimmed, it was recorded as evidence of a possible exoplanet transit and flagged for follow-up study with other telescopes.

REMEMBER Unlike with a typical narrow-angle telescope, which can take in just a few stars at a time, Kepler's wide-eyed approach allowed for many chances of exoplanet detection simultaneously — like buying thousands of lottery tickets instead of just one or two each week. From its airless location in space, even very faint transits could be detected accurately, allowing for smaller, more Earth-like planets to be detected.



(a) (b)

Credit: (a) NASA/Wikimedia Commons/Public domain (b) NASA/Ames/JPL-Caltech/https://commons.wikimedia.org/wiki/File:Kepler_FOV_hiRes.jpg/Public domain/last accessed Oct. 11, 2026

FIGURE 16-5: (a) Artist's impression of the Kepler Space Telescope. (b) The patch of sky observed by Kepler, close to the plane of the Milky Way.

TIP Kepler was an astoundingly successful space mission, whose data has currently been used to detect close to 3,000 exoplanets — far more than any other single observatory — with data analysis still ongoing.

Other space telescopes before and since have used a similar approach:

- ESA's **CoRoT mission (2006–2013)** predated Kepler and also used the transit technique to search for new exoplanets. With a much smaller telescope diameter, CoRoT data has been used to detect around 30 new exoplanets.
- NASA's **TESS mission (2018–)** was designed to look at the entire sky, but focusing on detection of small exoplanets around stars close to the Earth that are good targets for follow-on study.
- ESA's later **CHEOPS mission (2019–)** is another small space telescope with the goal of conducting accurate follow-up observations of known transiting exoplanets, as well as to search for exomoons.
- ESA's forthcoming **PLATO mission (2027)** will focus on bright stars close to the Earth, spending long periods of time looking specifically for Earth-like planets with surface temperatures that could be conducive for life.

Tricks of the trade



REMEMBER Although the Doppler and transit methods have been incredibly productive for detection of exoplanets, other methods have also been used, including:

- The **astrometric** method — rather than detecting the wobble of a star (as with the Doppler method), the astrometric approach records the position of the star in the sky with pinpoint accuracy, enabling any side-to-side motion to be detected.
- **Direct imaging**: in some cases, we can spot planets forming in disks without any need to resort to indirect information — refer to Figure 16-2.
- **Gravitation microlensing** uses a phenomenon predicted by Einstein where the light of a background object (such as a star) is bent and focused by the gravity of a foreground object (a nearer star, in this

case). If the nearer star also has a planet, this changes the effect of the lens, distorting the image of the background star in a detectable way.

Exoplanet diversity

Figure 16-6 shows a scatter diagram of the exoplanets known and characterized in 2026:

- The *x*-axis shows the orbital period (year) of the planet, with shorter orbits on the left and longer orbits on the right, in units of Earth days.
- The *y*-axis gives the size of the planet's diameter relative to the Earth.



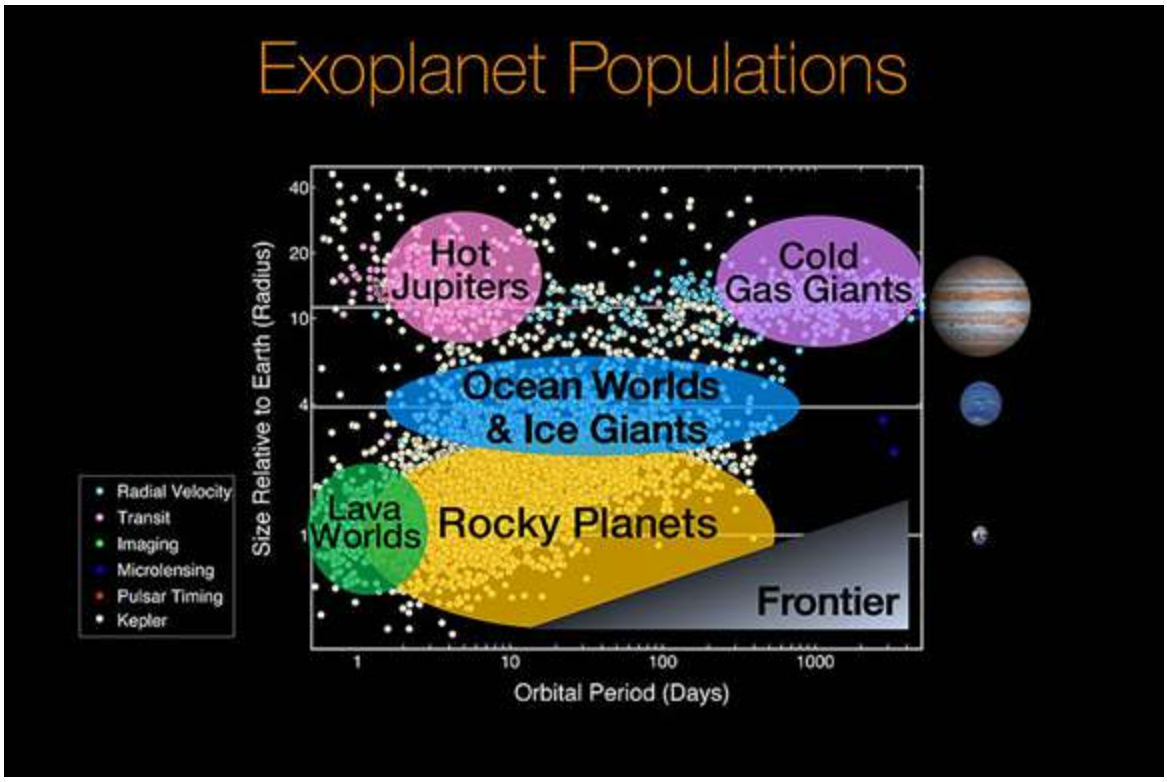
You'll notice from this figure that the points tend to cluster in the upper left of the chart, where the planets are larger and in shorter orbits, hence closer to their stars. This isn't surprising and reflects what astronomers call *observational bias* — that is, it's easier to detect planets that are larger with all available techniques, and if they are closer to the star then their transits will occur more frequently, and the wobble induced in the star will be greater, too. So overall, these large, close-in planets are easier to detect.

The lower right of the chart is comparatively sparse: this is the regime of smaller planets that are more distant from their host star. These planets are harder to detect, so many fewer are known — mostly around stars close to the Earth. However, this regime includes planets of similar size and temperature to the Earth, so these are also among the most interesting for astrobiology.



Missions such as TESS and PLATO are specifically designed to help fill in this sparse region of the chart, improving our knowledge

of potentially habitable worlds close to the Earth. In the next section, I take a closer look at what is meant by *potentially habitable.*



Credit: NASA/Ames Research Center/Natalie Batalha/Wendy Stenzel/Public domain

FIGURE 16-6: Scatter diagram of detected exoplanets.

Getting Comfy in the Habitable Zone



TIP In the children's story "Goldilocks and the Three Bears," the eponymous girl discovers a house in the woods inhabited by three bears. While the bears are out, she samples their hot porridge (oatmeal), finding one bowl too hot, one too cold, and one just right, which she proceeds to eat.

This story has been adopted by astronomers to convey in simple terms the concept of the "habitable zone." In our solar system, we can compare the three 'terrestrial' planets with atmospheres: Venus, Earth, and Mars. Venus, closest to the Sun, is too hot, which led to its runaway greenhouse atmosphere (refer to Chapter 14). Mars, the furthest of the three from the Sun, is too cold, whereas the Earth in the middle is "just right." This results in our home world with liquid water on the surface, ripe for the incubation of life as opposed to planets with water lost to space (Venus) or frozen into polar caps and permafrost (Mars).



REMEMBER This idea that the amount of solar heating is the dominant factor determining habitability leads to the definition of a *habitable zone (HZ)*, also known as the *Goldilocks zone*, which is simply the zone of minimum and maximum distance from a star where liquid water can exist on the surface of a planet. Depending on the brightness of the star, the habitable zone will be closer or further relative to the HZ around our Sun. For cooler stars, the HZ is closer to the star, to avoid planetary oceans from freezing. For hotter stars, the HZ is more distant to prevent the oceans from boiling away.



TECHNICAL STUFF It's important to note that distance alone is not the only metric that determines the HZ. In fact, the size of the planet (its gravity) and atmospheric composition are also important factors, which can determine how much atmosphere and heat is retained. Think of wrapping up in a blanket near a campfire: It's the thickness and type of the blanket as well as your proximity to the heat that determines how warm you are. In our solar system, Mars may have been able to hang on to more of its atmosphere, and therefore to be warmer at the present day, if it were larger.

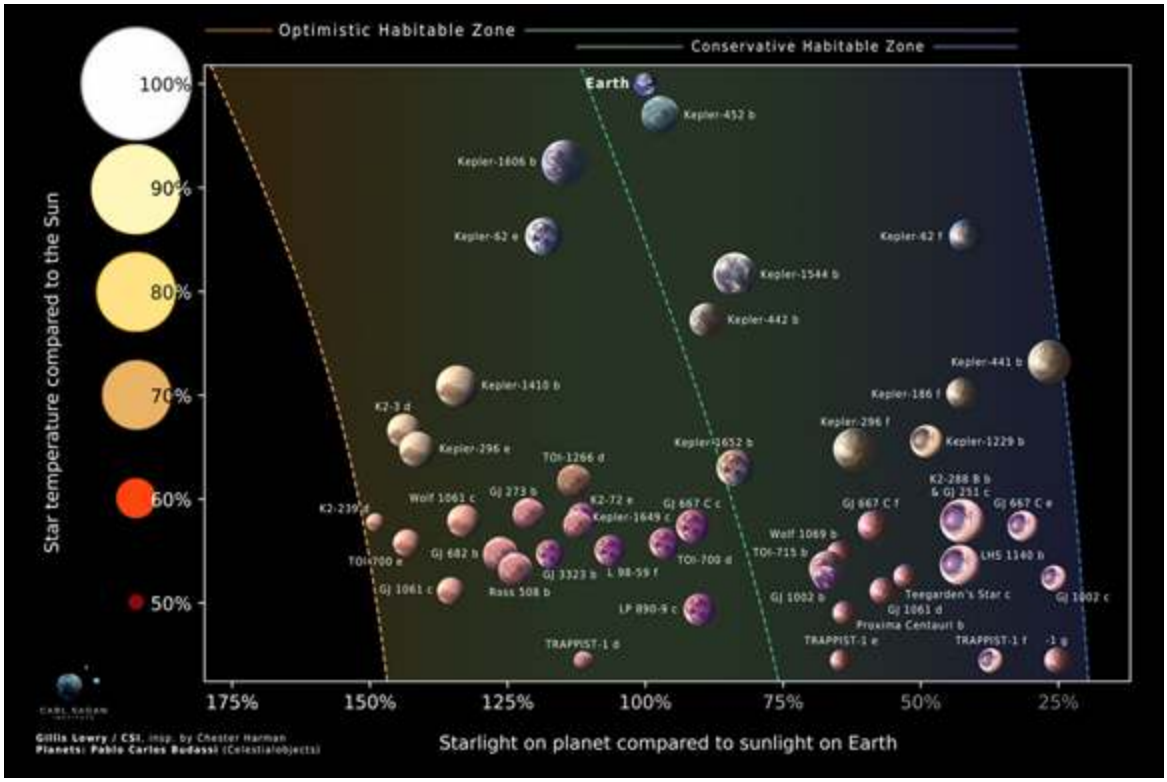


TIP Setting aside these complications, the simple view of the HZ determined by distance alone is still useful, since it gives us a basic guide to where planets are most likely to be habitable.

Figure 16-7 shows a subset of 45 known exoplanets, similar in size or slightly larger than the Earth, and their positions relative to the HZ of their stars. At present, these are our best candidates for habitable — or even inhabited — worlds.



WARNING Note that the depictions of each planet in Figure 16-7 are purely fictitious: We have never been able to take a photograph of an exoplanet that shows it as anything more than a dot.



Credit: Spacegel/Wikimedia Commons/CC BY 4.0

FIGURE 16-7: The habitable zone.

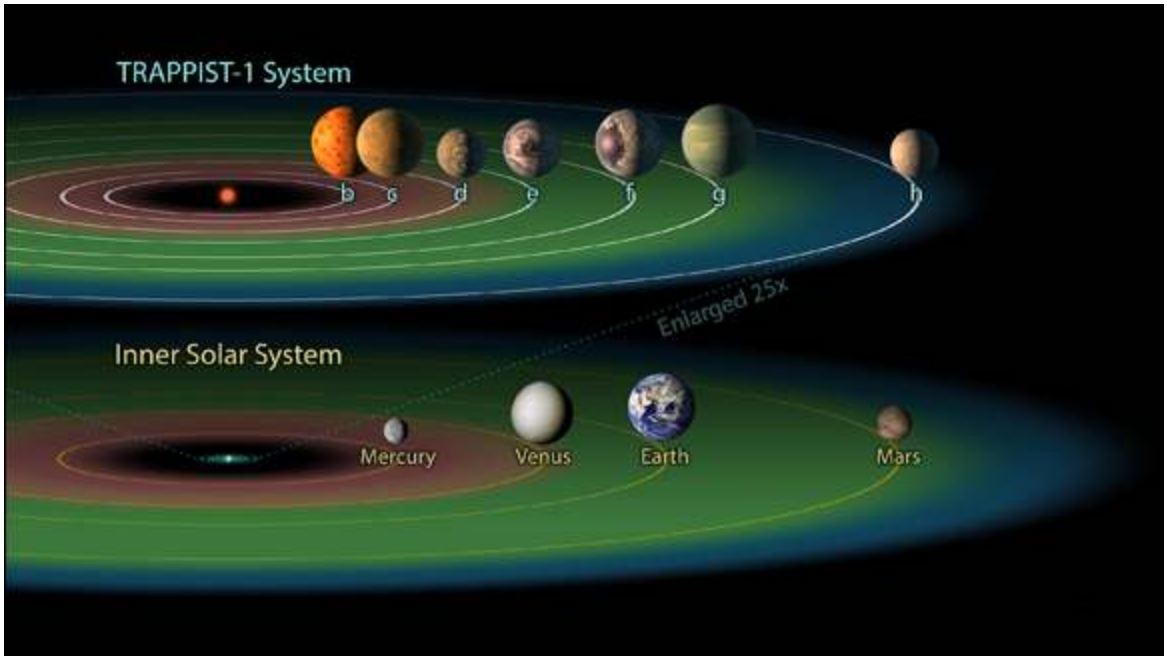


Some of the most notable, potentially habitable exoplanets known include:

- **Kepler 452b:** Number one on many astronomer's lists of "Earth 2.0 candidates" is the planet Kepler 452b, a world orbiting a Sun-like star 1,800 light years away in the direction of the constellation Cygnus. Its orbital distance and year are almost identical to the Earth's, and it lies within the conservative HZ of its star. Kepler 452b, however, is significantly larger than Earth, with 63 percent greater diameter and a mass that may be five times greater. Its star is also somewhat older and brighter than the Sun, so without further data we are currently unsure whether it has an Earth-like temperature, atmosphere, and climate.
- **Kepler 186f:** Kepler 186f is a near–Earth-sized exoplanet orbiting a cooler star than the Sun — host star Kepler 186 is an M-type dwarf star with a surface temperature 2,000°C cooler than the Sun. Despite this, Kepler 186f orbits much closer to its cool star than the Earth's orbit around the Sun, meaning that its surface temperature may in fact be quite similar. Kepler 186f is one of five known planets in the Kepler 186 system, with the other four all being closer to the star and too hot to be in its HZ.
- **Kepler 62f:** This is another habitable planet candidate, orbiting a slightly cooler (K-type) star at a distance of 0.72 AU (72 percent of the Earth-Sun distance). Due to the cooler star, this distance puts Kepler 62f firmly within the habitable zone. The planet is about three times heavier and 60 percent larger than the Earth.
- **Proxima Centauri b:** Much closer to home, the planet Proxima Centauri b (Prox Cen b) orbits the nearest star to us — the small red dwarf star Proxima Centauri (Prox Cen). Remarkably, Prox Cen b is not only within the habitable zone of its host star, but also similar to Earth in size and mass. Little else is known at present, since the planet does not transit the star, making investigations of its

atmospheric composition difficult. Due to the excitement of being one of the closest planets to Earth (along with several siblings in the same system), interstellar missions have been proposed to reach the Prox Cen system and investigate its planets.

- **TRAPPIST 1 planets:** From 2016 to 2017, no fewer than seven planets were discovered orbiting the ultracool dwarf star TRAPPIST 1, 41 light years from Earth in the direction of Aquarius. Given designations 1b through 1h, these planets orbit the host star at close distances of 0.01 to 0.06 AU (1 to 6 percent of the Earth-Sun distance) and very short orbital periods (or years) of just 1.5 to 19 Earth days. Planets d through f or even g may be inside the star's HZ (see Figure 16-8). Five of the seven planets are close in size to the Earth.



Credit: NASA/JPL-Caltech/Public domain

FIGURE 16-8: Comparison of the TRAPPIST 1 system to our solar system.

Exoplanet Atmospheres



REMEMBER At present, our knowledge of exoplanets is still in its infancy. We are now able to detect planets orbiting stars near to the Earth, typically within tens to a few thousands of light years away. For many of these planets, their existence and orbital period are all that is known. For some, we know a little more, such as size and mass. With such sparse knowledge, we cannot be sure if any are habitable, let alone inhabited. Imaging the surfaces of these planets remains far out of reach for even the largest telescopes for now. How then can we begin to probe their potential for life?

Splitting light into colors



REMEMBER As mentioned elsewhere in this book, a key tool used by astronomers is *spectroscopy* — the splitting of light into its different component colors, revealing what chemicals the light has passed through and interacted with.



TIP Spectroscopy has many applications, and one of these is measuring the composition of exoplanet atmospheres.



TECHNICAL STUFF Isolating and measuring just the light from an exoplanet against the glare of its much brighter and nearby companion star is extremely difficult — simply trying to view these separately in a telescope is rarely possible — they are just too close together. However, astronomers can use a clever "trick" to achieve the same end. The trick has two variants:

- **Primary transit spectroscopy:** The dimming of the star during a planetary primary transit (when the planet moves in front of the star) is measured at different wavelengths of light. By mapping how the starlight is dimmed differently at different wavelengths, a spectrum of the planet's atmosphere can be obtained.
- **Secondary transit spectroscopy:** In this version, the planet passes behind the star rather than in front. By subtracting the starlight when the planet is hidden from the combined light of the star and the light of the planet when the planet is not hidden, the light from just the planet can be obtained.

Both these approaches require incredibly precise measurements of starlight at different wavelengths — something astronomers refer to as *photometric* (or brightness) accuracy. To achieve such difficult goals, the best tools at our disposal are space telescopes: the Hubble and James Webb Space Telescopes (HST and JWST) — see Chapter 3.

Atmospheric composition

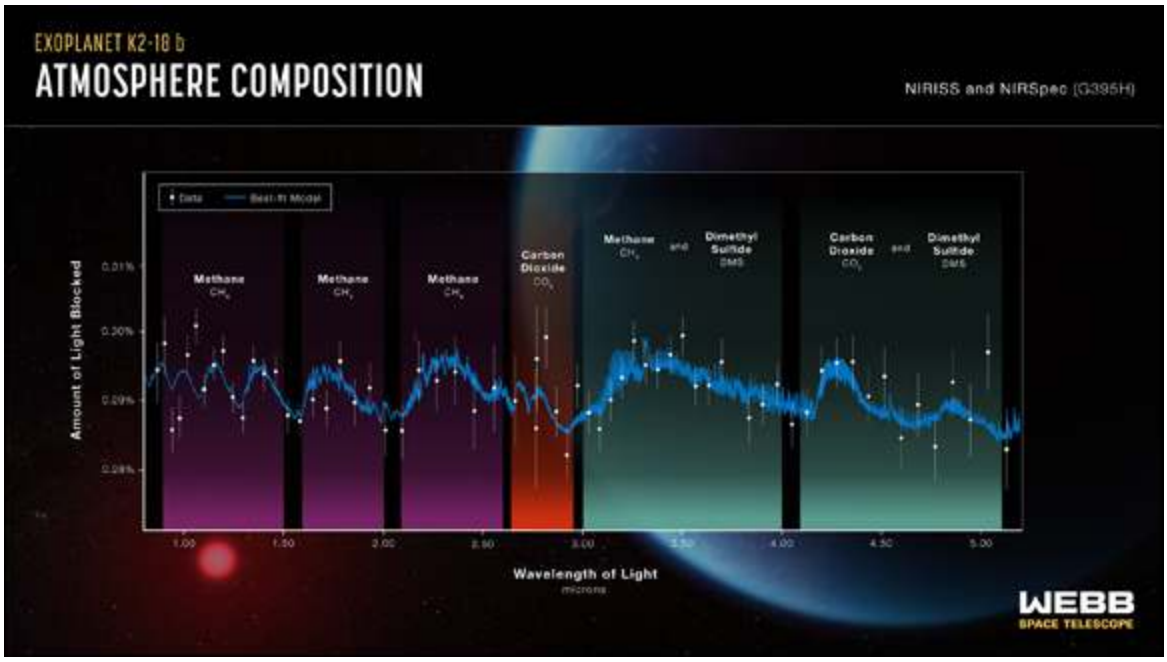
With the ability to perform some limited spectroscopy of exoplanets in some cases, astronomers lost no time in beginning to characterize their atmospheres wherever possible. In particular, astronomers have looked for so-called atmospheric biosignatures — combinations of gases that are relatively unstable over time, and therefore would require life to produce.



