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Early Ideas and Lessons from Our Own Backyard

Moving Off the Center

The ancients of many cultures understood the concept of "world" in the sense that Aristotle did—our Earth held court at the center, attended by the Moon, the Sun, and the planets embedded in their crystalline spheres. Beyond us shimmered the sphere of the distant stars. Alexandrian astronomer Claudius Ptolemy later adopted and refined the Aristotelian, Earth-centered model. His work dominated western thought for the next fifteen centuries.

Many ancient thinkers advocated the concept of the "plurality of worlds." The plurality of worlds concept suggested that many such universes existed, each sovereign and self-sufficient, with an inhabited Earth at the center of each. They based their interpretation on the presupposition that the universe was infinite. Their perspective was also informed by the principle of plenitude, which states that the physical universe must encompass all possible forms of existence. Metrodorus of Lampsacus, a disciple of Epicurus,[1] said, "To consider Earth as the only populated world in infinite space is as absurd as to assert that in an entire field sown with millet only one grain will grow." Others were not so sure. Both Aristotle and Plato opposed the concept of plurality of worlds. Aristotle's concept of the universe described only one Earth at the center of a finite universe.

Sixth century B.C. Greek philosopher Thales of Miletus may have been the first person to wonder aloud about what the universe was made out of.

[1] Most famous for his founding of Epicureanism (~307 BC), which taught that pleasure and tranquility were the greatest good.

M. Carroll, *Earths of Distant Suns*,
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He suggested that water comprised most things in the universe, and that Earth floated on a vast sea. Significantly, Thales understood that whatever the universe was made of had a bearing on the possibility of life "out there." His student, Anaximander, took it a step farther, envisioning a universe filled with other worlds arising and dying from an eternal "ether." Although he did not make any specific predictions of life in other parts of the universe, Anaximander did suppose that other Earths—with other beings upon them—might exist.

Medieval thinkers such as Augustine (fifth century) used theological reasoning to champion Aristotle's model. Augustine rejected the idea of a plurality of worlds. He argued that the Incarnation of Christ, designed specifically for the human race, implied that there could be no other inhabited Earths. Other theologians disagreed with Augustine on both logical and theological bases. Albertus Magnus reasoned that since God is omnipotent, he must have created many other worlds. Giordano Bruno also promoted the plurality of worlds' idea, but his motives were not pure. He used his arguments to weaken the Church's position on the uniqueness of Christ. Sadly for him, the Inquisition was catching on at the time, and Bruno is often portrayed as the first person to be martyred in the name of science. A careful reading of history actually contradicts this.[2] Bruno died for his heretical views on salvation, not for his thoughts about the planets.

The sixteenth century ushered in our modern view of plurality of worlds on the heels of Nicolas Copernicus. Copernicus developed the heliocentric—Sun-centered—Solar System. In concert with Galileo's observations of moons moving around planets,[3] astronomers tumbled to the fact that Earth was not the center of all things. The profound implication was that if our world revolved around the Sun, and the distant stars were all Suns like ours, there might be countless Earths revolving around them, a plethora of Earthlike worlds scattered across the cosmos.

Just how distant those worlds were came into focus in the eighteenth century. Astronomer Friedrich Bessel was the first person to suspect that interstellar expanses were far greater than once supposed. In 1838, he was able to measure the distance to the faint double orange dwarf stars of 61 Cygni.[4] He ascertained the distance at 10 light-years, or 200 million times the distance to the Moon.

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[2] Claims by Carl Sagan and others notwithstanding, Bruno was burned at the stake for his position on several important Church doctrines, along with his views on the Church's politics and theology. Science was the least of his troubles.

[3] In specific, Galileo discovered the four Galilean satellites moving around Jupiter in 1610.

[4] James Bradley first noticed that 61 Cygni was actually two stars in 1753, but the true double nature of the stars, in orbit around each other, was not confirmed until 1934.

Because of its relatively swift motion against the stars, Bessel knew it was one of the closer stars. The neighborhood was getting a lot bigger.

Still, observers began to realize that stars are like our own Sun. This revelation buttressed the assessment that countless Earths could exist in the universe. Whether those worlds were inhabited was another argument altogether.