TIP At present, our knowledge of atmospheric gases on exoplanets is rudimentary, although changing rapidly. Some current highlights include:

- Detection of sodium vapor in the atmosphere of the hot exoplanet HD 209458b (2001), followed later by detection of a vast cloud of oxygen, carbon, and hydrogen atoms surrounding the planet as well.

- Detection of clouds in the atmosphere of Kepler-7b, and later the planets Gliese 436b and Gliese 1214b, as well. The clouds on Kepler-7b, a hot exoplanet, may be made of heavy substances such as iron or even rock.
- Detection of water vapor, and later also methane and carbon monoxide in the atmosphere of HD 189733b.
- The first detection of water in the atmosphere of an exoplanet within the habitable zone of its star, for planet K2-18b, in 2019, using data from the Hubble Space Telescope.
- The possible detection of dimethyl sulfide (DMS), a complex molecule and potential biosignature, also on K2-18b. This detection has been disputed. The spectrum of K2-18b as measured by JWST is shown in Figure 16-9.



Credit: NASA/ESA/CSA/Ralf Crawford (STScI)/Joseph Olmsted (STScI)/Science: Nikku Madhusudhan (IoA)/Public domain

FIGURE 16-9: Spectrum of exoplanet K2-18b showing dips in the light due to the presence of different gases.

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Chapter 17

Extra-Terrestrial Intelligence and Technosignatures

IN THIS CHAPTER

- **Listening for alien radio broadcasts**
- **Reaching out to aliens with active SETI**
- **Understanding the Kardashev scale**
- **Designing interstellar probes**

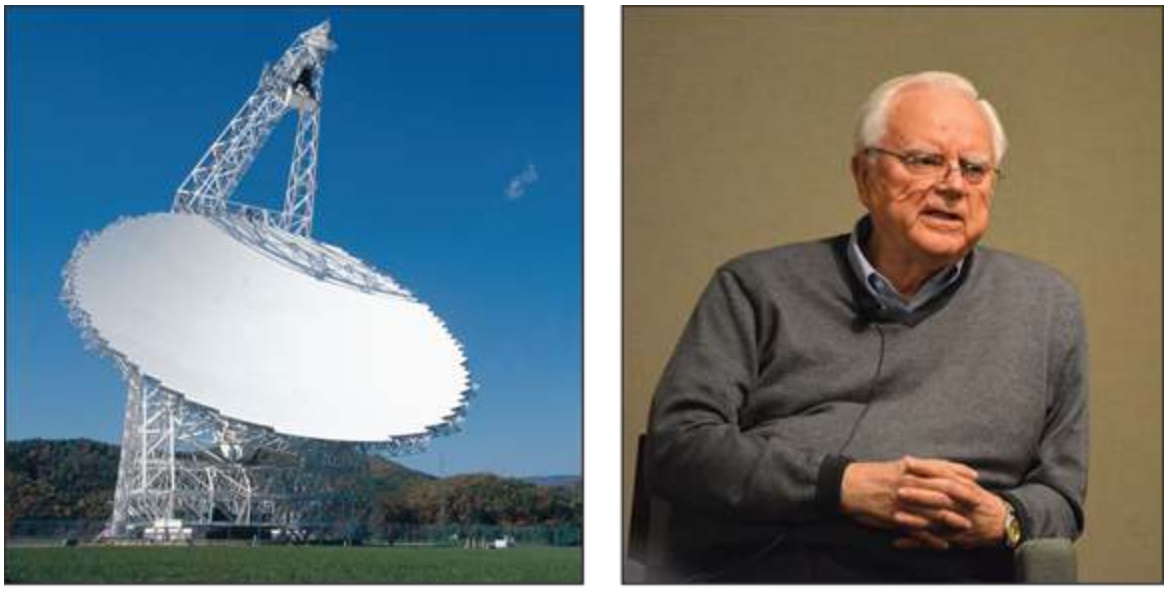
In this chapter, you finally address the biggest question of all, the one that probably caused you to pick up this book in the first place: Are there other thinking beings in the universe, with an intelligence similar to, or even exceeding our own? This is a question that has obsessed philosophers for millennia; however, until recently, we have had very limited means of finding out. But this is now changing.

In the following sections, you find out how astronomers started to take alien-hunting seriously: building giant radio receivers, listening for extraterrestrial radio signals, and even sending our own messages out among the stars. You also learn about the riddles of Fermi's paradox and how alien civilizations might harness the energy of their home planet, star, or even an entire galaxy.

Hunting for Aliens

In 1961, as the space age was beginning to lift off, a meeting was convened at the National Radio Astronomy Observatory in Green Bank, WV (see Figure 17-1a), to consider this very question. Previously, astronomers had tried a piecemeal approach to searching for alien civilizations, leading to the many outlandish claims and false alarms

over cities and canals on Mars (refer to Chapter 12). These repeated false alarms had led to the entire hunt for extraterrestrial intelligence (ETI) falling into serious disrepute.



(a) (b)

Image credit: (a) NRAO/AUI/NSF/CC BY 4.0 (b) Raphael Perrino/Flickr/CC BY 2.0

FIGURE 17-1: (a) The Robert C. Byrd Green Bank Telescope (GBT) at the National Radio Astronomy Observatory, West Virginia. (b) Astronomer Frank Drake.

Something needed to be done if alien hunting was to be taken seriously as a branch of astronomy, rather than philosophy. During the meeting, astronomer Frank Drake (see Figure 17-1b) proposed to break the vast question of how many alien civilizations we can hope to communicate with into a series of smaller questions, such as "what fraction of planets are habitable?" and "how long do technological civilizations endure?".

Over time, refining knowledge of any of these uncertainties would build up better knowledge about the existence of alien life. Importantly, different specialists could tackle different parts of the problem independently, and each would be advancing our overall progress toward the answer. This stroke of genius became encapsulated in a formula known as the Drake equation (see the nearby sidebar, "The Drake Equation").

THE DRAKE EQUATION

The Drake Equation is a series of numbers that when multiplied together — if we knew their values — would tell us how many civilizations (N) we could be communicating with today. Wouldn't that be nice to know? (Astrobiologists could then go on holiday, except for me, who would be busy rewriting this book). It looks like this:

$$N = R* \times f_p \times n_e \times f_l \times f_i \times f_c \times L$$

- N = the number of civilizations in the Milky Way galaxy with which communication might be possible,
- $R*$ = the average rate of star formation in our galaxy,
- f_p = the fraction of stars that have planets,
- n_e = the average number of potentially habitable planets per star,
- f_l = the fraction of habitable planets that go on to develop life (become inhabited),
- f_i = the fraction of inhabited planets that develop intelligent life (civilizations),
- f_c = the fraction of civilizations that transmit signs of their existence into space (effectively, civilizations that develop radio technology),
- L = the length of time for which such civilizations release detectable signals into space.

However, of the seven numbers we need to calculate N, we only have good estimates for the first two: $R*$ — the rate of star formation — and f_p — the fraction of stars that have planets. (But hey, this is progress: Back when I was in college, we only knew the first number.) So, scientists still have a lot of work to do. The focus for exoplanet astronomers right now is on number three — n_e, the number of planets that are hospitable to life. I looked at this question earlier in Chapter 16 regarding exoplanets, and also in Chapter 5 for the Earth. For biologists, the focus is on the fourth element of the equation (f_l) — how often does simple life arise from prebiotic chemicals? Only when we have a better handle on these numbers can we eventually move on to the fifth, sixth, and seventh values in the equation, which deal with the probability of intelligent life capable of interstellar communication — like us. The Drake Equation has been criticized at times for being too broad and ambitious to be useful, but I disagree. It lays bare the biggest problems that need to be solved in astrobiology, challenging us with its simplicity to seek out the answers.



TECHNICAL STUFF The Drake Equation can take on a vast range of answers for how many advanced alien civilizations exist now in our galaxy, depending on what values are assumed for the important missing numbers, such as f_i — the fraction of life-bearing planets that develop intelligent life. Estimates for N therefore range from 10 to 100 million!

Grappling with Fermi's Paradox

Estimates with the Drake Equation lead naturally to the question: Where are all the aliens? The logical chain reads as follows: If there are so many advanced technical civilizations out there, then many are likely older than ours, with just a few hundred years since the industrial revolution on Earth. Indeed, they are likely to be much older, even millions of years older, since our galaxy is at least 10 billion years old with stars forming all the time.

And if that's so, then these older civilizations must also be much more advanced than ours, if discovery and progress proceed at about the same pace. And if they are more advanced and older, then surely some have begun to explore the galaxy, and unless they are very sparsely distributed indeed, then some would surely have reached us by now … so where are they?



REMEMBER This question is now widely known as *Fermi's paradox* — named for the Nobel-winning physicist Enrico Fermi, who famously proposed it in 1950 — although certainly not the first to wonder about it. The mystery, of course, would go away if aliens have visited us; however, most scientists don't believe that there is solid evidence for alien visitations to Earth — but see Chapter 18 for more on this topic.



TECHNICAL STUFF So, in that case — how do we resolve this paradox? No one knows for sure, but some of the many proposed answers include:

- **Sparseness:** There are relatively few very-widely-dispersed civilizations in the galaxy, and therefore, even given long times of development, the physical limits of distance and maximum speed set by the speed of light mean that the civilizations haven't had time to connect yet with one another.
- **Self-annihilation:** Once civilizations develop nuclear, biological, and other weapons capable of destroying themselves, these weapons are inevitably used, causing any advanced civilizations to wipe itself out before exploring the galaxy.
- **Zoo hypothesis:** This fun and clever idea suggests that alien civilizations quickly develop to a very advanced state, far beyond our comprehension, but existing throughout the galaxy. Aliens have already visited and are watching our planet, waiting for us to develop to a level worthy of communicating with them. In the meanwhile, they continue to watch us and monitor our development — in much the same way we keep animals in a zoo. This idea has formed the basis for many books and movies — see Chapter 19.

This is just a sample of the possible explanations — what do you think?

Little Green Men, WOW!



TIP One of the first ways astronomers tried to detect extraterrestrial civilizations was to hunt for unusual radio signals. Radio signals tend to penetrate through clouds of gas and aren't absorbed like typical light waves. But how can we know what to listen for? Would we recognize alien speech, or music if we heard it? And

would we even be able to decode a complex transmission? Astronomers in the early years of SETI listened for the simplest possible signal — a repeating beep like the Sputnik spacecraft (for more on this, see *Space Exploration For Dummies* by Cynthia Phillips and Shana Priwer [Wiley]).

LGM-1 and pulsars

In 1967, a young graduate student at Cambridge University in England was monitoring reams of data from a new type of astronomical receiver: the *Interplanetary Scintillation Array (IPS Array)* (see Figure 17-2a). Her name was Jocelyn Bell (see Figure 17-2b), and the IPS was the brainchild of her PhD advisor, Anthony Hewish.



If you expect a telescope to look like a tube with a circular piece of glass at one or both ends, you would struggle to recognize the IPS Array as a telescope — instead, it appears as a four-acre field of wooden sticks strung with metal wires. In fact, this *phased array antenna* was a clever invention, with the field of wires working as a team, together able to measure longwave radio waves (wavelengths of several meters, or about 10 feet).

Hewish, assisted by Bell, was trying to measure interplanetary scintillation of radio waves — essentially the same twinkling of starlight you see outside at night, but, in this case, the twinkling of radio waves. The twinkling would tell them about what gases occupy interstellar space that cause the radio waves to twinkle on their way to reach us.



(a) (b)

Image credit: (a) Science Museum Group/https://collection.sciencemuseumgroup.org.uk/objects/co8105496/parts-from-the-cambridge-interplanetary-scintillation-array//CC BY 4.0/last accessed Oct. 11, 2026 (b) Roger W Haworth/Wikimedia Commons/CC BY-SA 2.0

FIGURE 17-2: (a) The Interplanetary Scintillation Array at Cambridge, used to detect the "LGM-1" signal. (b) Graduate student Jocelyn Bell in 1967.

However, Bell noticed something unusual: a repeating, regular pattern of pulses spaced 1.3 seconds apart. Excited, Bell and Hewish pored over the data. Nothing with this regularity had been seen before or anticipated to exist in nature. They wondered if it could it be an alien radio beacon, dubbing the signal "LGM-1" — for "Little Green Men 1" (see Figure 17-3).

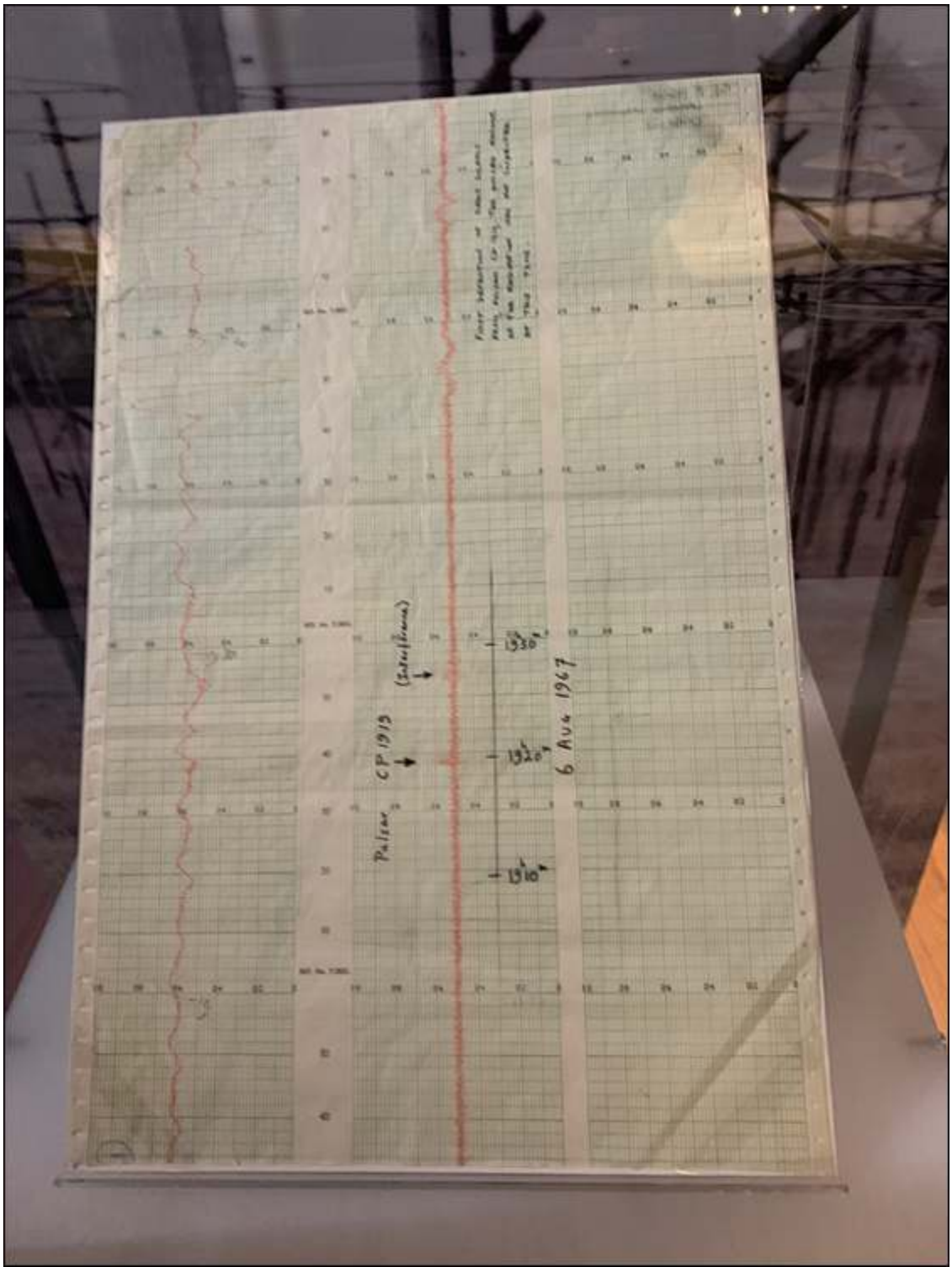


Image credit: Billthom/Wikimedia Commons/CC BY-SA 4.0

FIGURE 17-3: The printer chart used by Jocelyn Bell to note repeating radio bursts from the "LGM-1" signal.

A NOBEL CONTROVERSY

The LGM-1 signal and subsequent discovery of pulsars made celebrities of Hewish, Bell, and their collaborator at Cambridge, Martin Ryle. However, when the 1974 Nobel Prize in Physics was awarded for pioneering work in radio astronomy, only Hewish and Ryle were recognized, whereas Bell was apparently overlooked, igniting a controversy that continues to this day. However, at the time, it was customary for professors to be recognized for the work of their students, a tradition that Bell herself acknowledged, saying that it would "demean" the Nobel Prize to recognize students. In later years, however, Bell conjectured that the combination of being both a student and woman had caused the Nobel committee to omit her from the Prize. Ultimately, Bell went on to receive many prestigious prizes and awards in physics and astronomy for her work, including a knighthood as Dame Jocelyn Bell Burnell in 2007.

Soon afterwards, Bell discovered other similar signals, which came to be known as *pulsars*. These were eventually explained as rapidly rotating neutron stars — collapsed cores of massive stars that have exploded in a supernova and died (for more on neutron stars, see *Astrophysics For Dummies* by Cynthia Phillips and Shana Priwer [Wiley]). An exciting discovery for physics, but in the end — no evidence for life.

The WOW! signal

A decade after LGM-1, another unusual radio signal had astronomers excited again that *maybe this time* an alien radio signal had finally been found. Starting in 1973, a SETI search had begun at Ohio State University using the "Big Ear" antenna — another unusual receiver like IPS in Cambridge that also occupied a field, rather than being a steerable "dish."

Four years into the search, things had become humdrum and routine. Then one day in 1977, volunteer astronomer Jerry Ehman was reviewing a routine printout of the receiver measurements (much like Bell in 1967) and noticed something extraordinary: an incredibly strong signal blast that lasted for 72 seconds as Big Ear swept across a patch of sky (see Figure 17-4).

The signal was so strong that the computer had to print out letters instead of the usual numbers for the signal strength — about 30 times higher than the background "hiss" of noise from the night sky. When

Ehman saw this patch of printout he circled it in red ink, writing "WOW!" beside it, a name that has stuck ever since.



REMEMBER So, what was the WOW! Signal? Was it evidence for alien life? Many subsequent attempts were made to find the signal again, using Big Ear and other telescopes, but nothing like it was ever detected again.

This has led to skepticism that the signal was a real alien beacon. Instead, natural phenomena such as intense bursts of starlight have been proposed to explain it. However, there are no very good explanations for the WOW! signal, and to this day, scientists are quite divided about whether it was an alien radio beaming in our direction for a short time. What do you think?

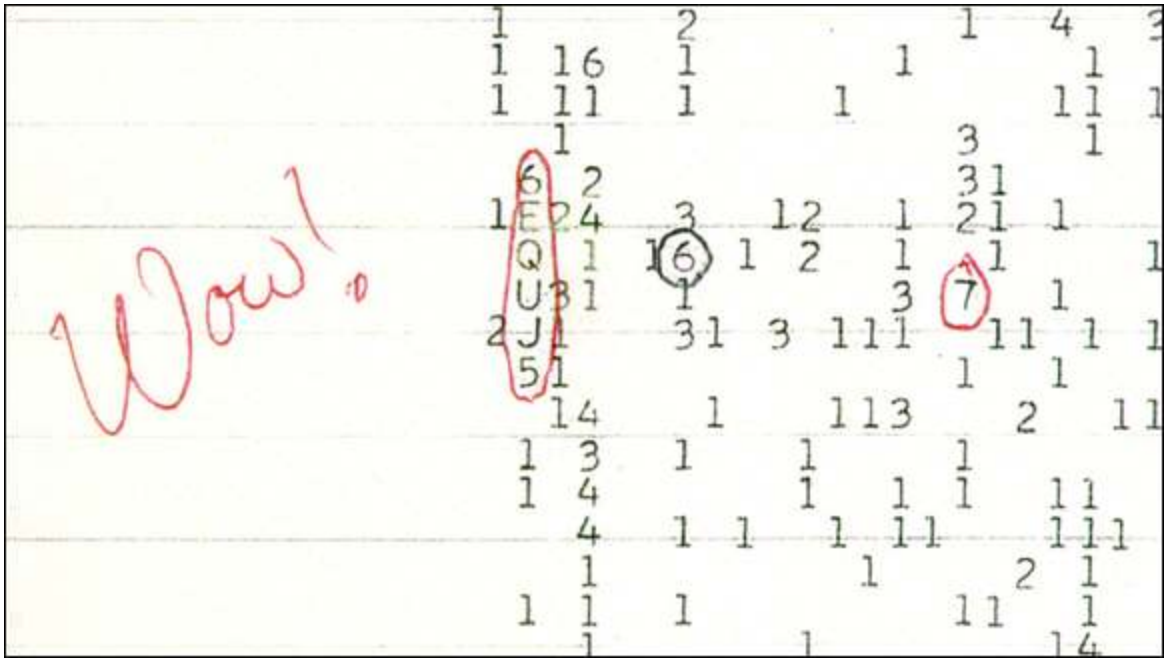


Image credit: Big Ear Radio Observatory and North American AstroPhysical Observatory (NAAPO)/Wikimedia Commons/Public domain

FIGURE 17-4: The WOW! signal detected by the Big Ear telescope at Ohio State University. To this day, no one knows for sure what caused this intense burst of radio waves.

Scaling Up with Present Day SETI

Since its beginnings post-World War II, radio SETI (the search for alien radio signals) has had a checkered history of stops and starts. Despite the attempts of Frank Drake and others to put it on a more scientific footing, the huge uncertainties involved in *where* to look and *what* to look for have meant that SETI has been largely relegated to the margins of astronomy, working with borrowed time on large radio telescopes.

One question that may have occurred to you is how we would recognize an alien radio signal if we found it — after all, the LGM-1 signal turned out to be a natural phenomenon in the end, showing us that a simple repeated beeping is not enough to declare finding of an alien radio station. The consensus is that the signal must be complex enough to be beyond any reasonable expectation that it could be natural: for example, beeping sequences of prime numbers with breaks between numbers seem hard to envisage being accounted for by a natural process.



TIP There have been many organized radio SETI attempts since the mid-twentieth century, and a few of the most prominent are mentioned here:

- **OSU SETI:** The program at Ohio State University from 1973 to 1995 that found the WOW! signal using the Big Ear telescope. The search wrapped up in 1995 after 22 years, earning the Guinness World Record for Longest Extraterrestrial Search. The Big Ear telescope was sadly dismantled in 1998 and is now a golf course (maybe to attract golf-playing aliens?).
- **SERENDIP:** The SERENDIP program cleverly overcomes the historical funding and observing time limitations endured by SETI programs by piggybacking on mainstream large telescopes as they conduct their regular astronomical observations. SERENDIP consists of a separate, broadband radio receiver that rides alongside the other scientific receivers, recording vast quantities of radio transmissions

that are later analyzed for unusual signals back at the Berkeley SETI Research Center.

- **Allen Telescope Array (ATA):** The ATA — funded by a donation from Microsoft co-founder Paul Allen — began operations in 2007 to simultaneously conduct astronomical observations and a SETI search. ATA is designed as an array of small (6.1 m, 20 ft) radio dishes that can operate together as though they were a much larger telescope. At the site in northern California, 42 dishes have currently been commissioned, with ambitions to eventually reach a much larger collecting area of 350 dishes covering one square hectare.
- **Breakthrough Listen:** One of the largest and more ambitious SETI programs, Breakthrough Listen — like ATA and SERENDIP — is led by the Berkeley SETI Lab. The project began in 2015 with a $100 million donation from entrepreneur Yuri Milner to undertake a 10-year deep radio listening of 1 million nearby stars and 100 galaxies using large telescopes such as the GBT and the 64 m (210 ft) Parkes telescope in Australia (see Figure 17-5). The project also made extensive use of volunteer computer time, through a downloadable computer program called SETI@Home. This could run quietly on home computers and even gaming consoles such as the PlayStation 3, when not being used. The team continues to analyze data and is planning follow-up listening toward any stars exhibiting anomalous radio signals.

No team has yet announced any firm detections of any alien radio signals, but the search continues.



Image credit: Daniel John Reardon/Wikimedia Commons/CC BY-SA 4.0

FIGURE 17-5: The 64 m (210 ft) Parkes radio telescope in New South Wales, Australia — one of the cornerstone observatories of the Breakthrough Listen SETI project.

Reaching Out with Active SETI

Many forms of SETI rely on a big assumption — that alien civilizations are trying to contact us. If they are not actively beaming radio signals toward habitable stars like our own, their civilizations may be much harder to detect, leaking out only fainter signals intended for communications inside their own planetary system.



WARNING This naturally leads to the question: Should we be doing the same, broadcasting signals toward other promising stars, and hoping that they pick up our signals? This has proved a somewhat controversial topic, not to mention the inspiration for many science fiction stories — see Chapter 19. Why so?

As we saw earlier in this chapter ("Grappling with Fermi's Paradox"), because we have just developed the ability for radio communication and space travel in the last two centuries — a cosmic eyeblink — most other civilizations in the galaxy we could communicate with are likely to be much older and more advanced than our own. History has sadly shown time and time again that more technologically advanced civilizations tend to conquer, subjugate, and even eradicate less advanced ones. Yikes. Therefore, attracting their attention may not be in our best interests — a view espoused by the famous cosmologist Stephen Hawking.

A more optimistic view is that technologically advanced civilizations will have eradicated hunger, disease, and even the need for work (think AI and robots). So, the reasoning goes, they will be more interested in communication and contact with other species for the purposes of knowledge, cultural exchange, and curiosity rather than conquest. Or so we hope.



REMEMBER This has led to attempts to reach out and actively communicate with alien races, a quest known as *active SETI*. Several famous attempts to send radio signals to other civilizations have been made — see the nearby sidebar "The Arecibo Message" for more.

The 1970s was clearly a time of high optimism for SETI, with the WOW! signal and the Arecibo message keeping the alien hunters busy at their large radio telescopes. However, it was also a time when humanity was beginning to send space probes to the outer solar system — in particular, the *Pioneer* and *Voyager* missions — which became another opportunity for active SETI.

THE ARECIBO MESSAGE

In 1974, to celebrate upgrades to the Arecibo Telescope in Puerto Rico, a team led by Frank Drake (see earlier in this chapter) and others designed a simple pictorial message that was beamed to a cluster of stars known as M13, which is about 25,000 light years from the Earth. Anyone familiar with 1970s-era Space Invaders games or,

more recently, the Minecraft games will recognize the type of blocky pixelated diagram used in the Arecibo Message — see below (the pixels sent are on the left, and an interpretation of the meaning is given on the right). The message is exactly 23 pixels (blocks) wide and 73 pixels tall: values that are chosen because they are prime numbers (indivisible by smaller numbers other than 1). This means that the stream of 1679 pixels can only be reconstructed back into rows and columns making up a 2D shape in at most 2 ways (23 x 73, or 73 x 23) — only one of which leads to a meaningful pattern. In the diagram are important pieces of human culture and knowledge, including the decimal numbers, the key chemical elements of life, the building blocks of DNA, and the shape of a human and a telescope.

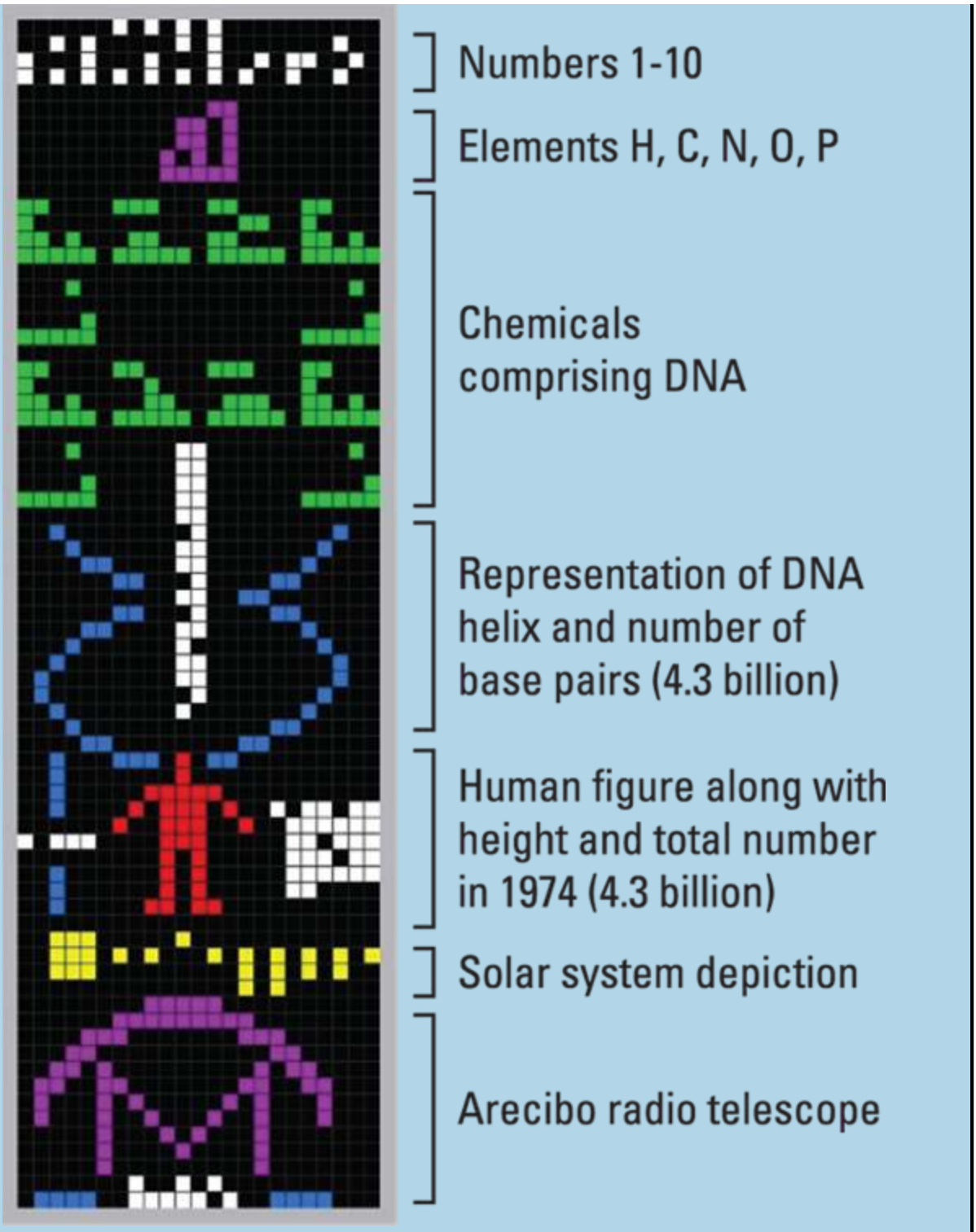


Image credit: Arne Nordmann (norro)/Wikimedia Commons/CC BY-SA 3.0

The Pioneer Plaque

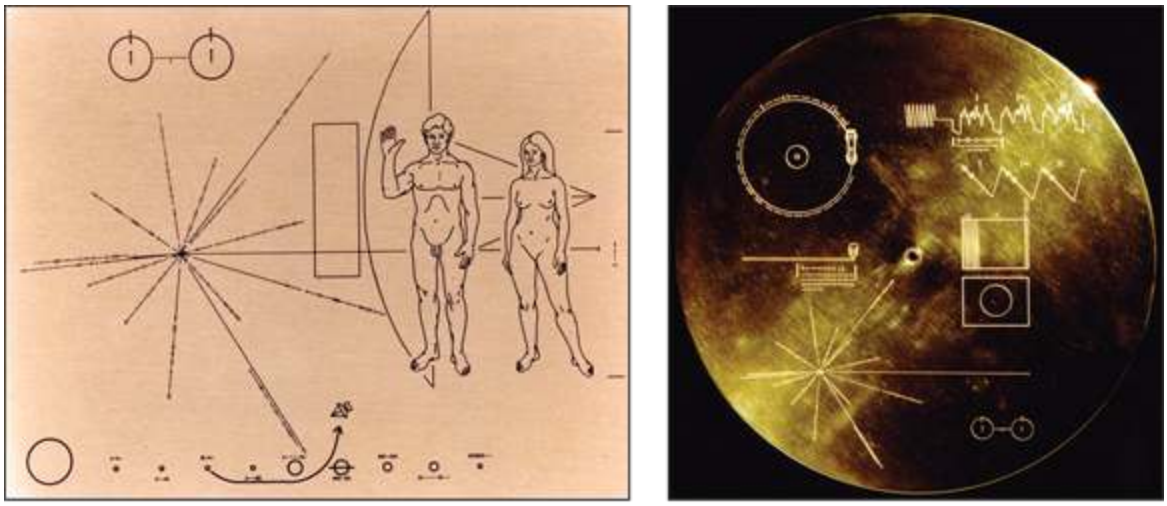
The *Pioneer 10* and *11* missions, launched in 1972 and 1973, respectively, were the first spacecraft from Earth to visit the outer planets Jupiter and Saturn (refer to Chapter 13). After these flybys, the high-speed spacecraft continued onwards on trajectories that leave our solar system entirely. They now travel through vast reaches of interstellar space and will eventually reach other nearby stars in our galaxy, thousands of years in the future.



REMEMBER This fate for the spacecraft was known before launch. So, an imaginative British author, Eric Burgess, made the bold suggestion that the spacecraft carry messages from us to any alien civilizations that might eventually intercept the spacecraft. This proposal led to the creation of the Pioneer Plaque — a metal plate affixed to each spacecraft with a pictorial message conceived by scientists Carl Sagan and Frake Drake and drawn by Sagan's wife Linda Salzmann Sagan (see Figure 17-6a).



TECHNICAL STUFF The image shows a man and woman, a hydrogen atom emitting radio waves at 21 cm wavelength (a useful frequency for interstellar communication), and a map showing the location of the Earth relative to nearby radio stars (in fact, pulsars — see earlier in this chapter) and within our solar system.



(a) (b)

Image credit: (a) Linda Salzman Sagan/Wikimedia Commons/Public domain (b) NASA/JPL-Caltech/Public domain

FIGURE 17-6: (a) The Pioneer Plaque. (b) The Voyager Golden Record.

The Voyager Golden Record

A more sophisticated version of the Pioner Plaque was included on the dual *Voyager 1* and *2* spacecraft launched in 1977, which visited all four outer planets (Jupiter, Saturn, Uranus, and Neptune) in the decade from 1979 and 1989. (Refer to Chapter 13 for more on the missions).

The Voyager Golden Record (12 inches, 30 cm — see Figure 17-6b) contained sounds, images, and other data from Earth carefully selected by a committee led by Carl Sagan. The sounds encompassed natural sounds such as surf and birdsong, greetings in 55 languages, and music including classical, blues, and rock. Photographs of humans and Earth scenes are on the record, along with the pulsar map of Earth's location as carried on the Pioneer Plaque.



REMEMBER The scientists thoughtfully included a needle to play the record, so many years from now, the music of Bach, Beethoven, and Berry may be echoing around the concert halls of an alien city. (I wonder if they will have feet to tap?)

Other Technosignatures

The term *technosignatures* refers to any signs of technological activity — including our own — but is most often used in the context of the detection of alien civilizations. Any alien radio signals would of course count as a technosignature, and the search for these has been discussed already in this chapter. But what about other types of technosignatures?

Dyson Spheres and ringworlds

An extremely advanced civilization might be capable of capturing the entire energy output of its host star, enclosing it in a vast spherical structure. This is now known as *Dyson Sphere*, following a 1960 essay on the topic by physicist Freeman Dyson — although the idea had already featured in a 1937 novel by Olaf Stapledon.



TECHNICAL STUFF A Dyson Sphere is typically envisaged in popular culture as a vast globe constructed from a mesh or gauze, although a more stable variant is many unconnected pieces orbiting on similar orbital paths (sometimes called a *Dyson Swarm*). Another variant is a *ringworld*: like the name suggests, a solid ring, or densely packed convoy of craft, that completely occupies a single circular orbit around a sun.

On the inner surface of a Dyson Sphere or ringworld, crops could be grown in permanent sunlight, and inhabitants on the surface would live in effectively a single, giant interconnected city encircling the star. (Just imagine the traffic jams in that metropolis.)



REMEMBER Naturally, astrobiologists have searched for these megastructures, which could be detectable due to their effect on the light of the star. Rather than energy reaching us mostly as visible light, the sphere would convert the light into heat (think of a solar

panel powering your home heating). The star's energy would then show up as *infrared light* instead. For now, the search continues.

The Kardashev scale

In 1964, astronomer Nikolai Kardashev proposed a simple but powerful three-point system to describe the level of advancement of an alien civilization, now known as the Kardashev scale:

- **Type I Civilization:** Can harness all the energy from its home planet.
- **Type II Civilization:** Utilizes all the energy from its host star — an example would be a Dyson Sphere.
- **Type III Civilization:** Captures and exploits all the energy from an entire galaxy — clearly not a species to be trifled with.



TIP On this scale, humans would not merit the designation of a Type I Civilization — some have proposed a lesser "Type 0" to describe our technological level instead. Truly a lesson in cosmic humility.

Interplanetary Missions



REMEMBER The four *Pioneer* and *Voyager* spacecraft — along with the *New Horizons* spacecraft that visited Pluto in 2015 — are all now well on their way to leave the solar system and journey to other stars.

However, the interplanetary voyage for these craft was a bonus ending to their main mission — visiting the outer planets — rather than the main goal. For this reason, their speeds are slower than desirable for stellar visitation, and the nuclear power sources of these craft will long be dead before they encounter a nearby star — in about 40,000 years for *Voyager 1* and *2*.

But what if we wanted to really take close-up pictures and gather other data for a nearby star system in a more reasonable time, would it be possible to get there much faster? Recently serious proposals have been put forward to do exactly that.

Interstellar Probe and StarChip

InterStellar Probe (ISP) was a NASA-funded study in 2018 that examined the concept of accelerating a probe using a slingshot around the planet Jupiter. This craft would exit the solar system faster than the *Voyagers* — in only 16 years — and investigate the gas and dust between the stars, known as the interstellar medium, for a further 34 years before its nuclear power source expires.



An even more ambitious idea dreamed up by Yuri Milner's Breakthrough Foundation is the Breakthrough Starshot — a plan to send a flotilla of tiny spaceships (dubbed *StarChips*) to our nearest neighbor star, Proxima Centauri b. The micro-craft, weighing just a few grams each, would be ejected from Earth orbit by powerful laser bursts directed at them from the ground, catching the laser light in 4 m × 4 m "light sails," and accelerating them to reach speeds of up to 20 percent of the speed of light.

At these high speeds, the craft would reach Proxima Centauri b in only 30 years and could send back data that would reach us in 4 more years. If alien civilizations existed, we'd get some great postcards of them.

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Part 5

Astrobiology and Culture

IN THIS PART …

Find out how ideas of alien life have crossed lines between science, science fiction, and belief.

Learn about myths, beliefs, and hoaxes concerning mistaken and falsified discoveries of alien life.

See how writers and filmmakers have envisaged “first contact” with aliens, friend and foe.

Discover how scientists draw inspiration from science fiction and vice versa.

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Chapter 18

Hoaxes and Conspiracies

IN THIS CHAPTER

- **Discovering the wide variety of accounts of alien visits to Earth**
- **Finding out how UFO stories increased dramatically after World War II**
- **Learning the facts about recent reports of alien spaceships in our solar system**

The search for alien life, not surprisingly, strays easily across the murky boundary between factual truth and credulous belief. Although scientists try to bring rigor, experiment, evidence, and skepticism to all claims, it's human nature to become excited about fantastical possibilities, sometimes on the flimsiest of evidence.



REMEMBER Let me be clear about one thing — there is no known and widely accepted evidence for *any* alien life that meets scientific standards, at least at the time of writing this book (check the publication date). I hope I can say something different in a future edition, but that's the status right now. Anything else you have heard on TV shows, in tabloid magazines, pseudo-factual books, or sensational websites is not widely accepted by the scientific community.

At the benign end of the scale, "anything else" includes weaker scientific evidence proposed and believed by only a few scientists, including:

- Life on Venus deduced from possible phosphine gas (see Chapter 14)
- Subsurface ecosystems on Mars inferred from possible methane leaks (see Chapter 12)

- Evidence for life on planet K2-18b from possible evidence of DMDS gas (see Chapter 16)

Although these ideas have been published in mainstream scientific journals, the evidence remains far too weak *at present* for widespread acceptance by the majority of scientists. This may change in future as new data arrives.

Somewhere in the middle of the alien-claims scale, we find photos of UFOs and other phantom flying, walking, swimming, or underwater objects or creatures that are genuinely believed to be evidence for aliens by their excited photographers, which sometimes include respected military pilots and other hard-nosed figures. Most of these photographs can be shown to be clouds, experimental aircraft, and the like, and none have ever been seen close enough to verify claims of extraterrestrial origin.

At the far end of the scale, evidence for alien life can be an outright fabrication, sometimes done for innocent fun (as with the quite beautiful crop circles), and at other times as a more cynical money-making venture, exploiting natural human curiosity for the new, unexplained and unknown.



TIP Earlier in this book, I covered some of the more marginal scientific claims for detection of alien life. In this chapter, I debunk a few of the more pervasive and fantastical hoaxes and conspiracies about evidence for alien life.