Although the plurality of worlds was popular in the nineteenth century, it was not universally embraced. William Whewell, scientific theologian and Master of Trinity College, Cambridge, was the first to counter the concept of plurality of worlds using contemporary science. He explored both sides of the argument. In 1853, he pointed out that conditions on other planets in the Solar System are so different from those on terra firma that no known life could ever arise there. At the time, there was also no proof that planets orbited other stars. Whewell also asserted that during most of Earth's history, our world lacked any intelligent beings. But despite his own objections to the idea of life on other worlds, Whewell admitted that "…No one can resist the temptation to conjecture, that these globes …are, like ours, occupied with organization, life, intelligence."[5] As for the stars, Whewell said that "they may have planets revolving round them; and these may, like our planet, be seats of vegetable and animal and rational life…but however many, however varied, they are still but so many provinces in the same empire, subject to common rules, governed by a common power."

Alfred R. Wallace, the British naturalist who cofounded the theory of evolution, argued against the idea of intelligent life in the universe. In the 1905 edition of his book *Man's Place in Nature*, Wallace observed that mankind is the result of a sequence of unique and unpredictable events in the long evolutionary chain. He estimated that the probability that this same chain of events should occur elsewhere—even under Earthlike conditions—is practically nonexistent.

Wallace's reasoning, adopted by some modern biologists, is that a sequence of events may be of little importance when they are taken separately, but in combination, their effects are magnified to such a degree that the final result becomes completely unpredictable. Life, intelligent or otherwise, is not a given on Earthlike worlds. Virtually identical initial conditions can lead to completely different results.

But others reasoned that if Earth was simply a member of a family of planets, then it was likely that even our nearby worlds might share characteristics of our own planet, including seasons, mountains and seas, plantlife, creatures, and perhaps sentient beings. Early Darwinian evolutionary theory held that

[5] William Whewell, *Of the Plurality of Worlds*, 1853, London, p. 206.

given time, life should become advanced in intelligence and technology. Mars, long thought to be more ancient than Earth, held the most promise for hosting advanced civilizations, and it was close enough that we just might be able to communicate. But how could we go about it?

Getting the Message Across

Nineteenth century French poet and inventor Charles Cros had heard observers' reports of pinpoints of light visible on both Mars and Venus. Cros assumed that the phenomena heralded the existence of Martian metropolises. He attempted to get funding from the French government to build a giant mirror with which to signal the inhabitants of the Red Planet. His plan was to focus sunlight from the mirror onto the Martian plains, burning diagrams and various shapes into the Martian landscape as evidence to them of our presence across the void. The massive etchings might have lacked the desired effect. Who knows what the poor Martian farmers might think of a brilliant death-ray cauterizing their fields?

Johann Carl Friedrich Gauss—perhaps the most respected mathematician of the nineteenth century[6]—suggested that a giant triangle and three squares, a shape known as "the Pythagoras," could be etched across the Siberian tundra. Ten-mile-wide strips of Siberian pine forest could be left at the center of clear-cut regions, leaving great geometric paths of trees. Within those green lines, the interiors would be cleared and filled with rye or wheat. The hope was that alien beings would see the patterns and recognize that there was intelligent life on Earth.

Joseph Johann Littrow, director of the Vienna Observatory, also advocated the idea of communicating with nearby planets. It may have been Littrow who originally proposed using the Sahara Desert as a gigantic artist's pallet. The idea was to excavate gigantic trenches several hundred yards wide. The canals would transcribe perfect circles, right triangles, and other geometric forms. After filling them with water, engineers would fill the trenches with enough kerosene (called paraffin in those days) to form a skin on top of the water. When lit, the vast shapes could burn as a great beacon throughout an entire night. Different shapes could be illuminated on consecutive nights, showing the inhabitants of nearby planets that we are here, and we know something about geometry, at least (Fig. 2.1).

[6] Gauss's mathematics led to the rediscovery of the first asteroid, Ceres; the object disappeared behind the Sun soon after Piazzi discovered it, but Gauss successfully calculated where it should be.

Fig. 2.1 Proposed techniques for contacting Martian civilizations included incandescent, kerosene-filled canals in the Sahara Desert (*left*) and geometric shapes made of Siberian forests and planted wheat. (Art © Michael Carroll)

The prospect of making contact with extraterrestrial beings was all the nineteenth-century rage. In 1891, the Prix Pierre Guzman was established. A bequest from the estate of Anne Emilie Clara Goguet, the award was named after Anne Emilie's son, a major in the French army. Two prizes were to be given, one for medicine and one for astronomy. In the case of the astronomical one, a prize of 100,000 francs was up for grabs to the first person who succeeded in communicating with another planet. According to her will, the award was to be granted to anyone "who shall discover a way to correspond with one of the heavenly bodies—that is to say, to receive an answer from the inhabitants of a planet to some sign made to them on ours." Mars was pointedly excluded from the contest, as it was considered too easy a target. If no communication was made, the accumulated interest over each successive five-year period would be awarded to those making significant contributions to the field of astronomy.[7]

The twentieth century opened with the invention of radio transmitters and receivers, devices that would revolutionize global communication. Italian Guglielmo Marconi is generally credited with bringing practical radio into the public realm. In 1901, Marconi successfully transmitted a radio signal across the Atlantic Ocean, from Cornwall, England, to St. Johns, Newfoundland, proving that radio signals could communicate over long distances. In the early

[7] Prizes were awarded to French astronomers Louis Fabry and Henri Joseph Perrotin in 1905, and to Maurice Loewy, Viennese-born director of the Paris Observatory.

Fig. 2.2 Marconi, at *left*, supervises the raising of a communications kite at St. Johns, Newfoundland. (Courtesy of Wikipedia commons: https://commons.wikimedia.org/wiki/File:Marconi_at_newfoundland.jpg)

1920s, Marconi claimed to have picked up signals from an interplanetary source (Fig. 2.2).

Marconi had company in the United States. When he wasn't investigating electrical currents or radio waves, inventor Nikola Tesla used his fertile mind to turn toward the problem of interplanetary communication, too. As early as 1893, Tesla lectured on the possibility of radio transmission as a mode of communicating over great distances. Five years later, Tesla demonstrated a remote-controlled boat, called a "teleautomaton." He asserted that his inventions might be used to communicate with other worlds. Tesla erected a 6-m-tall tower strung with copper wiring to monitor radio signals. In 1901, the inventor wrote that his tower was picking up radio "disturbances" that he attributed to interplanetary communiqués. Tesla wrote that "The feeling is constantly growing on me that I had been the first to hear the greeting of one planet to another."

In the March 20, 1920, issue of *Scientific American,* H. W. Nieman and C. Wells penned the article "What Shall We Say To Mars? A System for Opening Communication Despite the Absence of any Common Basis of Language." The authors proposed a series of dots and dashes, resembling Morse code, along with simple pictures, to communicate with beings on other planets in the Solar System. Their approach foreshadowed later efforts using messages bolted to the side of spacecraft (see Chap. 7).

The year 1924 saw an opposition of Mars and Earth, a point at which both planets passed nearest each other in their orbits. The U. S. Army combined forces with Marconi and others to listen for Martian signals. While many noted radio signals, there was no evidence of extraterrestrial sources. In fact, the frequencies used in those days were largely deaf to signals outside Earth's atmosphere. Their low frequencies caused signals to bounce back from the ionosphere. (In fact, the ionosphere made Marconi's transatlantic communication possible, with radio signals from England reflected off the ionosphere to radiate over the horizon, making their way to Newfoundland.) Only later did experimenters come up with equipment able to receive signals of higher frequency, the kind that could travel between stars.

Several researchers claimed to have received transmissions from cosmic sources. Competition was beginning to grow. In 1937, Nikola Tesla petitioned the Guzman overseers to award him the prize for his—as he put it—"discovery relating to the interstellar transmission of energy." He was not a recipient.

Advances in radio equipment during and shortly after World War II made technology readily available. The new radio antennae could study the skies in higher frequencies that penetrated Earth's atmosphere. The time was ripe for the modern search for extraterrestrial signals coming from distant Earths. But where would we look?

The Goldilocks Principle

As astronomers gained further insight into the nature of the Solar System, it became obvious that Mars was too cold—and its air too thin—to support liquid water on its surface. This is significant, says NASA Ames exobiologist Chris McKay. "On Earth, wherever you have life, you have some access to liquid water, even if that means water vapor. In places on Earth where the water is frozen, like on the Greenland ice cap, it's essentially lifeless and sterile. But even at those margins where the ice is melting, you get microbial mats and other biology. Life on Earth requires liquid water."