Ancient Aliens

The idea that aliens visited the Earth in the distant past — either as progenitors, helpers, or sometimes combatants with humans of that era — is not a new idea. Such stories can be found in ancient religious texts including the biblical contemporary Book of Enoch (and possibly in the

Books of Genesis and Ezekiel), and countless other myths and legends, although the lines between gods, angels, and aliens are often blurred.

Others have looked at ancient monuments, statues, and carvings and surmised that only intelligent, highly technical alien civilizations could be responsible. In the heady days of the early space age in the 1960s and 1970s, such ideas underwent a mainstream revival, spearheaded by the popular writings of Swiss alien evangelist Erich von Däniken and his bestselling book *Chariots of the Gods?*



TECHNICAL STUFF Von Däniken and other proponents of the "ancient aliens" hypothesis often point to ancient structures and stone workings as evidence for their theories, ignoring mainstream scientific and cultural explanations. I've listed some in Table 18-1, along with the more widely accepted archaeological interpretation.

TABLE 18-1 Disputed Evidence for Ancient Aliens

Artifact	*Alien interpretation*	*Archaeological explanation*
Pyramids	The occurrence of pyramids in multiple, unrelated cultures worldwide, along with the apparent technological leap required to create these structures relative to the technologies of earlier cultures, implies the sudden influx of high technology from outside the Earth.	Pyramid building developed gradually over time, and the gradual evolution of pyramid architecture is preserved, for example, in Egypt, where simpler tombs were gradually stacked on top of each other, eventually resulting in the grander pyramid style. Pyramid development in other cultures, such as Mesoamerica, underwent a similar development.

Artifact	*Alien interpretation*	*Archaeological explanation*
Moai of Easter Island	The iconic “giant heads” seen on Easter Island (Rapa Nui) could not have been moved to their locations far from their quarries with the technology available to the culture of the time. Moreover, the statues are intentional depictions of an alien race with features different from the appearance of the islanders.	The evolution of stone working on Rapa Nui leaves no doubt that the crafting of stones was developed incrementally over time. Smaller statues require no surprising technological leaps for the islanders to create and place. Larger statues are indeed remarkable creations, but plausible technologies for their movement have been demonstrated including rolling on logs, and a gradual “shuffling” process.
Nazca lines	These huge ground drawings and lines in Peru cannot be seen properly from the ground, requiring an altitude of several thousand feet to see the entire depiction. The creation of such artifacts nearly two thousand years ago must have required coordination from an aerial vehicle such as a plane.	Although the exact reason for creation of the Nazca images is not known, plausible theories include religious and cultural significance, depictions of constellations, and even irrigation. Although the images are best seen from above the ground, many terrestrial vantage points on nearby hills provide reasonable views. Creation of the lines requires only removal of vegetation and topsoil.
Stonehenge	The famous British circles of standing stones are evidence for alien technology, worship, or influence.	Although Stonehenge is an iconic structure, its creation as an astronomical and seasonal marker and site of religious and cultural importance is entirely within the sphere of stone age cultures at the time, with similar less well-known structures found across Europe.
The Sarcophagus of Palenque	The intricate carving on the sarcophagus of 7th century Mayan ruler K’inich Janaab’ Pakal found at the Temple of the Inscriptions in present-day Mexico depicts an astronaut lying on his back in a spaceship, working the controls of a rocket.	The depiction of the Mayan ruler is not unusual among other contemporary Mayan art, with iconography including a two-headed serpent, the World Tree, noblemen and typical cosmological symbols of the Sun, Moon, and a star. No elements require interpretation as being representative of high technology.

Figure 18-1 shows some of these misinterpreted artifacts.



(a)



(b)



(c)

Credit: (a) Diego Delso/Wikimedia Commons/CC BY-SA 4.0 (b) Douwe C. van der Zee/Wikimedia Commons/CC BY-SA 4.0 (c) Madman2001/Wikimedia Commons/CC BY-SA 2.0

FIGURE 18-1: (a) Nazca geoglyphs known as “the Spider”; (b) the Great Pyramid of Khufu at Giza, Egypt; (c) Carved lid of the tomb of K’inich Janaab Pakal I in the Temple of the Inscriptions.

The Flying Saucer Craze of 1947



REMEMBER The modern fascination with UFOs originates in the summer of 1947 in the United States. The "flying saucer craze" began when businessman and private pilot Kenneth Arnold reported seeing a string of nine shiny objects flying past Mount Ranier on June 24th. Arnold's detailed and convincing descriptions of objects shaped like "saucers," "disks," or "pie pans" proved highly convincing, and after being interviewed by newspaper and radio stations, the story spread quickly across the United States.



TIP In the subsequent days and weeks, hundreds more sightings of "flying disks" or "flying saucers" were also soon reported across the US, peaking around July 7th and diminishing soon afterwards. However, this craze set the stage for another bombshell news story that was to come soon afterwards, forming one of the most enduring myths about recovered alien artifacts.

The Roswell Incident



REMEMBER On June 4, 1947, researchers at Alamagordo Army Air Field in New Mexico launched the latest in a series of top secret balloon experiments, known as "Project Mogul." These strings of balloons were designed to listen for Soviet bomb test explosions. Later that month, the June 4th balloon string crashed on the land of rancher Mac Brazel, who found debris, including tinfoil, wood beams, rubber, and tape scattered over a wide area.

Unaware of the flying saucer craze that was then gripping the rest of the country, Brazel contacted the sheriff in the nearby town of Roswell, who alerted the Roswell Army Air Field (RAAF). The base then sent two

officers, Major Jesse Marcel and Captain Sheridan Cavitt, back to the property with Brazel, where they collected much of the debris.



REMEMBER On July 8th, the Army made a swift and ill-advised press release informing local newspaper that they had recovered pieces of a "flying disk," but amended it soon afterwards to a story that the debris was from a crashed weather balloon, somewhat closer to the truth.

The story soon faded from the headlines, until it was dramatically revived 31 years later when prominent ufologist Stanton Friedman interviewed Major Jesse Marcel from the original investigation team, who now stated that he believed the debris was extraterrestrial. In 1979, Marcel was interviewed by the tabloid *National Enquirer* magazine, which brought widescale attention to the story.

More attention followed in 1980 with publication of the book *The Roswell Incident* by Charles Berlitz and Bill Moore, purporting to reveal the "truth" about what happened in Roswell. The book speculates that an alien spacecraft was struck by lightning and crashed. The spacecraft parts and bodies were subsequently found and concealed by the US Government in an elaborate cover up to prevent widespread panic.



TIP The Roswell incident has remained a prominent feature of extraterrestrial conspiracy theories ever since, with versions of the story being revived and embellished at regular intervals. A prominent example was the 1995 pseudo-documentary movie *Alien Autopsy: Fact or Fiction* by British filmmaker Ray Santilli, showing faked footage of an alien corpse being dissected in the aftermath of the supposed 1947 UFO crashs.



TIP Other aspects of the story involve elderly Americans recalling seeing alien bodies recovered from the New Mexico desert at around the same time. These memories stem from a 1950s US Air Force program known as Operation High Dive, which used dummies to test high-altitude experimental parachute systems. Frequently, the fallen dummies were recovered, including from private civilian property, and placed in body bags or on stretchers for convenient transport back to military bases.



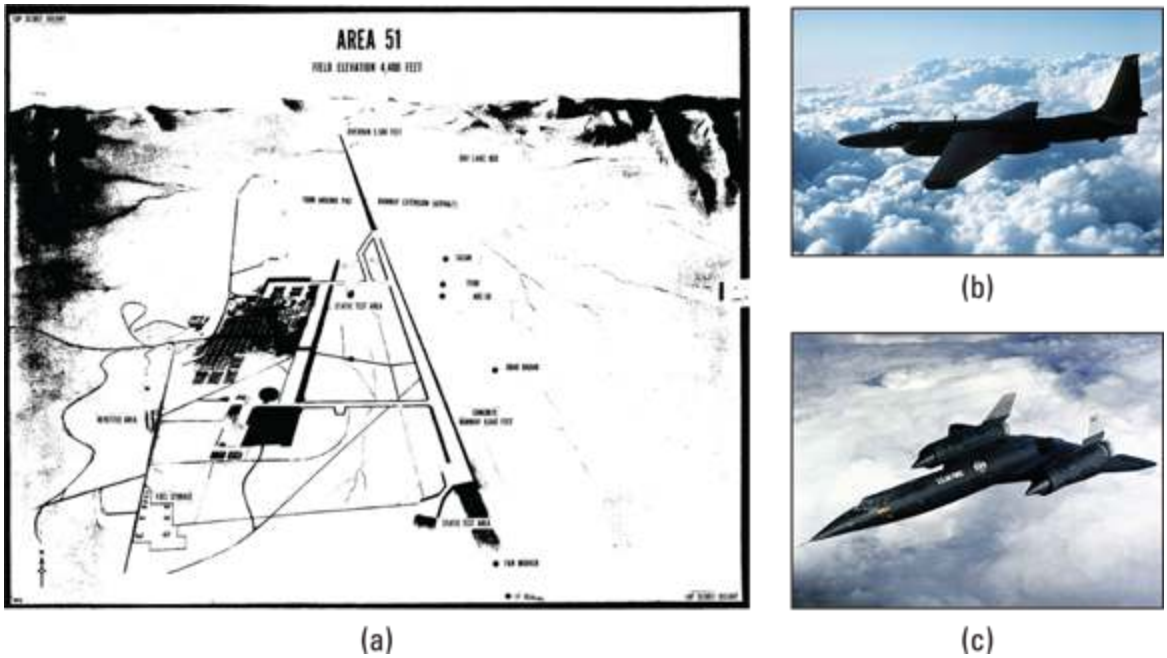
REMEMBER No doubt, the isolated nature of the desert location, combined with the very real but occasionally bizarre military experiments and the natural secrecy surrounding these, has contributed to the believability and longevity of the alien rumors in central New Mexico, despite the well-known terrestrial explanations. This has led to a booming *ufology* tourism around the small town of Roswell, including gift stores, events, and even an "International UFO Museum and Research Center."

Area 51



TECHNICAL STUFF Another US military test range, known as *Area 51* (see Figure 18-2a) in Nevada, is the center of a further set of rumors related to UFO sightings. Area 51 is centered on the Groom Lake salt flat, a natural landing strip used to test experimental aircraft such as the CIA U-2 (see Figure 18-2b) starting in 1955 (Project AQUATONE). The name switched from Groom Lake to Area 51 in 1959 with the inception of Project OXCART, a surveillance program that included the development of the A-12 aircraft, a

precursor to the famous SR-71 Mach 3+ high-altitude reconnaissance aircraft (see Figure 18-2c).



Credit: (a) Central Intelligence Agency/Wikimedia Commons/Public domain (b) U.S. Federal Government/Wikimedia Commons/Public domain (c) United States Department of the Air Force/Wikimedia Commons/Public domain

FIGURE 18-2: (a) CIA map of Area 51. (b) U-2 high altitude reconnaissance aircraft. (c) A-12 supersonic test aircraft.

During the 1950s and 1960s, the development of the experimental high-altitude aircraft led to UFO sightings by commercial pilots flying at much lower altitudes, often mistaking sunlight glinting from the wings or fuselages as fast-moving UFOs. Air force investigators working for Project Blue Book checked and crossed-referenced UFO sightings from 1952 to 1969 near to Area 51 against military records, eliminating most of them as matching up with known flights.



TIP Area 51 first reached the ears of the wider public when it was discussed in a 1988 TV show "UFO Coverup? Live." In this hoax, prominent UFO proponents related an elaborate story involving a supposed secret US Government group known as Majestic 12 or MJ-12. This was purportedly formed at the instigation of President Harry Truman in 1947 to investigate and recover pieces of alien spacecraft — tying neatly back to the initial Roswell Incident. In one part of the show, shadowy "former government" operatives recounted how the US government had permitted three "guest" aliens to reside and operative from Area 51.

In later years, Area 51 has popped up repeatedly in other TV shows and books, with claims from "former Area 51 workers" that they witnessed aliens being present on the site, or had seen parts of alien spacecraft. No evidence other than exaggerated claims has been provided.

Alien Abductions



TIP The most spine-chilling stories are those of direct human encounters with live aliens. These are often described in terms of forced abductions, where the humans are subjected to a series of medical examinations and tests, before being returned to their point of abduction with fragmented and partial memories of the incident (see the sidebar, "The Hill Abductions").



TIP The "Hill abductions" provided a template for many subsequent abduction accounts that tend to feature recurring details such as:

- Abductions in isolated locations, often at night

- An alien spacecraft descending with blinding lights
- Aliens with large eyes and similar uniforms
- Loss of memory for periods of time during the encounter ("missing time")

As with other alien stories, the Hill incident inspired many TV show episodes, fictional novels and stories, and even movies such as *Close Encounters of the Third Kind* — a topic discussed further in Chapter 19.

THE HILL ABDUCTIONS

A key early example is the famous "abduction" of Barney and Betty Hill over the night of September 19–20, 1961. The Hills were driving home in rural New Hampshire when they first witnessed a bright point of light in the sky moving rapidly upwards. They stopped and looked at the object through binoculars — it appeared to be an odd-shaped craft flashing multicolored lights and moving erratically. Further up the road, the craft, now seen to be a flying saucer, descended toward their vehicle and hovered over the road. Barney Hill got out of the car and approached the saucer, seeing alien figures inside. The Hills then attempted to flee in their car, but claimed to have fallen unconscious and awoke much later near the town of Concord. Later, under hypnosis, they provided more details of their "abduction," although their individual accounts differed significantly. Some researchers have noted that details of incidents resemble those of TV shows that aired around the same time as the hypnosis sessions, including Barney's recollection of aliens with "wraparound eyes."

Interstellar Spacecraft



REMEMBER The topic of UFOs came sensationally back into the spotlight again in 2017 with the discovery of the first confirmed interstellar object: 1I/'Oumuamua (refer to Chapter 10). This object is deemed by astronomers to have an irregular shape and be tumbling in space, due to its highly variable and oscillatory light signature. Nevertheless, the vast majority of astronomers believe it to be of natural origin: some kind of interstellar comet or asteroid.

Not so, said Harvard professor Avi Loeb, who in 2018 pronounced that the anomalous characteristics of the object could only mean that it was an alien spaceship. He emphasized the "non-gravitational acceleration" of the object, meaning that it changed direction in ways that were not due to the Sun's gravity. Nevertheless, such changes in direction are common with regular comets, due to jets of gases erupting from them in various spots.

When a third interstellar object (3I/Atlas) was discovered approaching the inner solar system in 2025, Loeb again pronounced that it was an alien spaceship. This time, his evidence centered on a statistical analysis of its trajectory, musing that its flight path in close alignment with the orbit of the Earth was unlikely to be an accident. In addition, Loeb says that the path of the object, passing close by several major planets, is unlikely to have happened pure chance, and so the object must be targeted by alien direction.

EXPLODING METEORITE OR SPACESHIP?

Loeb made an even more sensational claim in 2019: a fireball (exploding meteorite) previously detected to have occurred in 2014 over the Pacific Ocean near Papua, New Guinea was in fact an exploding alien spaceship. Loeb and collaborator Amir Siraj subsequently mounted an expedition to visit the site, dredging the ocean floor with a magnetic sled and finding "fragments" of material that they claimed originated from the exploding spacecraft. Other scientists, however, pointed to more prosaic explanations: volcanic ash or terrestrial pollution, which can produce similar types of particles. In a further blow for Loeb and his cohort, some seismic data used to pinpoint the location of the fireball was later determined to have mistaken the rumblings of a truck passing near the seismometer station on Manus Island for the fireball explosion.



REMEMBER Other scientists, however, dispute that the path of 3I/Atlas is in any way unlikely, and all evidence from observations of the object's outgassing show that it resembles expectations for a comet, albeit a very ancient one, having formed 10 billion years ago, more than twice the age of our solar system.

Crop Circles



TIP An amusing and fairly harmless offshoot of ufology was the dramatic rise in the appearance of *crop circles* in the late 1980s and afterwards, especially in the UK, although there were records of earlier such phenomena. A *crop circle* is a large pattern made in an arable field (wheat, barley, and the like), usually circular in nature, although later circles became increasingly complex geometric patterns (see Figure 18-3).

Frequently in the news during the 1980s, the circles fascinated the public and experts of various types speculated on a wide array of possible causes:

- Meteorological phenomena
- Paranormal or ghostly activity
- Landing sites or messages from aliens



Credit: Jabberocky/Wikimedia Commons/Public domain

FIGURE 18-3: A crop circle seen near Lausanne, Switzerland in 2007.



TIP The origin of the modern craze was explained not long afterwards in 1991, when two British pranksters, Doug Bower and Dave Chorley, came forward to take responsibility for creating many circles in the UK beginning in 1978, and inspiring a wave of copycat activities in the UK and around the world. Bower and Chorley then demonstrated the activity to news journalists, which entailed using just a simple plank of wood connected via a rope to a central anchor point, enabling a hoaxer to crush crops in a neat circle.

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Chapter 19

Astrobiology in Arts and Culture

IN THIS CHAPTER

- **Learning how science and science fiction can influence each other**
- **Finding out ideas about alien races, technologies, and cultures**
- **Seeing how thoughtful writers have leveraged scientific knowledge to create engaging stories**

If you've ever attended a science fiction convention, you've probably noticed many attendees wearing shirts with NASA logos, and panels running in side rooms with space scientists talking about space missions — even as there are tutorials on costume and makeup running in next-door rooms.

Likewise, if you've attended a professional scientific conference, or visited a science museum, you've probably seen people of all ages wearing t-shirts with images from science-fiction movies and TV shows. The museum gift shop will likely be selling introductory science books alongside sci-fi titles.

All this to say that science fact and fiction go together very closely hand-in-hand to the point where they are sometimes almost indistinguishable. It's perhaps not surprising that fans of space adventures are eager to learn what sorts of space exploration are being undertaken in the real world. Indeed, much of science fiction takes inspiration from real-world science.

However, the relationship also runs the other way, with scientists and engineers taking inspiration from science-fiction ideas, which

occasionally are brought to reality.

In this chapter, I won't try to span the huge topic of the connection between science and science fiction. However, I more narrowly discuss some of the most interesting examples where science and science fiction have met in the topic of astrobiology.



WARNING You may encounter some "spoilers" in the chapter ahead, so read at your peril!

Cells and Spores from Space

Perhaps the easiest aliens to imagine are types of primitive life, although those certainly don't always have to be benign. In science fiction, alien microbes have been a staple fixture for as long as science fiction has existed.

These can provide thought-provoking ideas for scientists contemplating possible types of extraterrestrial primitive life to search for, as well as contributing sobering motivations for planetary protection.

Here are a few examples:

- In the 1969 novel ***The Andromeda Strain*** by Michael Crichton, an alien microbe is brought to Earth by a crashing military satellite. Unfortunately for humans, the alien life kills any human life it touches and infects, requiring heroic amounts of biocontainment. The alien life mutates rapidly, but strangely lacks any DNA or RNA (you may notice this violates one of the key traits of life — see Chapter 4 — but hey, this is science fiction); rather, it can transform energy directly into matter. This causes problems for the team of scientists when the containment facility is rigged to explode to contain a possible outbreak, since it would make the viral outbreak even worse. I won't give away the ending; you can read the book or watch the 1971 movie to find out.

- In the video game series **Halo**, a parasitic alien lifeform known as "the Flood" infects and controls any sentient beings that it comes into contact with. So dangerous is the Flood, that the alien race known as the Forerunners engineered Halos, superweapons that could sterilize a whole galaxy as a last resort defense against the Flood spreading. This dangerous adversary returns in the *Halo* TV series (2022–).
- ***The Expanse*** novel and TV series by James S. A. Corey features a deadly infection known as the protomolecule, a type of "organosilicon" being. Those infected often die in a grisly fashion, but may also become connected to each other in a vast shared consciousness. The protomolecule was designed by a long-ago extinct civilization to adapt any biomass (including humans) that it comes into contact with to build "ring gates" that connect all infected planetary systems.
- Yet another primitive but dangerous alien emerges in the 2021 Korean TV series ***The Silent Sea***, which takes place on the Moon in an abandoned lunar base where the entire crew perished in an unknown disaster. The reason is discovered by a team sent to investigate, who find that the original science base discovered "lunar water," a strange living liquid that can transform (or kill) those who come into contact with it.
- More recently, you may have watched the 2026 blockbuster movie ***Project Hail Mary*** or read the book by Andy Weir. The Sun is suffering a terrible fate, having its energy consumed by an infectious organism known as "astrophage," which threatens to dim the Sun to the point where all life on Earth will freeze. The team investigating the contamination discover that nearby stars are all also infected, except for Tau Ceti, and send three scientists to investigate. This results in "first contact" with a different, intelligent alien life form, described later in this chapter.

Decoding Alien Broadcasts

Some science fiction writers have imagined what would happen if a SETI-like project achieved its goal and discovered a true alien radio signal. These ideas have contributed synergistically to SETI projects, stretching scientists' imagination about what sort of signals might be possible, what forms they might take, and whether we could decode them, if we even recognized them in the first place. Here are a couple of those ideas:

- The thought-provoking 1957 novel ***The Black Cloud*** by British astrophysicist Fred Hoyle relates events where a huge cloud of gas enters the solar system and stops near the Sun where it intermittently blocks light to the Earth, causing huge suffering and loss of life. Eventually terran scientists discover that the cloud is sentient and succeed in communicating with it, finding that it is vastly more intelligent than humans and unaware of life existing on a rocky planet.
- In the 1985 novel ***Contact*** by Carl Sagan (later made into a movie featuring Jodie Foster, and famously the VLT), SETI scientists discover a series of alien radio signals, beginning with a retransmission of one of Earth's first mass television broadcasts in 1936, and leading finally to a blueprint for an unknown machine. At the end of the movie, we find the heroine searching for further messages hidden in the digits of pi.
- In the 2008 novel and more recent 2023+ TV series ***The Three Body Problem*** by Liu Cixin, a disillusioned Chinese astronomer reaches out to the stars with a radio broadcast, and is surprised to receive a response eight years later from a civilization that turns out to be on Alpha Centauri. The "Trisolarans," now alerted to Earth's existence, decide to pay a visit …

Alien Languages

In many science fiction tales, aliens are encountered, but language barriers prove difficult to overcome. Writers imagine all different types of alien forms of communication, from telepathy to sounds to gestures.

Although physical encounters with sentient aliens seem a remote possibility for now, linguistic concepts are one aspect of thinking about the range of alien civilizations that might be attempting communication with us. Some examples include:

- In perhaps one of the most iconic sci-fi communication moments, aliens in the 1977 sci-fi epic ***Close Encounters of the Third Kind*** attempt to communicate with humankind through music, resulting in the famous five-tone sequence familiar to any child of the 1970s. This sets the stage for further, more advanced communication through musical score.
- In the ***Star Trek: The Next Generation*** episode ***Darmok*** (1991), the *Enterprise* meets a ship from the alien Tamarian race, whose language has hitherto been translatable into English but remains unintelligible gibberish. While imprisoned along with the Tamarian captain, Captain Picard finally realizes that the Tamarians are communicating in allegories, referencing myths and legends from their past to convey meaning.
- In the 2016 movie ***Arrival*****,** a linguist is recruited by the US military to attempt to communicate with an alien spacecraft that has arrived in Montana, one of twelve that have landed on Earth. The thinking process of the alien "heptapods" is so different from that of humans that some of their messages are misconstrued as threatening, due to biases in the human decoders. Eventually, the heptapods are understood to be able to see the future as well as the past and present, and by learning their language and way of thinking, humans can achieve these insights, too.
- The 2021 book (and 2026 movie) ***Project Hail Mary*** features an encounter between a human astronaut, Dr Ryland Grace, and an alien, who appears as an animated boulder ("Rocky"). Dr Grace has to learn to communicate with Rocky, training an AI model to learn Rocky's un-pronounceable tonal language and translate it into English, and vice versa.

Alien Invasions

Many sci-fi stories feature invasions of conquest by malignant aliens. Fortunately, none of these have come to pass, but contribute ideas of space travel and colonization that also make us question our own goals in space exploration. Among this diverse crop include:

- The archetypical Martian invasion story, ***The War of the Worlds*** was originally an 1898 novel by H. G. Wells set in southern England. It was famously transformed into a faux radio news story broadcast on CBS in 1938 by Orson Welles, terrifying the American public already on tenterhooks at the brink of World War II.
- Insect-like and frequently war-mongering aliens are prominent aggressors in novels such as Robert A. Heinlein's 1959 novel ***Starship Troopers*****,** and Orson Scott Card's 1985 novel ***Ender's Game*****.** The biologies of the alien insects or bugs in these stories are not highly developed, but they serve rather as an anonymous "other" that reflect humanity's moral attitudes toward war and the dehumanizing of the enemy.
- In the 1964 British TV series *Doctor Who*, the 22nd-century Earth has been invaded by a race of cyborg aliens known as "Daleks." In the six-part series ***The Dalek Invasion of Earth***, the Doctor and his companions have to team up with the local resistance to destroy the fleet of Dalek ships. The Daleks provide one example (there are many) where future evolution of a sentient species leads to the melding of organic and machine life — a project already being attempted on Earth in experiments with "cyber" interfaces that place electrodes on or implants in the brain.
- The 1987 to 1994 TV series ***Star Trek: The Next Generation*** (and subsequent related movies and series) features yet another hostile cyborg race known as The Borg. In this case, however, unlike the Daleks, the Borg are largely composed of "drones" connected to a single "hive mind" controlled by a queen — not unlike bees or ants on Earth.

Unleashing Aliens

Alternatively, sometimes it is humans visiting alien planets that unleashes disaster. Such stories provide cautionary tales that we should not take biological isolation and contamination protection lightly:

- In the 1956 novelette ***Colony*** by writer Philip K. Dick, a crew of human astronauts seeking habitable worlds finds a remarkably Earth-like planet that is lush with vegetation and prey animals but apparently devoid of higher predators. After landing, however, they find this is a deadly misapprehension, with the planet in fact rife with impossible-to-detect, predatory shape-shifting aliens akin to invisible amoebas.
- In one of the most-famous cinematic outings, the 1979 film ***Alien***, a crew of low-life space truckers ill-advisedly respond to a seeming distress call from an alien planet. They discover that the signal is emanating from a crashed alien spacecraft, which contains a cargo of eggs, one of which manages to infect a human investigator. The signal is too late recognized to be not an SOS but a warning signal, and the crew battles to rid itself of alien menace that now threatens their survival. It should be noted, however, that pathogens that infect humans and other animals have needed to co-evolve with us, so finding alien pathogens ready to infect us is actually considered unlikely by most scientists.
- The 2013 movie ***Europa Report*** imagines the sequence of events as a human crew first reach the surface of Jupiter's moon Europa. Hoping to find aquatic, subsurface life, they soon meet more than they bargained for.

Exotic Planets

Long before exoplanets had been discovered, writers had no problem imagining a vast array of alien planets. These range from different versions of Mars, Venus, and other solar system worlds to alien planets

of all kinds. Ideas of exotic exoplanets with differing gravities or atmospheres in turn have challenged scientists to imagine what adaptions lifeforms might have evolved to life there: from tall, spindly bodies for low-gravity worlds, to more powerful lungs and tetrapodal bodies for high-gravity worlds.

Our scientific concepts are now being challenged in the opposite direction by the discovery of myriad types of exoplanets, many undreamt-of even by science fiction writers. These have in turn provided fodder back to creative industry:

- In perhaps one of the most imaginative alien worlds of all, the 1961 novel ***Solaris*** by Soviet writer Stanislaw Lem (made into several movie adaptions) features a conscious alien planet, Solaris, that manipulates energy, matter, and human consciousness, leaving human investigators grappling with the nature of their perceived reality.
- In the 2014 film ***Interstellar***, explorers from Earth descend to the surface of a water-covered planet orbiting a supermassive black hole. They soon find the planet to be supremely dangerous, as the gravity of the black hole raises enormous, tsunami-like tides that threaten to drown the whole team. Another entirely ocean planet is Kamino in the *Star Wars* movie ***Attack of the Clones*.**
- The superbly imaginative 1962 novel ***Hothouse*** by Brian Aldiss imagines Earth in the far future, when it has become tidally locked to an enlarged Sun, with one side permanently in daylight and transformed into a teeming jungle. The population of humans, much reduced in size, now live in the canopy layer of a planet-wide banyan tree trying to evade predation. Meanwhile, the Moon has become physically linked to the Earth by a network of cobweb-like plant tendrils.
- In the 2000 movie ***Pitch Black***, the idea of planetary orbital dynamics is made a central plot feature. A spaceship crash lands on a planet orbiting a trinary system (with three central Suns, similar to the Alpha Centauri system) and the survivors soon learn that when

one of the stars is blocked and twilight descends, predatory bats emerge from underground. To make matters worse, a rare triple eclipse is imminent, when all three Suns will be blocked by another planet on a smaller orbit.

- The planet ***Helliconica***, superb leap of imagination by Brian Aldiss, is a world with very long years (about 2,500 Earth years) inhabited by two sentient races in constant conflict — a human-like species, as well as a less-developed, shaggy, Sasquatch-like race known as Phagors. Through a trilogy of books set in the spring, summer, and winter of Helliconica, the changing seasons on the planet provide major plot themes as the power balance between the two species shifts as they adapt to the changing environment.
- The planet Trantor, center of the Galactic empire in the ***Foundation*** book series of Isaac Asimov, is entirely covering a single city of 200 million km^2 supporting over 40 billion inhabitants, which extends below the surface and connects beneath the continents. Many inhabitants never see the sky.

Extraterrestrial Anatomy

In many sci-fi movies and TV especially (see *Star Trek*), aliens are often lightly modified humans (humanoids), largely for practical reasons of budget, but also since our imagination tends to fail when tasked to envisage the possible range of alien shapes, forms, and biologies with no current examples to build on. Nevertheless, many aliens of stories are inspired by Earthly creatures, including symbionts, shape-shifting protists, extremophiles, and predatory impersonators:

- As with the *Colony* story mentioned above, shape-shifting aliens can provide one of the most reliable sources of horror, as friends can be replaced by alien doppelgangers. This is the plotline of the 1938 story ***Who Goes There?*** by John W. Campbell, later made into the cult 1982 movie ***The Thing*** by John Carpenter. Aliens impersonating humans (although by addition of skin masks, not shape-shifting) is also used to good effect in the TV series ***V***. On Earth, we see

predators often using camouflage to evade detection — think leopard spots or chameleons color-shifting.

- In the aforementioned ***Alien*** movie, one of the most successful aspects of the film is the quite non-humanoid, insect-like alien, conceived in terrifying detail and complete with acid for blood and a parasitic, insect-like life cycle.
- Symbionts appear in multiple sci-fi stories. An example is the wise and ancient Dax creature that lives inside the young Trill woman Jadzia in the series ***Star Trek: Deep Space Nine*** (1991), giving her wisdom far beyond her years. Another case of a humanoid inhabited by an alien conveying special powers is the ***Venom*** character in the Marvel universe.
- The Oankali are a three-gendered race that feature in the trilogy of novels ***Lilith's Brood*** by Octavia Butler. The Oankali genders include male, female, and third, neutral type, the ooloi, which can manipulate genetic material from their mates to build new offspring.
- A truly diverse set of aliens appear in the ***Galactic Milieu*** novel series by Julian May, which are said to represent all races of the galaxy to develop higher technology as well as telepathic powers that promote peaceful cooperation. These include small, purple, humanoid Poltryans, tentacled "monsters" known as Krondaku, green and slimy Simbiari, and feathered hermaphroditic Gi, as well as mysterious super-beings called the Lylmik.

Alien Civilizations

Although some intelligent aliens feature very terrestrial-like civilizations, such as the human-like races of the ***Dune*** and ***Foundation*** novel series, others are very different, designed to reflect different anatomies, environments, and histories.

- The five races of the *Galactic Milieu* series of Julian May, mentioned earlier, all have different home planets and cultures that are reflected

in their body types: The kraken-like ***Krondaku***, for example, mate in a watery dance on their high-gravity home world.

- Hive minds are common sci-fi tropes, including *Star Trek*'s ***the Borg***, a hive-mind race that assimilates other races and implants cyborg technology into the host nervous system, allowing them to become drones for a central, intelligent queen. The ***Formics*** of *Ender's Game* are another example.
- The many races of *Star Wars* reflect their home planets, such as the amphibious **Gungans** living in the swamps of planet Naboo, the nomadic **Sand People** of desert Tattooine with its sparse water and food, the pastoral **Ewoks** of forest moon Endor, and more.

Alien Technology

Alien technology ranges from faster-than-light starships to laser weapons, wormholes, and megastructures. Although these might seem fantastical, according to the Copernican principle, our own species, which has only recently learned how to leave its home planet, should be far from unusual in the galaxy, and perhaps even backward compared to multiple, likely much older sentient races. This gives some hope that alien megastructures, such as Kardashev Level 2–type Dyson spheres, may be amongst the simplest ways to detect alien civilizations, being the largest and most obvious signs. Similarly, we can envisage alien communication technology and use it to inform our search for interstellar broadcasts.

- The seminal 1972 novel ***Roadside Picnic*** by the Russian Strugatsky brothers imagines the aftermath of an alien visitation to Earth. The aliens have visited Earth in six places without making contact, but they left behind discarded artifacts both advanced and potentially lethal to the humans who find them. The novel proved highly influential with many subsequent adaptions for TV, stage and film, providing a cautionary tale of what an infusion of advanced alien technology might mean for humanity.

- In the *Star Trek: The Next Generation* episode ***Relics,*** the crew of the Enterprise-D discover a long-missing Federation ship crashed on the outer surface of a Dyson sphere.
- The Imperial probe droids of ***Star Wars*** provide an interesting take on our own robotic space explorers: from *Voyager*s to Mars rovers. These autonomous robots can travel across the galaxy and explore different planets, not unlike the interstellar probes dreamed of by human scientists.

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Part 6

The Part of Tens

IN THIS PART …

Review ten of the most important outstanding questions in astrobiology today.

Check out ten future space missions that could help us to answer these questions.

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Chapter 20

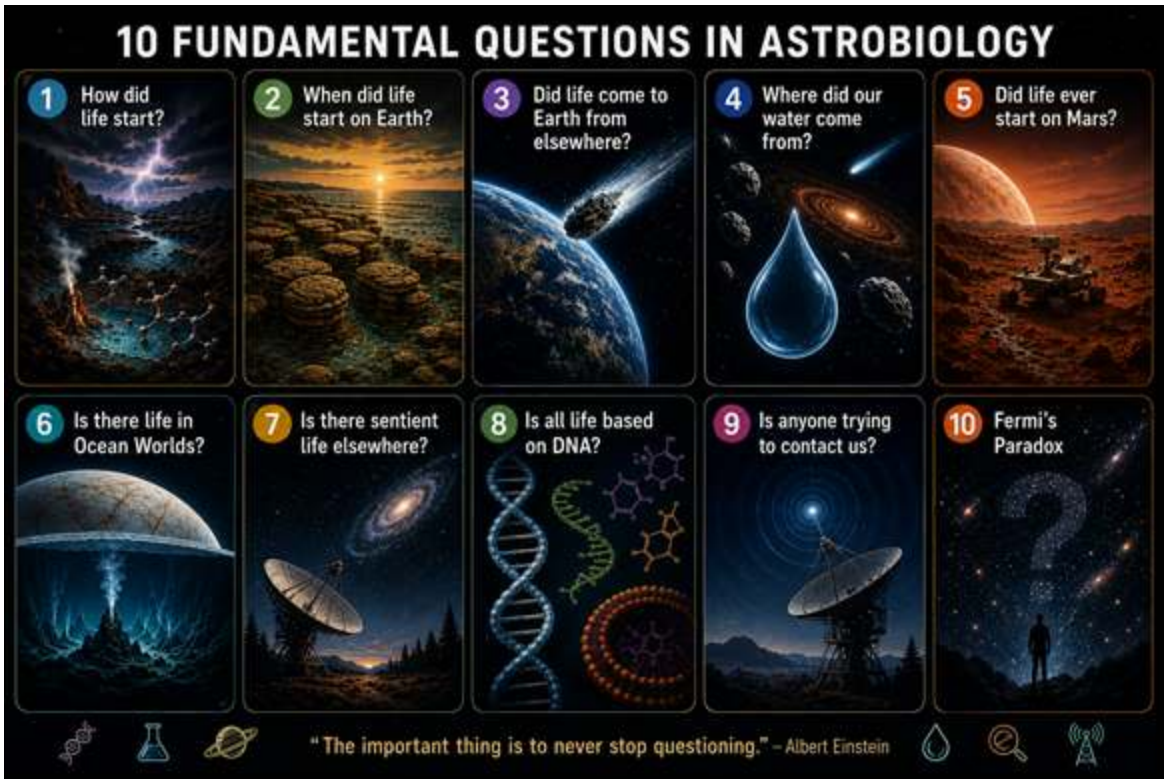
Ten Questions in Astrobiology

This book has focused on conveying the current state of knowledge in astrobiology, what we know so far about the origins of life on Earth, and our emerging knowledge of the possibilities of life in space.

However, it's also clear that we are just at the start of the process of searching for life in our galaxy: After all, exoplanets were first discovered only a few decades ago — less than the span of a single academic career.

This is both an exciting and perplexing time: a time when we might finally get the answers to questions asked by our ancestors for millennia, but also a time when we frustratingly don't yet have those answers.

For the more youthful readers considering a career in astrobiology (yes, you should), here's a rundown of ten key questions in astrobiology (see Figure 20-1) that you may be able to answer during your careers — with a caveat that these ten are the exclusive choices of the author and many more exist besides.



Credit: Generated with AI using OpenAI

FIGURE 20-1: Ten of the key open questions in astrobiology today.

How Did Life Start on Earth?

Biologists have made immense progress in understanding present-day life (refer to Chapter 4), whereas astrochemists have successfully probed the formation of large molecules in space (refer to Chapter 15). However, scientists still struggle to find the final missing links between the formation of nucleobases — as found in meteorites and asteroid samples — and their organization into RNA. From that point, the "RNA world" hypothesis (refer to Chapter 6) predicts that RNA was able to self-catalyze into life, although many details of this scenario remain to be worked out and puzzles remain.

When Did Life Arise on Earth?

As I discussed in Chapter 5, there remains an intense debate as to when life first appeared on Earth — was it 4.1 billion years ago (Bya), as

hinted by zircons found in the Jack Hills of Western Australia? 3.8 to 3.7 Bya, as indicated by carbon isotope anomalies in Greenland rocks? Or as recently as 3.5 Bya, when we see unambiguous evidence from stromatolite fossils? The question is important for more than merely record-keeping, since the timing will connect the origin of life to Earth's surface conditions at the time, giving us crucial insights into what the first habitable environment was.

Did Life Come to Earth from Elsewhere?

The debate about *panspermia* — life being seeded from space (refer to Chapter 10) — has evolved since first proposed. As our understanding of how abiogenesis could have occurred on Earth has improved, there is now less need to invoke an extraterrestrial origin. However, we also know now that the building blocks of life such as nucleobases *are* created in space and could have arrived at least in small quantities through space rocks — meteorites. Whether chemicals from space directly led to terrestrial life remains unknown, despite many wild theories in the pseudoscience sphere (refer to Chapter 18).

Where Did Our Water Come From?

Water is essential for life on Earth, although debate continues about whether life originated in the ocean (perhaps at deep-sea vents, refer to Chapter 9), in "warm little ponds," or even in watery pockets in ice. However, we also know that any early water covering on Earth would very likely have been lost and therefore replenished later, either endogenously (released from the Earth's mantle) or exogenously (from meteorites and comets) — or perhaps a little of both. The degree, sources, and timing of this "late veneer" remain an area of active study.

Did Life Ever Start on Mars?

In Chapter 11, you learned about the influential Martian meteorite ALH84001, which generated an active debate among geologists in 1996 when some scientists proposed that it contained life. Even earlier, there was the ambiguous evidence for metabolism from the *Viking* labeled release (LR) experiment, which may have just been peroxide in the Martian soil (refer to Chapter 12). In the 2000s, there has been the debate over Martian methane: whether it comes from microbial life in the soil, or even whether it exists at all. Despite all these controversies, we still don't have definitive evidence for life on Mars, although evidence appears to show that Mars could have been habitable during its early Noachian period. Perhaps a sample return (see next chapter) will finally settle the question, or the riddle may remain for human excursions to the Martian surface to investigate.

Is There Life in Ocean Worlds?

My favorite question! In the previous question we noted that life on Earth needs water; however we also know that there is actually plenty of water in space. Not only frozen water (as in comets), but liquid water, in the moons of the outer solar system such as Europa and Enceladus (refer to Chapter 13). These environments certainly appear to be warm, wet, and *habitable* (having access to nutrients from surrounding rock), leaving only the question: Are they currently *inhabited*?

Must Life Be Based on DNA?

All life on Earth uses DNA for its genetic code, but we also believe that all terrestrial life sprang from a "last universal common ancestor" (LUCA). If there was a "second origin" (or third, or fourth …) in space, would it necessarily use the same encoding of genes and proteins as on Earth, or are other types of biology possible, uniquely evolved for different extraterrestrial environments? The answer to this question has big implications for how we search for, and attempt to recognize, alien life.

Is There Sentient Life Elsewhere?

This is the big question of SETI — is there intelligent life elsewhere in the universe? Right now, we haven't found any definitive evidence, but the search is expanding and continuing, reinvigorated by the certain knowledge of exoplanets since the 1990s.

Is Anyone Trying to Contact Us?

Building on the previous question, we can ask not only whether there is sentient life in the universe, but whether it has the means, ability, and desire to contact us. Alien life may be so advanced that it has no desire to communicate with humans, or may remain stuck in a primitive, pre-technological civilization for reasons unknown, unaware that we are trying to determine its existence.

Fermi's Paradox

The last and greatest mystery was famously stated by Enrico Fermi: If we are relative newcomers in the age of the universe with our technological abilities, then most other galactic civilizations must be much older and more advanced than us. In that case, why haven't they visited us yet? (assuming that all current reports of alien UFOs are incorrect, as discussed in Chapter 18). Some possible answers are given in Chapter 17, but the truth is, this remains a mystery.