If liquid water is a necessity of life, Mars was looking more and more dismal as an abode for it. And on the other side of Earth, cosmic neighbor Venus was far too hot, simmering at some 462 ° C (864 ° F) on the surface. Venus receives nearly twice the solar energy that Earth does, while Mars' portion is a dim 50 % of that of our own world. Like the fabled porridge of Goldilocks, Earth was not too hot and not too cold, but just right. The idea led scientists to realize that every star has a zone in which liquid water could, theoretically, exist on the surface of a planet (Fig. 2.3). These zones have come to be called "habitable zones."

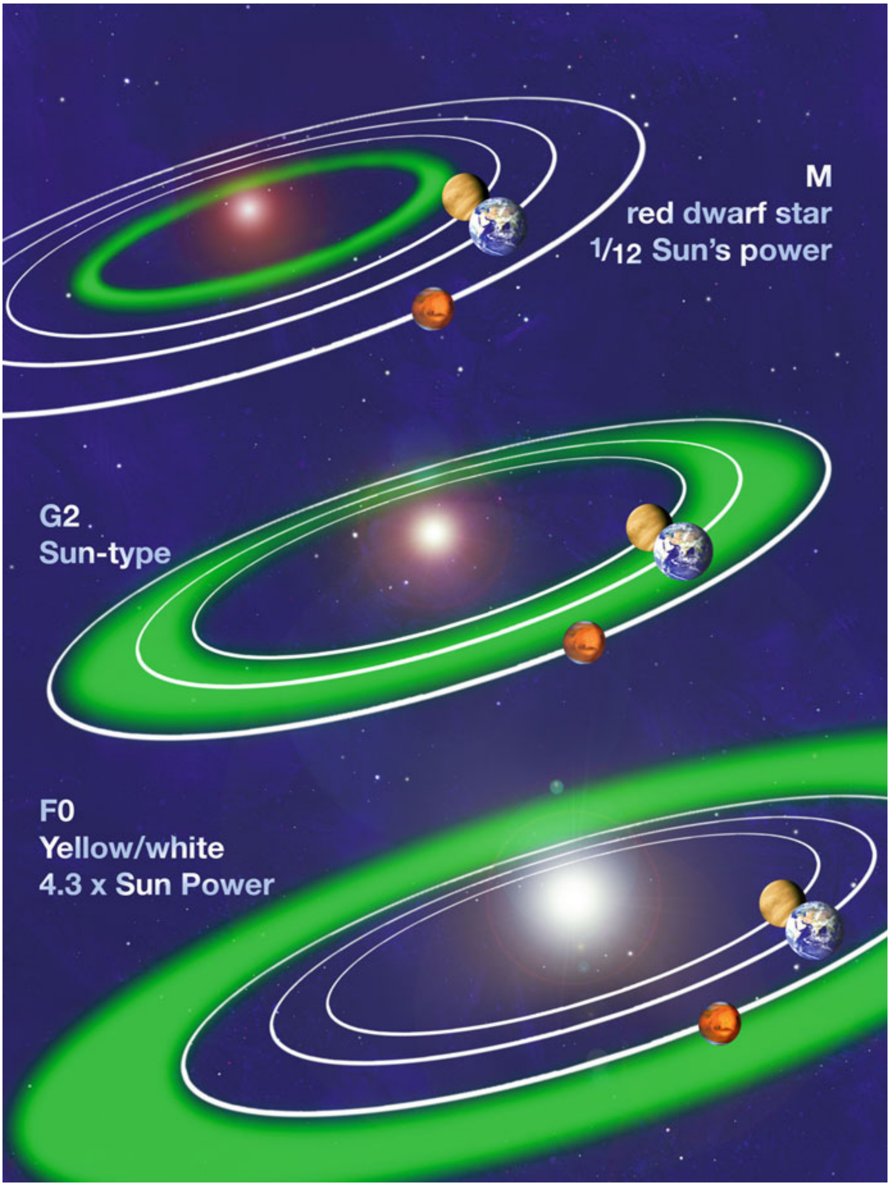

Fig. 2.3 The habitable zone of an exoplanet is determined by the size and temperature of its parent star. Here, our familiar paths of Venus, Earth and Mars are superimposed on several example systems. (Art © Michael Carroll)

The habitable zone of a star varies with the nature of the star itself. The habitable zone of a hot young sun will arc around the star at a greater distance than the habitable zone of a cool red dwarf. An exoplanet (a planet beyond our own solar family) needs to be farther away from a hot star for conditions to have liquid water. An M star (sometimes called a red dwarf) is not only cool but also smaller. The surface temperature hovers around 3000 °C (the Sun reaches 15 million degrees Celsius), glowing like an ember just three thousandths as bright as our Sun. Nearly 80 % of all stars in the universe are M stars. The habitable zone of a small star is close to itself, where its feeble heat can still allow liquid surface water.