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Chapter 21

Ten Future Astrobiology Missions

For many years, NASA focused its attention on "following the water" — mostly to Mars (refer to Chapter 12). However, in the early years of the 21st century, it became apparent that the rusty red planet was not the only place — or even the best place — to look for a watery habitat.



TIP We now know from previous missions that water abounds in the solar system, from the icy moons of Jupiter and Saturn to wandering comets, distant Kuiper Belt objects (KBOs), and beyond, giving us plenty of places to search for life of all kinds.

In this chapter, I show you some exciting glimpses of future space missions that will help us to determine which niches in the solar system could be abodes of life. At present, some of these are just the far-off dreams of scientists and engineers — sketches and studies that may come to fruition someday — whereas others are already being built, or are even in flight.

For some other missions that could venture even further to other stars, refer to Chapter 17.

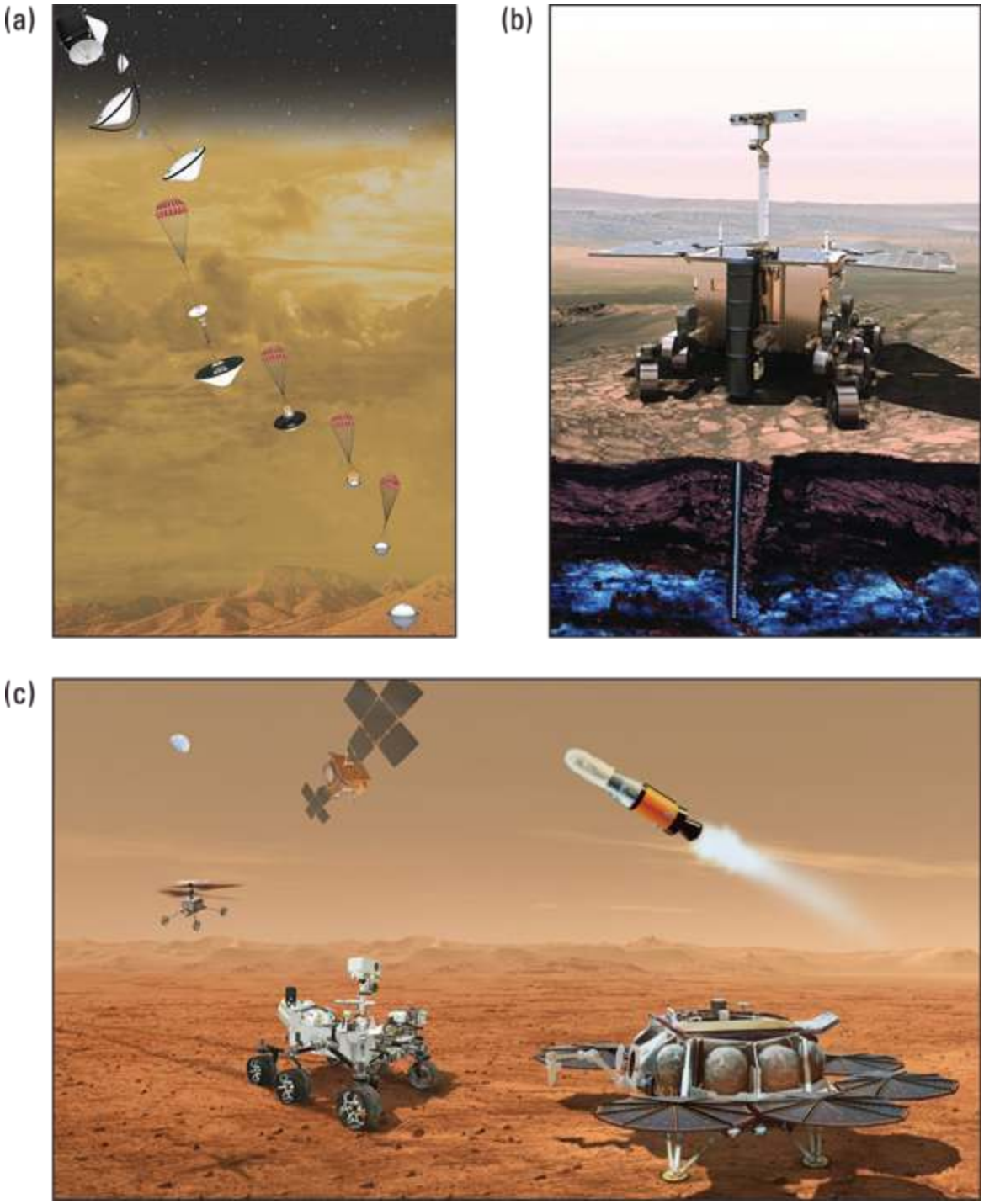
Cloudy with a Chance of Life: The DAVINCI Mission to Venus

Named for the famous renaissance scientist and engineer, *DAVINCI* is an atmospheric probe mission to Earth's wild sister planet Venus, currently scheduled to launch in 2031.



Even though it's the closest planet to Earth, there's a lot we don't yet know about Venus (refer to Chapter 14), including whether there could be a "habitable zone" in the clouds 50–55 km above the planet. At temperatures of 70 to 30°C (158 to 86°F) and highly acidic conditions, life would be unpleasant for humans, but perhaps more balmy for *thermoacidophilic* extremophiles (refer to Chapter 9).

DAVINCI will enter the atmosphere at high speed, initially protected by a heat shield (see Figure 21-1a). After decelerating, the probe will deploy a parachute and descend slowly to the surface while making measurements of temperature, pressure, gas concentrations, and, of course, taking photographs. A "mother ship" that carries the probe to Venus will fly past or possibly orbit, taking images and collecting spectra of the atmosphere.



Credit: (a) NASA Goddard Space Flight Center/Wikimedia Commons/Public domain (b) NASA/https://astrobiology.nasa.gov/missions/rosalind-franklin//Public domain/last accessed Oct. 11, 2026 (c) NASA/JPL-Caltech/Public domain

FIGURE 21-1: (a) The *DAVINCI* probe descending through the Venusian atmosphere. (b) The *ExoMars* rover that will drill to search for life on Mars. (c) Concept of the multi-step Mars sample return (MSR) mission.

Sampling Mars: ExoMars and MSR

Despite the many previous missions to Mars, we have barely scratched its surface — literally. Missions including *Phoenix* (refer to Chapter 12) have shown that water ice is present just below the red rocks and dust, providing a possible niche for life to cling on.

The forthcoming *ExoMars* rover from the European Space Agency (ESA) plans to remedy this. Named *Rosalind Franklin* after the DNA pioneer (refer to Chapter 4), the new rover carries a 2-meter (79-inch) drill (see Figure 21-1b) to extract subsurface material (*regolith*). The *ExoMars* rover is currently scheduled to head to the Red Planet in 2028.



Drilled samples will be passed to a sophisticated chemical analysis laboratory (named *Pasteur)* to characterize the types of rocks and minerals present, and search for organic materials that could indicate the presence of life. The rover is also ably equipped with cameras and even a ground-penetrating radar that will provide information about the geologic history of the landing site, and help to select the most promising drill sites.

Although the new *ExoMars* rover will be highly capable, its instruments can't hold a candle to the laboratories back on Earth. For this reason, Mars astrobiologists have set their sights on an even more ambitious goal: Mars sample return (MSR).

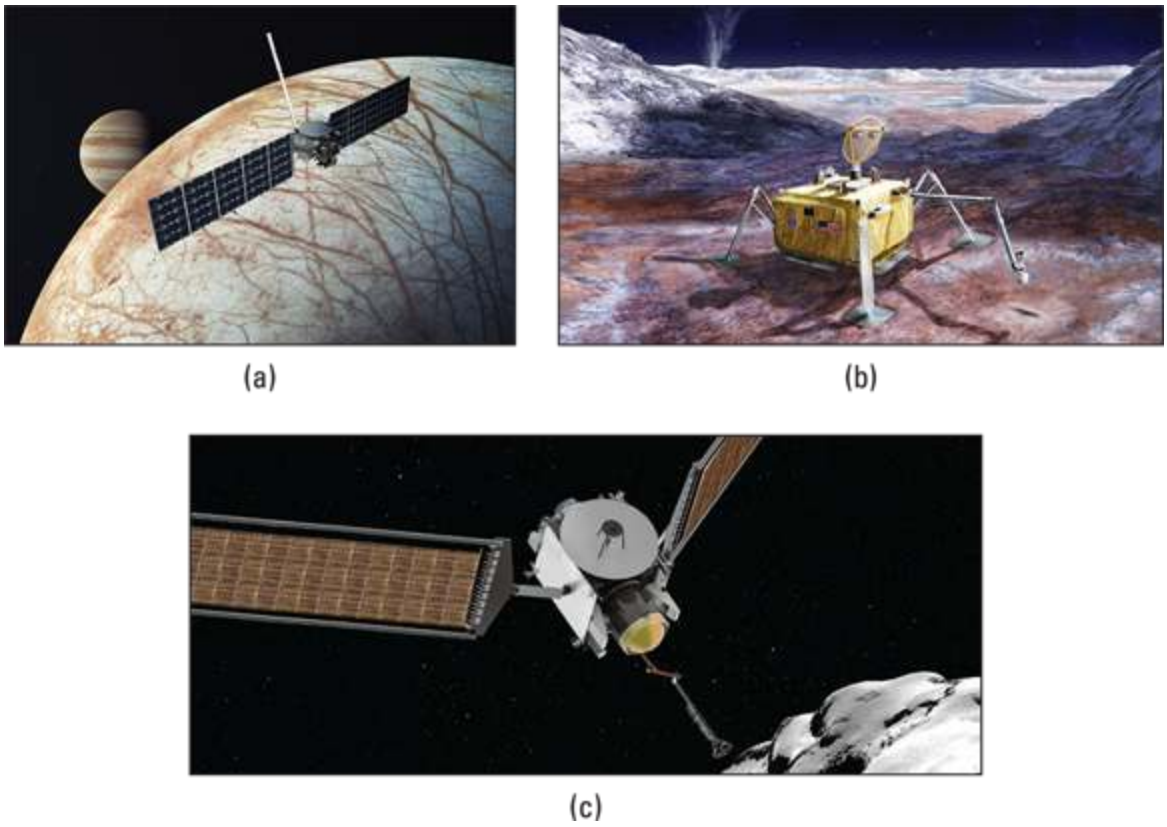
Recall back in Chapter 11 when I discussed meteorites that some are known to be pieces of Mars. So why then do we need to bring more rocks back to Earth at great cost and complexity? The reasons are numerous, but the most important include *site selection* (being able to target interesting locations for sampling), *history* (we will know what the samples have been through, unlike meteorites) and *processing (*meteorites are heated up and become highly processed, and interesting evidence may therefore be destroyed).



TIP The first samples returned from Mars could arrive as soon as 2031, courtesy of the CNSA (China National Space Agency) mission *Tianwen-3*. The mission is composed of two parts that will be launched separately in 2028: a Mars orbiter and Earth return vehicle, and a descent/ascent stage that will include a lander and possibly rover on the Martian surface to collect samples.



TECHNICAL STUFF NASA has already commenced its own MSR mission with the *Perseverance* rover that we met back in Chapter 12. While *Perseverance* is collecting samples, the later parts of this ambitious mission are more complex and not yet decided. A fetch vehicle (rover or helicopter) is envisaged to collect the samples collected by *Perseverance*, bringing them to a rocket which will transport them in a safe capsule to Mars orbit. Finally, an Earth return stage will rendezvous with the capsule in Mars orbit and return the samples back to Earth (see Figure 21-1c). These parts of the mission are currently awaiting funding, but if successful, the scientific results could be vast.



Credit: (a) NASA/JPL-Caltech/Public domain (b) NASA/Public domain (c) NASA/Public domain

FIGURE 21-2: (a) The *Europa Clipper* mission. (b) Concept of future *Europa Lander*. (c) Comet sample return mission — *CAESAR*

Visiting and Landing on Europa

While *Perseverance* roams Mars, another mission is already on its way to a further and more watery destination: Jupiter's moon Europa. You saw back in Chapter 13 that Europa is an *ocean world*, harboring a vast sub-surface global water ocean that dwarfs the combined volume of all the seas, lakes, and oceans on Earth. And everything we know about life so far tells us that oceans are usually teeming with all kinds.



The *Europa Clipper* mission (see Figure 21-2a) was launched in 2024 with scheduled arrival at Jupiter in 2030, when the spacecraft

will enter Jovian orbit and begin a series of more than 40 close flybys of Europa. *Clipper* will use a suite of instruments — including radar, cameras, spectrometers, and gas-composition–measuring devices — to characterize the surface, atmosphere, and subsurface and assess Europa's geologic history and potential habitability.

A future *Europa Lander* to further search for life would be a complicated undertaking, requiring an interplanetary cruise stage to carry the lander from Earth to Europan orbit, a de-orbit stage that would slow the lander down and lower it gently to the surface, and the lander itself, heavily shielded to protect sensitive instruments from the fierce particle bombardment (electrons and protons) of Jupiter's magnetosphere.



REMEMBER After landing at a promising site — most likely near a surface crack where water may have erupted recently (see Figure 21-2b) — the lander is estimated to survive for several weeks on Europa's surface, limited by battery life and radiation damage. This should be just enough time to scrape a few precious ice samples into its interior chemistry laboratory and test for any traces of life that have spilled out of the interior ocean and onto the surface — perhaps revolutionizing astrobiology as we know it.

Sampling an Icy Wanderer

Although Mars and the ocean world moons of Jupiter and Saturn get a high billing in the search for life, smaller objects — comets — may be just as important for understanding our origins and the potential for life elsewhere. You can revisit the section on the panspermia hypothesis in Chapter 10 to remind yourself how some scientists have mused that life on Earth could have been seeded from comets, which are known to carry many of the essential building blocks of life.



REMEMBER A comet sample return mission — building on the excellent groundwork by comet exploration missions such *Rosetta* (refer to Chapter 10) — would go a step further, and like MSR, return previous samples of cometary ice and gases back to Earth for detailed analysis. One mission concept — *CAESAR* (see Figure 21-2c) — proposed to return samples from Comet 67P, which was already visited by *Rosetta*. Such data could help us to better resolve the panspermia debate, and help us gain better insights into our own origins.

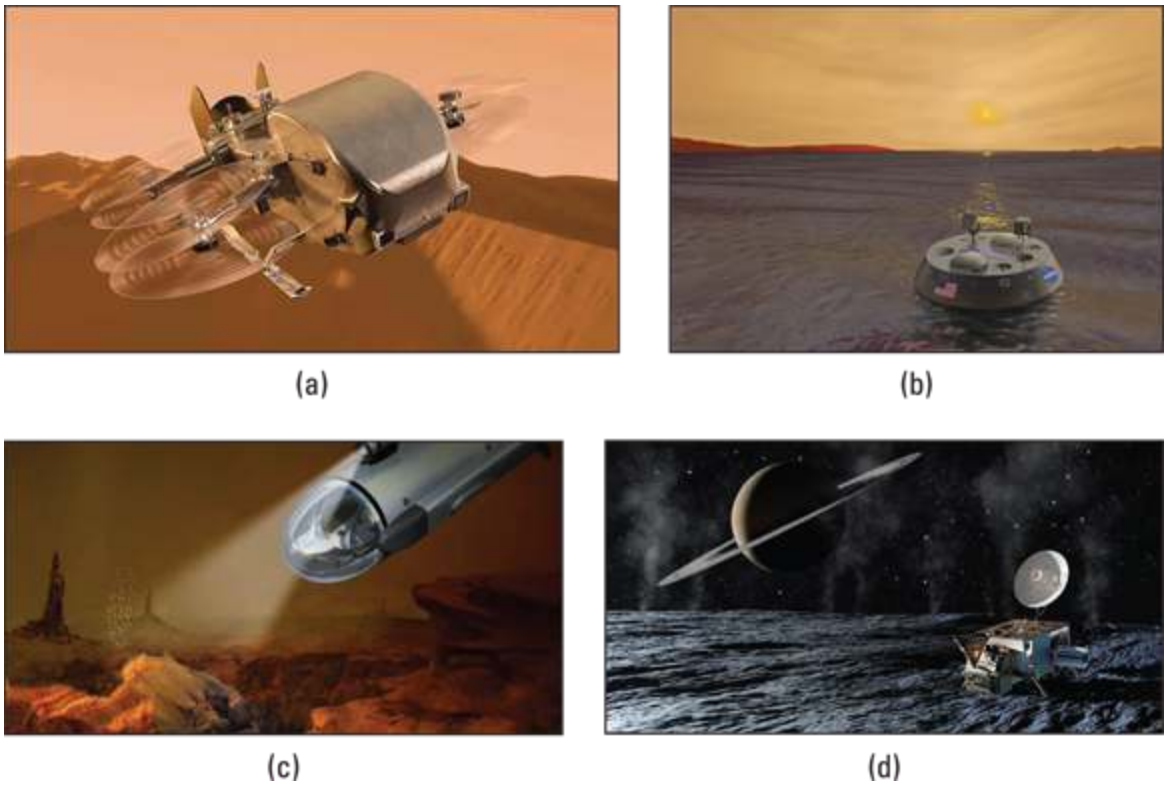
Jetting to Enceladus

It would be impossible to think of promising destinations to search for life without including Enceladus — Saturn's show-off moon with the spectacular water jets erupting into space and creating Saturn's icy E-ring (refer to Chapter 13).

The Enceladus *Orbilander* mission concept combines both orbital remote sensing and landed sampling measurements of Enceladus into a single mission. This ambitious undertaking (see Figure 21-3d) is made possible by Enceladus's small size and low gravity, so that landing is much easier than on Europa or Mars.



REMEMBER If approved to fly one day, a mission such as *Orbilander* could tell us whether the plume materials at Enceladus hold any evidence of life down in the interior ocean, such as biological materials.



Credit: (a) NASA/Johns Hopkins APL/Public domain (b) NASA/Public domain (c) NASA/Public domain (d) NASA/Public domain

FIGURE 21-3: (a) The *Dragonfly* Titan aerorover. (b) Proposed Titan sea exploration mission *TIME*. (c) Concept of a submarine exploring Titan's seas. (d) Enceladus *Orbilander*.

Three Titanic Missions

Saturn's moon Titan, that we learned about back in Chapter 13, evokes fascination for science, and astrobiology in particular, for many reasons. Of course, Titan has an atmosphere, and this produces many complex chemicals including many thought to be precursors or sustainers of life.

Unsurprisingly then, Titan has become a focus for future missions, including the *Dragonfly* drone now being built for NASA by the Applied Physics Laboratory (APL) in Maryland, USA. *Dragonfly* (see Figure 21-3a) — scheduled for launch in 2028 to arrive at Titan in 2034 — will investigate the crater Selk, where transient water melted by an asteroidal impact may have provided inviting conditions in the past for life to arise.



TIP Titan also has the famous seas of methane which may provide alternate abodes for life — albeit of a very different kind than lives in water. Two mission concepts to explore Titan's seas are the *Titan Mare Explorer* (*TIME*) (Figure 21-3b) — a floating science probe — and a proposed Titan submarine (Figure 21-3c), which would explore beneath the surface to see what lies in the depths of the methane lakes. Both these missions remain on the drawing board for now, but it seems certain that one day some version of these exciting missions will be sent to answer our questions about Titan's seas.

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Index

Numerics

3I/Atlas, 262
1I/'Oumuamua, 262

A

abiogenesis, 144, 159
    carbon bonding, 72–74
    conditions for, 72–76
    ingredients for life, 74–75
    origin of life, 75–76
accretion, 150, 189
acetaldehyde, molecular clouds, 214

acidophiles, 117, 119
Acidithiobacillus ferrooxidans, 118
adaptions, 118
alkali production, 118
DNA and protein repair systems, 118
less permeable cell membranes, 118
proton consumption, 118
proton efflux systems, 118
extreme, 117
iron, 118
moderate, 117
thermoacidophiles, 203
acid-tolerant species, 117
Adami, Chris, 107, 108
aerogel, 146, 147
aeroplankton, 201–202
Age of Enlightenment, and Scientific Revolution, 23
Aldiss, Brian, 271
ALH 81005, 160

alien
abductions, 261
ancient, 256
in arts and culture
broadcasts decoding, 267–268
cells and spores from space, 266–267
civilizations, 272–273
exotic planets, 270–271
extraterrestrial anatomy, 271–272
invasions, 269
languages, 268
technology, 273
unleashing, 269–270
disputed evidence for ancient, 257
hill abductions, 261
hunting for, 238
Alien (movie), 270, 272
Alien Autopsy (movie), 259
alien-claims scale, 256
alien contact, 280

alkaliphile, 119
adaptions, 119
alkaline-stable proteins, 119
cytosol acidification, 119
osmotic stress management, 119
sodium-driven energy, 119
stabilized membranes, 119
Lost City Hydrothermal Field, 120
Allchemy simulation, 108–109
Allende (1969) meteorite, 157, 158
Allen Telescope Array (ATA), 245
ALMA. *see* Atacama Large Millimetersubmillimeter Array (ALMA)
Alvarez, Luis, 69
Amazonian (3,000 Mya–present), 177
amines, molecular clouds, 213
amino acids, 77, 78, 84, 101–103, 106, 107, 113, 116, 119, 157, 159, 196
ammonia
molecular clouds, 213
on Venus, 204
amoebas, 88, 90, 270
anatomy, of comet, 137
coma, 138
nucleus, 137–138
tail, 138
Anaxagoras, 143
ancient rocks, clues in, 58–59
Anderson, Arthur, 126

The Andromeda Strain (Crichton), 266
anhydrobiosis, 122
ANSMET. *see* Antarctic Search for Meteorites (ANSMET)
Antarctica, 123–124
Antarctic Search for Meteorites (ANSMET), 156, 160
Apophis, 163
apoptosis, 95
apparition, 137
AQUATONE project, 260
Archean Earth, 76, 100, 102, 144
Archean eon, 62, 63–64, 99
Arecibo Message, 247, 248
Aristotle, 2, 7, 18, 23, 24, 117, 135
    atmospheric vapors theory, 135–136
Arnold, Kenneth, 258
Arrhenius, Svante, 143
Arrival (movie), 268
arthropods, aeroplankton, 201–202
artificial intelligence (AI), 44
artificial lifeform, 107
    and life simulations, 11
Asimov, Isaac, 271
asteroids, 117, 142, 146, 149, 154, 159, 162–164
astrobiologists, 111, 112, 117, 125

astrobiology
and culture, 13
evolution, 27–28
relationship to exobiology, 28
science fiction, 27–28
fundamental questions, 8
scope of, 9
astrochemistry, 13
atoms with nucleosynthesis, 209–210
Big Bang, 210
clouds, 213–215
future observatories, 218–219
life and death of star, 210–212
rainbow decoding with spectroscopy, 215–218
stellar generations, 213
astrochemists, 278
Astrology For Dummies (Orion), 17

astronomy
ancient observers, 16–17
philosophers, 17–19
Anaxagoras, 18
Anaximander, 18
Aristarchus, 18
Aristotle, 18
Bruno, Giordano, 19
Copernicus, Nicolaus, 19
Ptolemy, Claudius, 18–19
Pythagoras, 18
telescopic observation, 19–21
visible spectrum, 21–22
Astronomy for Dummies (Maran and Fienberg), 16, 150, 183
*Astrophysics for Dummies (*Phillips and Priwer), 22, 150, 210, 243
Atacama, 122, 123–124, 204, 218, 219
The Atacama Large Millimeter/sub-millimeter Array (ALMA), 32, 33, 204, 218–219
PDS 70 system from, 224
Atlas, 141

atmospheric composition, detection of, 234–235
carbon monoxide, 235
clouds, 235
dimethyl sulfide (DMS), 235
methane, 235
sodium vapor, 235
water, 235
water vapor, 235
atmospheric energy, source of, 102
atomism, 22, 23, 27
Attack of the Clones (movie), 271
autoinducers, 89
autotroph, 118
Avida program, 107–108
azotosome, 46, 197

B

Bayeux Tapestry, 135
Bell, Jocelyn, 241
Berlitz, Charles, 259
'Big Bang' theory, 33, 144, 150, 210
Big Ear antenna, 243, 244
biocrusts, 123
biofilms, 88, 89, 90, 93
bioleaching, 118
bioremediation, 121
biotic molecules vs abiotic molecules, 109

Biot, Jean-Baptiste, 152
Black Cloud (novel), 267
black hole, 212
black smokers, 104, 105, 114–115, 119
Borg, alien civilizations in arts and culture, 272–273
Borisov, 141
Borucki, Bill, 34
bounty of meteorites, 161
    drawbacks, 161–162
    Hayabusa, 162, 164
    Hayabusa 2, 162–164
    OSIRIS-REx, 163, 164
    Ryugu, 162–163
Bower, Doug, 264
Brahe, Tycho, 135, 136
Breakthrough Listen, 245, 246
broadcasts, alien in arts and culture, 267–268
Bruno, Giordano, 19, 222
buckminsterfullerene, 217
Burgess, Eric, 248
Butler, Octavia, 272

C

CAESAR, 287
Callisto, 189, 198–199
Cambrian Explosion, 59, 66–67
camera and video technology, space missions, 37

Campbell, John W., 272
canals, 166–167, 170, 171. *see also* Mariner 9
cannibalism, 86
carbonaceous meteorites, 157–159
    Allende (1969), 157, 158
    Murchison (1969), 157, 158
    Orgueil (1864), 157, 158
    Tagish Lake (2000), 158
carbon-based molecules, 72–74
    inorganic molecules, 72
    organic molecules, 72
carbon dioxide, molecular clouds, 213
carbon, molecular clouds, 217
carbon monoxide, 235
Card, Orson Scott, 269
career in astrobiology, 277
carotenoids, 114, 121
Cassini, 195, 196
Cavitt, Sheridan, 259
celestial motions, 17
Ceres, as ocean world, 198
Chariots of the Gods? (Däniken), 256
Charon, 200
Chatton, Eduard, 54
Chelyabinsk (2013) meteorite, 153–154

chemical evolution
abiogenesis, conditions for, 72–76
carbon bonding, 72–74
ingredients for life, 74–75
origin of life, 75–76
complex molecules, formation, 77
amino acids, 77
lipids, 77
nucleobases, 77
phosphates, 77
saccharides or sugars, 77
protocell formation, 81–83
cellular signaling, 82–83
membrane diversity, 83
ribonucleic acid (RNA), 77–81
catalysis, 79
information coding, 79
self-replication, 79
chemical soup, 100–103
The Miller-Urey experiment, 100–102
"muddy" with Titan's "tholins," 102–103
primordial soup, 100
Chemistry for Dummies (Moore), 209
chemolithoautotroph, 118
chemosynthesis, 46, 205
CHEOPS mission, 229
Chevaya Falls, 175, 176

China National Space Agency (CNSA), 285
Chlamydomonas nivalis, 117
chloroplast, 86
chondrites, 156
Chorley, Dave, 264
chronostratigraphy, 58, 59
Chroococcidiopsis, 128
civilizations, alien in arts and culture, 272–273
Cladosporium sphaerospermum, 127
Close Encounters of the Third Kind (movie), 261, 268
clouds, 235
Colony (Dick), 269
COM. *see* complex organic matter (COM)
coma, 137, 138, 140, 141, 146
Comet 67P/ *Churyumov–Gerasimenko*, 146

comets, 133–134
appearance and composition, 137
anatomy, 137–138
meteor shower, 138–139
sandbanks or snowballs, 138
in history, 133–134
Aristotle's theory of atmospheric vapors, 135–136
Halley's Comet, 136
omens and harbingers, 134–135
and life, 141–142
and meteorites, 11–12, 17
missions, 144
Halley Armada, 145
Rosetta, 146–148
Stardust, 146
origins and populations, 139
Earth's water from space, 142
interstellar objects, 140–141
panspermia, 142–144
visitors from outer solar system, 139–140
Comet Wild-2, 146
communication and signaling, unicellular cooperatives, 89–90

complex molecules
formation, 77
amino acids, 77
lipids, 77
nucleobases, 77
phosphates, 77
saccharides or sugars, 77
in space, 214
complex organic matter (COM), 157
computer simulations, 107–109
Allchemy simulation, 108–109
Avida program, 107–108
modern astrobiology, 40
Confidence of Life Detection (CoLD), 52–53
conspiracies, 255–264
constellations, 16, 138, 232
Contact (Sagan), 267
contamination, 161, 181
continuum of life, 50–51
Copernican principle, 53, 273
Copernicus, Nicolaus, 19
Corey, James S. A., 266–267
CoRoT mission, 229
Cretaceous-Paleogene extinction event, 68
Crichton, Michael, 266
Crick, Francis, 27, 84
crop circles, 263, 264

cryptobiosis, 129
Curiosity rover, 175, 180
cyanides, molecular clouds, 213
cyanoacetylene, molecular clouds, 213
cytokinesis, 94

D

The Dalek Invasion of Earth (TV series), 269
Dalton, John, 23
Däniken, Erich von, 256
Darwin, Charles, 25, 26, 67, 76, 96, 100
Darwin and Russell's theory, 26
Darwinian evolution, 9, 44, 81
DAVINCI mission, 204, 283–284
Debaryomyces hansenii, 180
deep-sea vents, simulation of, 63, 104–105
Deinococcus radiodurans, 126, 127
Democritus, 22, 23
deoxyribonucleic acid (DNA)
    and information encoding, 83–85
    minimal cells, 106–107
    vs ribonucleic acid (RNA) structures, 78
devolatilization, 191
diamond, 217
Dick, Philip K., 269
differentiation, 191
dimethyl sulfide (DMS), 235

Dimidium, 225
dinosaurs and extinctions, 68–70
    Cretaceous-Paleogene extinction event, 68
    late Devonian mass extinction, 68
    late Ordovician mass extinction, 68
    Permian-Triassic extinction event, 68
    Triassic-Jurassic extinction event, 68
Dione, 199
disks, protoplanetary, 223
DNA
    donations, radioresistant organisms, 127
    repair, radioresistant organisms, 127
    structure, radioresistant organisms, 127
Doppler effect, 226
    advantage, 226
    limitation, 226
Dragonfly Titan aerorover, 288
Drake Equation, 13, 34, 238, 239, 240
Drake, Frank, 238, 248
dwarf planet, 198
Dyson, Freeman, 250
Dyson Sphere, 250
Dyson swarm, 250

E

Earth, 135, 141–142, 144, 159, 160, 178. *see also* panspermia
and analog fieldwork, modern astrobiology, 39–40
extremophile investigations, 39
instrument field testing, 39
meteorite collection, 39
sample collection, 39, 40
atmosphere of, 136, 153
emergence of life, 278–279
geological history
ancient rocks, clues, 58–59
Archean eon, 63–64
geological record, 59–61
Hadean eon, 61–63
evidence of life, 62–63
zircons, 62
Phanerozoic eon, 66–70
Proterozoic eon, 64–66
dinosaurs and extinctions, 68–70
great oxygenation event (GOE), 65
oxygen and cells, 65–66
reactive oxygen species (ROS), 65
meteorites on, 153, 157, 160–162
origin of life on, 9–11, 278
origin of Moon, 151

telescopes on
The Atacama Large Millimeter/sub-millimeter Array (ALMA), 32, 33
The Jansky Very Large Array (VLA), 3, 31–32
The NASA Infrared Telescope Facility (IRTF), 32, 33
The Very Large Telescope (VLT), 32, 33
twinkling atmosphere, 166
watering from space, 142
Ehman, Jerry, 243
Einstein, 2, 7, 229
electromagnetic (EM) spectrum, 21
electronic transitions, 215
electrons, from Big Bang, 210
elements, from Big Bang, 212–213
Enceladus, 287–288
ocean world, 194–195
spray of water on, 195
Ender's Game (Card), 269
endoliths, 123
endosymbiosis, 86
environmental responses, 49
Eris, 200
ethane, 196
Eukaryota, 86, 87
eukaryotes, 10, 45, 54, 55, 65, 67, 86, 93

Europa, 185, 188
chaos, 193–194
cracking up, 192–193
ocean world, 192–194
visiting and landing on, 286–287
Europa Clipper mission, 286–287
Europa Report (movie), 270
European Space Agency (ESA), 285
evolution
and adaption
genetic drift, 50
horizontal gene transfer, 50
life, characteristics of, 49–50
mutation, 50
natural selection, 50
multicellular life, 93–94, 96–97
from colony, 93
failed cell division, 94
from single-celled eukaryotes with multiple nuclei, 93
from symbiosis, 93
Ewoks, alien civilizations in arts and culture, 273
exobiology, 28, 29, 30
ExoMars, 284–286
ExoMars Trace Gas Orbiter (TGO), 180

exoplanet, 221, 224
atmospheres, 233–234
detection of, 224–225
diversity, 229–230
habitable, 221–235
unexpected survivors, 224
exotic planets, alien in arts and culture, 270–271
The Expanse (Corey), 266–267
Exposing Organisms to a Space Environment (EXPOSE), 128, 129
extracellular polymeric substances (EPS), 88, 89
extra-terrestrial anatomy, alien in arts and culture, 271–272
extra-terrestrial intelligence (ETI), 237–251
extremophiles, 111, 112, 121, 124, 128, 179
thermoacidophilic, 284

F

falling rocks, 152
falling stars, 16, 153–154
FARSIDE, 219
female deities, 17
fermentation, 24, 46, 86
Fermi, Enrico, 240, 280
Fermi's paradox, 240, 280
grappling, 240, 246
self-annihilation, 240
sparseness, 240
zoo hypothesis, 241

Fienberg, Richard Tresch, 16, 20, 150, 183, 187
"fingerprint," 142, 215, 226
fireball explosion, 153, 263
flyby missions (Voyager 2), 36, 37, 184
flying saucer craze of 1947, 258
formaldehyde, molecular clouds, 213
Formics, alien civilizations in arts and culture, 272–273
Foster, Jodie, 32, 267
Foundation (Asimov), 271
Frail, Dale, 224
Friedman, Stanton, 259
Fuller, Buckminster, 217

G

Gaia hypothesis, 47
Galactic Milieu (May), 272
Galilean satellites, 188–189
    radioactivity, 189
    tidal forces, 190
    tidal heating, 190–191
Galilei, Galileo, 19, 20
Galileo, 187–188
    discovery of, 31
Ganymede, 185, 189, 198–199
gas chromatograph, 38, 172
gas chromatograph-mass spectrometer (GC-MS), 172
gas exchange (GEX), 172

GC-MS. *see* gas chromatograph - mass spectrometer (GC-MS)
gene expression, 48, 94, 95
genetic drift, 50
Genetics for Dummies (Kratz and Spock), 95
geological record, 59–62, 177
geologic and fossil record, 58
Geology for Dummies (Spooner), 58
germ theory of disease, 24
GEX. *see* gas exchange (GEX)
giant telescopes, 31–35
    Earth-based telescopes, 31–33
    space telescopes, 33–35
Giotto (ESA), 145
Goldilocks zone, 231, 232
gold, supernovae explosion, 212
Google Scholar, 4
Grand Prismatic Spring, 114
graphite, 217
gravitation microlensing, 229
Great Comet of 1577, 136
"Great Opposition," 166
Great Oxygenation Event (GOE), 65
Greaves, Jane, 204
greenhouse effect, in Venus, 202
Gungans, alien civilizations in arts and culture, 273

H

habitable exoplanets, 221–235
Kepler 452b, 232
Kepler 62f, 232
Kepler 186f, 232
Proxima Centauri b, 233
TRAPPIST 1 planets, 233
habitable zone (HZ), 231, 232, 284
Hadean eon, 61–63
evidence of life, 62–63
zircons, 62
Haeckel, Ernst, 54
Haldane, JBS, 76, 100
Hale-Bopp, 134, 139–140
Halley Armada, 145
Halley, Edmund, 136
Halley's Comet, 136, 139
Halo (video game and TV series), 266

halophiles, 120–121
adaptions, 121
osmoprotectants, 121
potassium accumulation, 121
extreme, 120
moderate, 120
piezophiles, 124
adaptions, 125
in Antarctica, 125–126
radioresistant organisms, 126
adaptions for, 127
Cladosporium sphaerospermum, 127
in salty lakes and seas, 121
xerophiles, 122
adaptions, 122
Atacama, 123–124
Hawking, Stephen, 247
Hayabusa, 162, 164
Hayabusa 2, 162–164
HED meteorites, 159, 162
Heinlein, Robert A., 269
helium, from Big Bang, 210
Helliconica (Aldiss), 271
hemispheric dichotomy, 177
Hesperian (3,700–3,000 Mya), 177
Hewish, Anthony, 241
hoaxes, 255–264

homeostasis, 44, 47, 83, 119
Hooker, Joseph, 76
horizontal gene transfer, 50, 67, 89
Hothouse (Aldiss), 271
Hubble, Edwin, 33, 34
The Hubble Space Telescope (HST), 33–34, 35, 234, 235
human evolution, 96
Hutton, James, 58–59
Huygens, 196
Huygens, Christiaan, 20, 188, 196
hydrocarbons, molecular clouds, 213
hydrogen, 117, 120, 142, 178, 196
    from Big Bang, 210
hydrogen cyanide, molecular clouds, 213
hydrothermal vents, 30, 46, 76, 105, 113, 114, 119, 126
hyperpiezophiles, 124
hyperthermophiles, 113
hypoliths, 123

I

imines, molecular clouds, 213
Infrared Telescope Facility (IRTF), 32, 33
insoluble organic matter (IOM), 157
International UFO Museum And Research Center, 260
interplanetary missions, 251
interplanetary scintillation array (IPS array), 241
Interstellar (movie), 270

interstellar objects, 140–141
interstellar probe (ISP), 251
interstellar spacecraft, 262
invasions, alien in arts and culture, 269
Io, 188
IOM. *see* insoluble organic matter (IOM)
ionization lines, 215
iron
    acidophile, 118
    meteorites, 155, 156
Itokawa, 162–164

J

James Clerk Maxwell Telescope (JCMT), 204
The James Webb Space Telescope (JWST), 34–35, 141, 234, 235
The Jansky Very Large Array (VLA), 31–32
Japanese Aerospace Exploration Agency (JAXA), 162
Jet Propulsion Laboratory (JPL), 105
JUICE mission, 199
Jupiter, 187–188, 225
    floaters, 205–206
    hunters, 205–206
    sinkers, 205–206
    temperate middle atmosphere, 205

K

Kardashev, Nikolai, 250

Kardashev scale, 250
type I civilization, 250
type II civilization, 250
type III civilization, 250
Karl Jansky VLA telescope array, 216
Lord Kelvin, 143
Kepler 452b, 232
Kepler 62f, 232
Kepler 186f, 232
The Kepler Space Telescope, 34, 35, 228
Kepler transit method, 228
Kratz, Fester, 95
Krondaku, alien civilizations in arts and culture, 272–273
Kuiper Belt, 139
Kuiper Belt objects (KBOs), 200, 283

L

labeled release (LR), 173
lab experiments, modern astrobiology, 38–39
biochemistry, 39
microbiology, 38
origins of life simulations (Miller-Urey type experiments), 39
sample analysis, 39
space instrument design and test, 39
Lake Vostok, 125–126
languages, aliens in arts and culture, 268
last universal common ancestor (LUCA), 10, 55, 280

late Devonian mass extinction, 68
Late Heavy Bombardment (LHB), 150, 152, 177
late Ordovician mass extinction, 68
late veneer hypothesis, 101, 142
law of definite proportions, 23
lead, supernovae explosion, 212
Lederberg, Joshua, 30
van Leeuwenhoek, Antonie, 24, 25
Lem, Stanislaw, 270
Leonids, 138
Leucippus, 22
lichens, 90–91, 97, 116–117, 123
LIDAR instrument, 174

life
characteristics of, 44–50
environmental responses, 49
evolution and adaption, 49–50
growth, 48
homeostasis, 47
metabolism, 46
organization, 44–46
reproduction, 48–49
classification of, 10, 53–55
Linnaeus, hierarchical classification, 54
in clouds, 201–206
definition of, 9
determination of, 50–53
Confidence of Life Detection (CoLD) scale, 52–53
continuum of, 50–51
NASA, life-detection ladder, 51–52
and DNA, 280
early forms, 10–11
on Earth, origin of, 278
emergence of, 278–279
extraterrestrial origin, 279
limits of, 11
Martian origin, 279
origin of water, 279–280

lifeform, multicellular life, 94–95
apoptosis and cancer, 95
differentiation and specialization, 94–95
Lilith's Brood (Butler), 272
Linnaeus, hierarchical classification
class, 54
genus, 54
kingdom, 54
order, 54
revisions to classification system
phylum and family, 54
three-domain system, 55
two-empire classification, 54
species, 54
lipids, 77, 81, 82, 88, 113, 118, 196, 197
Little Green Men 1 (LGM-1), 241, 242
Loeb, Avi, 262
long period comets (LPCs), 139–140
Lost City Hydrothermal Field, 120
Lowell, Percival, 167–168, 171
LPCs. *see* long period comets (LPCs)
LR. *see* labeled release (LR)
Lunar Crater Radio Telescope (LCRT), 219
lunar maria, 152
Lyell, Charles, 59
Lyttleton, Raymond, 138

M

magnetic fields, 191
Majestic 12 (MJ-12), 261
MakeMake, 200
Maran, Stephen P., 16, 20, 150, 183, 187
Marcel, Jesse, 259
Mariner 9, 170–171
Mariners 4 to 7, 168–171

Mars, 160, 165, 178
atmosphere, 178, 179
ExoMars, 285–286
future missions, 180
planetary protection, 181
return samples, 181
habitability of, 178–179
Martian atmosphere, 179
Martian soil, 180
methane and microbes, 180
water, 179
history of, 176
Amazonian (3,000 Mya–present), 177
Hesperian (3,700–3,000 Mya), 177
Martian atmosphere tragedy, 178
Noachian (4,100–3700 Mya), 177
Pre-Noachian (earlier than 4,100 *Mya*, or million years ago), 177
Martian civilization, 167, 168
MSR, 285–286
red planet, 165
Lowell's observatory, 167–168
Schiaparelli's canals, 166–167
soil, 173, 180

space age arrival, 168
Mariner 9, 170–171
Mariners 4 to 7, 168–170
Mars exploration rovers (MERs), 174
Mars 2020 rover (M2020), 175
Mars Science Laboratory (MSL), 174–175
Phoenix, 174
Viking landers, 171–173
water, 179
Mars exploration rovers (MERs), 174, 175
Mars 2020 rover (M2020), 175, 181
Mars sample return (MSR) mission, 284–286
Mars Science Laboratory (MSL), 174–175, 181
Martian meteorite ALH84001, 174, 279
May, Julian, 272
Mayor, Michel, 31, 225, 226
McKay, David, 160
meiosis, 48, 94
melanin, 127
Mendeleev, Dmitri, 23
Mendel, Gregor, 26
MERs. *see* Mars exploration rovers (MERs)
messenger RNA (mRNA), 79
metabolic cross-feeding, 89

metabolism, 46
energy acquisition
chemosynthesis, 46
photosynthesis, 46
respiration and fermentation, 46
metastasis, 95
meteorites, 1, 11, 12, 16, 18, 40, 62, 69, 74, 117, 143, 149
bounty of, 161
contamination, 161
diversity, 162
Hayabusa, 162, 164
Hayabusa 2, 162–164
OSIRIS-REx, 163, 164
processing, 162
provenance, 162
Ryugu, 162–163
falls and finds, 152–153
falling stars, 153–154
space rocks searching, 155–156
types and origins, 156
carbon, 157–159
irons, 156
pieces of asteroids, 159–161
stony, 156
stony-irons, 157
meteors, 16, 135
shower, 138–139

methane, 235
and microbes, in Mars, 180
molecular clouds, 213
in Titan, 195–196
methanol, molecular clouds, 214
methylamine, molecular clouds, 213
micelle, 82, 197
Milky Way, 16, 34, 228, 239
Miller, Stanley, 100, 101
Miller-Urey experiment, 11, 76, 100–103, 144
Milner, Yuri, 251
Mimas, 199
missions to outer planets, 184
mitosis, 48

modern astrobiology
computer simulations, 40
earth and analog fieldwork, 39–40
extremophile investigations, 39
instrument field testing, 39
meteorite collection, 39
sample collection, 39, 40
from exobiology to astrobiology, 29–30
giant telescopes, 31–35
Earth-based telescopes, 31–33
space telescopes, 33–35
lab experiments, 38–39
biochemistry, 39
microbiology, 38
origins of life simulations (Miller-Urey type experiments), 39
sample analysis, 39
space instrument design and test, 39
space missions, 35–38
camera and video technology, 37
flyby missions (Voyager 2), 36, 37
life detection experiments, 38
mass spectrometers, 38
orbiters (Galileo Jupiter), 36, 37
particle and field detectors, 38
rovers (Opportunity Mars), 36, 37
sample return missions (OSIRIS-REx), 36, 37
spectrometers, 38

modern biology, 22, 25, 87
molecular clouds, 213–214
Moon, 159, 160, 166, 168, 171
    formation, 142, 151
    telescopes on, 219
Moore, Bill, 259
Moore, John T., 209
Morowitz, Harold, 203
MSL. *see* Mars Science Laboratory (MSL)
"muddy" with Titan's "tholins," 102–103
multicellular life
    advantages, 92–93
    evolution of, 93–94, 96–97
        breeding, 96
        from colony, 93
        extinctions, 96
        failed cell division, 94
        human, 96
        from single-celled eukaryotes with multiple nuclei, 93
        from symbiosis, 93
    lifeform, 94–95
        apoptosis and cancer, 95
        differentiation and specialization, 94–95
multipotent stem cells, 95
Murchison (1969) meteorite, 157, 158
mutation, 50, 84, 97

Mycoplasma sp.
M. capricolum, 107
M. genitalium, 106
M. laboratorium, 107
M. mycoides, 106, 107
mysticism, 21

N

NASA, 285
astrobiology program, 30
astrobiology program of, 4
definition of life, 44
exobiology program, 30
nascent planets, 223, 224
National Enquirer (magazine), 259
National Radio Astronomy Observatory, 238
National Science Foundation (NSF), 156
nebula, protostellar, 211
nematodes, aeroplankton, 201–202
Neptune
ocean world, 199–200
Triton, 199–200
neutron star, 212
Newton's laws of gravity, 136
next-generation Very Large Array (ngVLA), 218–219
Nininger, H. H., 155–156
Noachian (4,100–3,700 Mya), 177

non-gravitational acceleration, 262
Norman conquest of England, 134–135
NSF. *see* National Science Foundation (NSF)
nuclear fusion, 211
nucleobases, 27, 77, 78, 80, 104, 158, 163, 278, 279
nucleosynthesis, 209–210, 211
nucleus, 137–138, 145–147

O

observational bias, 230
ocean worlds
    Cassini–Huygens, 188
    Galilean satellites, 188–189
    Galileo, 187–188
    Jupiter missions, 187–188
    missions of discovery, 183–185
    potential for life in, 280
    Saturn, 188
    space frontier pioneer, 185–186
    Voyager missions, 186–187
Olmsted, Denison, 138
Olympus Mons, 171, 177
On The Origin of Species (Darwin), 26
Oort Cloud, 139, 140
Oparin, Alexander, 76, 100
Operation High Dive, 259
Orbilander mission, 288

orbiters (Galileo Jupiter), 36, 37
organisms, 112, 113, 115–121, 123–125, 127, 130. *see also* radioresistant organisms
Orgueil (1864) meteorite, 157, 158
origins of life (OoL), 22–27
    atoms and elements, 22–23
    chemical soup, 100–103
        The Miller-Urey experiment, 100–102
        "muddy" with Titan's "tholins," 102–103
    computer simulations, 107–109
        Allchemy simulation, 108–109
        Avida program, 107–108
    deep-sea vents, simulation of, 104–105
    deoxyribonucleic acid (DNA), minimal cells, 106–107
    heredity and genes, 26–27
    investigation, 24–25
    natural selection, evolution, 25–26
    Oró's experiments, 104
    philosophers, 23–24
        Anaxagoras, 23
        Anaximander, 23
        Anaximenes, 23
        Aristotle, 24
    self-replicating deoxyribonucleic acid (DNA) test, 106
    theories, 23–24
Orion, Rae, 17
Oró, Juan, 104

Oró's experiments, 104
OSIRIS-REx, 163, 164
osmosis, 83, 119, 197
osmotic pressure, 121, 122
OSU (Ohio State University) SETI, 245
Owens, Steve, 16, 121
OXCART project, 260

P

panspermia, 130, 142–144, 279
    difficulties with abiogenesis, 144
    inhospitable early Earth, 143–144
Pasteur, Louis, 24
PDS 70 system, 223, 224
Peekskill (1992) meteorite, 153, 154
periodic table of elements origin, 210
Permian-Triassic extinction event, 68
Perseid meteor shower, 138, 139
Perseverance rover, 175, 176, 285, 286–287
Phanerozoic eon, 66–70
    Cambrian Explosion, 66–67
phased array antenna, 241
Philae, 146–148
Phillips, Cynthia, 21, 22, 150, 174, 187, 210, 215, 241, 243
Phoenix, 174–176, 178, 180
phosphates, 77, 78
phosphine, on Venus, 204

phospholipids, 83, 122
photosynthesis, 46, 63, 86, 123, 128, 205
Physics for Dummies (Phillips and Priwer), 21
piezophiles, 124
    adaptions, 125
        modified cell membranes, 125
        more rigid proteins, 125
        pressure-tolerant enzymes, 125
    in Antarctica, 125–126
    moderate, 124
piezotolerant, 124
Pioneer 10 and 11 missions, 185, 248, 249
Pitch Black (movie), 271
planetary protection, 125, 181
planetary tilts, 152
planetesimals, 149, 150
planets
    formation, 150
    and moons, 11, 12, 34, 35, 139, 190, 193
PLATO mission, 229
pluripotent stem cells, 95
Pluto, 139, 152, 183, 184, 200
polycyclic aromatic hydrocarbons (PAHs), molecular clouds, 214, 217
polyextremophiles, 112, 126
polyynes, molecular clouds, 213
PR. *see* pyrolytic release (PR)
Precambrian supereon, 61

Pre-Noachian (earlier than 4,100 *Mya*, or million years ago), 177
primordial soup, 75, 76, 100
Priwer, Shana, 21, 22, 150, 174, 187, 210, 215, 241, 243
Project Hail Mary (book and movie), 267, 268
Project Mogul, 259
prokaryotes, 10, 45, 54, 55, 86, 89
prokaryotic bacteria, 88
the protein code, 84
Proterozoic eon, 64–66
    dinosaurs and extinctions, 68–70
        Cretaceous-Paleogene extinction event, 68
        late Devonian mass extinction, 68
        late Ordovician mass extinction, 68
        Permian-Triassic extinction event, 68
        Triassic-Jurassic extinction event, 68
    great oxygenation event (GOE), 65
    oxygen and cells, 65–66
    reactive oxygen species (ROS), 65
protocell formation, 81–83
    cellular signaling, 82–83
    membrane diversity, 83
protons, from Big Bang, 210
protoplanet, 189
protoplanetary disk, 150, 223
protosolar cloud, 150
protostellar nebula, 211
Proxima Centauri b, 233, 251

psychrophiles, 115
adaptions, 116
antifreeze proteins, 116
chaperones, 116
cold shock proteins, 116
cryoprotectants, 116
increas molecular flexibility, 116
Rusavskia elegans, 116–117
pulsar, 241, 243
pulsar planets, 225
pyrolytic release (PR), 173

Q

Queloz, Didier, 31, 225, 226

R

radial velocity, 225, 226
radioactive carbon isotope C14, 173
radio astronomy, 21, 28, 217, 224, 243
radio observatories, next-generation, 218–219
radioresistant organisms, 126
adaptions for, 127
DNA donations, 127
DNA repair, 127
DNA structure, 127
Cladosporium sphaerospermum, 127
rainbow decoding with spectroscopy, 215–218

reactive oxygen species (ROS), 65, 122, 127
redox gradients, 46
red planet. *see* Mars
reproduction, 48–49
    asexual reproduction, 48
    sexual reproduction, 48
respiration, 46, 47, 59, 86, 172
retroviruses, 85
return samples, in Mars, 181
reverse transcriptase (RT), 85
reverse transcription, 85
ribonucleic acid (RNA), 77–81
    catalysis, 79
    vs DNA structures, 78
    information coding, 79
    self-replication, 79
ribosomal RNA (rRNA), 79
ringworld, 250
Roadside Picnic (Strugatsky), 273
The Robert C. Byrd Green Bank Telescope (GBT), 238
Rosalind Franklin, 285
Rosetta, 146–148, 287
Roswell incident, 259
The Roswell Incident (Berlitz and Moore), 259
rotational lines, 216
rovers (Opportunity Mars), 36, 37
Rusavskia elegans, 116–117

Ryle, Martin, 243
Ryugu, 162–163

S

saccharides or sugars, 78
Sagan, Carl, 141, 173, 203, 205, 213, 248, 267
Sagan, Linda Saltzmann, 248
Sagittarius B2, molecular cloud, 216
Salpeter, Edwin, 205
sample return missions (OSIRIS-REx), 12, 36, 37, 164
sandbanks, 138, 145
Sand people, alien civilizations in arts and culture, 273
Saturn
    Dione, 199
    Mimas, 199
    moons of, 199
    Tethys, 199
Schiaparelli, Giovanni, 138, 166
Schiaparelli's investigation, 31
Search For Extraterrestrial Intelligence (SETI), 241, 243, 244, 267, 280. *see also* broadcasts, alien in arts and culture
    Allen Telescope Array (ATA), 245
    Breakthrough Listen, 245, 246
    OSU (Ohio State University) SETI, 245
    reaching out active, 246–248
    scaling up, 244–246
    SERENDIP program, 245

self-replicating deoxyribonucleic acid (DNA) test, 106
self-replicating ribozyme, 106
self-reproducing organism, 106
self-sustaining life, 108
SERENDIP program, 245
serpentinization, 120
SETI. *see* Search For Extraterrestrial Intelligence (SETI)
sexual reproduction, mechanism of, 26–27
shadows, 227
shooting star, 16, 135
short-period comets (SPCs), 139
The Silent Sea (TV series), 267
single-celled organisms, 10, 24, 49, 55, 57, 93
single cellular development, 86
Siraj, Amir, 263
slight halophiles, 120
Smith, William, 59
snow algae, 117
snowballs, 138, 139, 145
sodium vapor, 235
Solaris (Lem), 270

solar system, 149, 150–151
hemispheric difference on Mars, 152
life beyond the, 13
lunar maria, 152
migrations and impacts, 150
origin of the Earth's Moon, 151
planetary tilts, 152
planetesimal formation, 150
planet formation, 150, 151
protoplanetary disk, 150
protosolar cloud, 150
search for life, 11–12
comets, 11–12
meteorites, 11–12
moons, 21
planets, 21
Soyuz, 129

space, 111, 112, 117, 121, 125, 128
asteroids in, 154
chemicals in, 143, 144
life in, 111, 112, 157, 159
missions, 35–38
camera and video technology, 37
flyby missions (Voyager 2), 36, 37
life detection experiments, 38
mass spectrometers, 38
orbiters (Galileo Jupiter), 36, 37
particle and field detectors, 38
rovers (Opportunity Mars), 36, 37
sample return missions (OSIRIS-REx), 36, 37
spectrometers, 38
rocks from, 149
rocks searches, 155–156
in Antarctica, 156
in Arabia, 156
in Australia, 156
in north Africa, 156
tardigrades in, 128–130
telescopes
The Hubble Space Telescope (HST), 33–34, 35
The James Webb Space Telescope (JWST), 34–35
The Kepler Space Telescope, 34, 35
in space mission, 229
The Spitzer Space Telescope, 34, 35

watering the Earth from, 142
Space Exploration For Dummies (Phillips and Priwer), 174, 187–188, 241
SPCs. *see* short-period comets (SPCs)
specialized cells, advantages
cell specialization, 92
enhanced survivability, 92
increased size, 92
longer lifespan, 92
resource storage, 92
spectroscopy, 234
applications, 234
primary transit, 234
secondary transit, 234
spiders, aeroplankton, 201–202
The Spitzer Space Telescope, 34, 35
Spock, Lisa, 95
Spooner, Alecia M., 58
Stapleton, Olaf, 250
StarChip, 251
Stardust, 146, 147
Stargazing For Dummies (Owens), 16
stars, 133, 135
life cycles of, 210–212
Starship Troopers (Heinlein), 269
Star Trek: Deep Space Nine (TV series), 272
Star Trek: The Next Generation (TV series), 268, 269, 273
Star Wars (movie), 273

Steensen, Niels, 58
stem cells, 95
potency, 95
multipotent, 95
pluripotent, 95
unipotent, 95
self-renewal, 95
types, 95
stony-iron meteorites, 157
stony meteorites, 156
Suisei and Sakigake (ISAS), 145
supercontinent cycles, 64
supernovae, 212
Synthia organism, 107

T

Tagish Lake (2000), 158–159
tail, 136–138, 140, 141
tardigrades (water bears), 115, 128–130
Taurus Molecular Cloud 1 (TMC-1), 213–215
technosignatures, 237–251
telescopes on moon, 219
telescopic observation, astronomy, 19–21
TESS mission, 229
Tethys, 199
tetrad, 127
the Theory of Evolution by Natural Selection, 25, 76

thermoacidophiles, 203
extremophiles, 284
Thermococcus gammatolerans, 126, 127
thermophiles, 113
adaptions, 113–114
amino acids, 113
chaperone proteins, 113
heat-loving enzymes, 113
more rigid proteins, 113
strong cell membranes, 113
black smokers, 114–115
extreme, 113
The Thing (movie), 272
Thomson, William, 143
The Three Body Problem (movie), 268
three-domain system, 86
Tianwen-3, 285
tidal forces, 190
tidal heating, 190–191
Tikhov, Gavriil, 29
Titan
interior ocean, 197–198
lakes and seas, 196–197
methane in, 195–196
missions, 288–289
ocean world, 195–196
Titan Mare Explorer (TIME), 289

Titan’s atmosphere, 102, 103
Torino scale, 154
trail blazing, 138–139
transcription RNA (tRNA), 79
transit depth, 227
transit method, 227
TRAPPIST 1 planets, 233
TRAPPIST-1 solar system, 34
tree of life, 10, 38, 55, 59, 66, 86
Triassic-Jurassic extinction event, 68
Triton, 187, 199–200
Truman, Harry, 261
Tunguska (1908) meteorite, 153, 154
typical thermophiles, 113

U

ufology tourism, 260
unicellular cooperatives
    communication and signaling, 89–90
    community building, 88–89
    grex, cooperative communities, 90
    lichens, 90–91
    living the slime life, 89
unicellular microorganisms, aeroplankton, 202
unipotent stem cells, 95
universe, history of, 211
Urey, Harold, 100

V

Valles Marineris, 171

Vega 1 and 2 (USSR/France), 145

Venus

- airborne life in clouds of, 203
- ammonia on, 204
- DAVINCI mission to, 283–284
- life at, 202–204
- phosphine on, 204
- thermoacidophiles, 203
- UV absorber, 203

The Very Large Telescope (VLT), 32, 33, 223

vesicles, 82, 105

vibrational lines, 216

Viking labeled release (LR) experiment, 279

Viking landers, 160, 171–173

- gas chromatograph — mass spectrometer (GC-MS), 172
- Gas exchange (GEX), 172
- labeled release (LR), 173
- pyrolytic release (PR), 173

Viking missions, 30

viruses, aeroplankton, 202

visible spectrum, 21

vitrification, 116

Voyager Golden Record, 249

Voyager missions, 186–187

W

Wallace, Alfred Russell, 25

wandering stars, 16

The War of the Worlds (Wells), 165, 269

water, 235

- in Mars, 179
- molecular clouds, 213
- origin of, 279–280

water bears, 11, 128, 130

watering Earth from space, 142

water vapor, 235

Watson, James, 27

Wells, H. G., 165, 269

Whipple, Fred, 138, 145

white smokers, 104, 115, 119

"Who Goes There?" (Campbell), 271–272

Winchcombe (2021), 154

wobbling stars, 225, 226

Woese, Carl, 55

World War II, 21, 269

worms, aeroplankton, 201–202

WOW signal, 243, 244

X

xenon, 142

xerophiles, 122
adaptions, 122
compatible solutes, 122
DNA and protein protection, 122
dormancy and spore formation, 122
efficient repair, 122
membrane stabilization, 122
water retention, 122
in Antarctica, 123–124
high life of Atacama, 123–124
strategies to survive
cellular antifreeze, 124
cold-active enzymes, 124
dormancy and resilient structures, 124
energy from chemistry, 124

Y

Yellowstone National Park, 114

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About the Author

Dr. Conor A. Nixon, PhD traces his family tree to around 4.2 billion years ago and is descended from the single-celled organism LUCA. More recently, he was created in an experiment when two individuals of the species *Homo sapiens,* acting under chemical impulses, decided to join half of each of their DNA strands together to create a new life form. Having differentiated into a large, multi-cellular creature, he undertook preliminary instruction in maths and science at Methodist College Belfast in Northern Ireland. While still building his neural circuits, he developed a fascination for solar-system exploration from watching the television show *Cosmos* and its inspirational presenter, Carl Sagan.

He went on to study at the University of Cambridge for a BA degree in natural sciences, followed by an MS in astronomy at the University of Manchester and then a doctorate of philosophy in physics at the University of Oxford. His advisor Professor Frederic Taylor suggested Conor's DPhil topic and first foray into astrochemistry: the spectroscopic study of the atmosphere of Saturn's moon Titan. Titan was at the time a poorly known and distant object that was to be revealed in much greater detail from 2004 by the *Cassini* and *Huygens* spacecraft.

After graduation, he moved to NASA's Goddard Space Flight Center as an associate on the *Cassini* Composite Infrared Spectrometer team, later becoming Deputy Principal Investigator of the instrument. Since the end of the *Cassini* mission in 2017, he has continued solar system research using large ground and space-based telescopes, including the James Webb Space Telescope and the Atacama Large Millimeter-submillimeter Array. Post-*Cassini*, he also developed an active interest in analog field work, exploring extreme environments on the Earth to investigate how his distant, unicellular cousins have adapted to life in highly challenging conditions. This included leading teams of scientists to sample glaciers in Iceland and hot springs in Yellowstone National Park.

Dr. Nixon is the two-time recipient of NASA's Robert H. Goddard award for Exceptional Achievement in Science and six-time co-recipient of

NASA's Team Achievement Awards for accomplishments of the *Cassini* mission. Outside of work, he enjoys running, hiking, scuba diving, cooking, movie watching, and traveling with family and friends.

Dedication

For Sam and Sophie,

Never give up wondering what might be possible.

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