Migrating Habitable Zones

The shift in a habitable zone was a concept first understood by astrophysicist Michael Hart. In 1978, Hart calculated that the Sun's habitable zone began farther in, and has migrated out over time as the Sun has aged and grown brighter. Four billion years ago, during Earth's formative years, Sol was only 70 % as bright as it is today, and Sol continues on this path, forcing our habitable zone outward. His analysis showed that Earth is in a central-enough location that it will remain in the habitable zone throughout this shift, but just barely. Hart's research demonstrated that had Earth formed only 5 % closer to the Sun, our planet would have experienced a runaway greenhouse effect, making us more of a twin to Venus than we already are. Had Earth coalesced 1 % farther away, the home world would have suffered a runaway glaciation, with the surface and oceans freezing over permanently. Hart's models portrayed both of these situations—chilled or cooked—as irreversible.

Hart's work led to a new term in exoplanet research: the continuously habitable zone. This is the sweet spot within a habitable zone where conditions remain stable for liquid water, despite the shifting of the habitable zone around it. The continuously habitable zone provides yet another limiting factor in our search for Earth's exoplanet twin. If Earth's orbit were a bit more out-of-round than it is, its path would also take it out of the continuously habitable zone as time progressed. But another implication is that a frozen planet on the outer edge of the zone may become habitable as its star ages and warms. Habitable worlds closer in may become too hot to support life as their suns brighten.

The continuously habitable zone in other star systems may be quite different from that of terra firma. Sol's continuously habitable zone is fairly thin, but for smaller suns like M stars, it may not exist at all. Still, stable regions within habitable zones of cooler stars, whose lifetimes are drawn out, last longer than those for short-lived suns because the habitable zones migrate over a longer period of time.

Hart's estimates are now thought to be too narrow because of several factors that have recently come to light. Climate stabilizers appear to be built in to the design of Earth. The most influential of these is a chemical recycling process called the CO_2-rock cycle. Carbon dioxide (CO_2) is a powerful greenhouse gas. Without it, Earth's surface would average 40 ° C colder than it does, because the CO_2 helps to hold the heat in. In a complex feedback loop, the CO_2-rock cycle stabilizes global temperatures. As Earth warms, increased weathering removes CO_2 from the air. That reduction in the greenhouse gas leads to a global drop in temperature. As the temperature sinks, the weathering processes abate, allowing the CO_2 levels to rise again.

A second stabilizing process—subtly different—depends on plate tectonics. The rocky surface of Earth acts as a chemical sponge, soaking up various gases and chemically locking them into the rock. (Mars is red because its oxygen has been locked away into the surface, "rusting" the planet.) Earth's plate tectonics bring the gas-impregnated rock down into the mantle, where it melts, freeing the chemicals and minerals. Then, these materials are recycled back into the environment through mountain uplift or volcanism.

Taking into consideration the CO_2-rock cycle and other moderating factors, atmospheric expert James Kasting has revisited the concept of the continuously habitable zone. Kasting estimates that the Sun's continuously habitable zone spans a distance of 0.95 AU to 1.15 AU from the Sun. Although this is more optimistic than Hart's estimate, it is still a thin portion of the current habitable zone. Earthlike planets with surface conditions that remain habitable over long periods may be rare indeed.

To understand habitable zones, those regions around distant suns where we might find Earthlike worlds, we must first take a look at the grand menagerie of stars in the cosmos.

Starring Roles

The most familiar star to any life form on Earth is the Sun. Sol dwarfs every other body in the Solar System, weighing in at a mass equivalent of 1,300,000 Earths. Our nearest star grips our entire planetary system—terrestrial and giant planets, asteroids and comets—in its powerful sway. Its heat drives our wind and ocean currents. It feeds energy into our biome, where it is converted into plant sugars, and then moves on through the food chain.

As stars go, the Sun is steady and sedate. Its surface simmers at 5500 °C, while temperatures at its core reach more than 15.5 million degrees Celsius. It radiates a steady flow of charged particles known as the solar wind. This stream moves at about 450 km a second throughout the Solar System. Occasionally, a solar flare erupts, sending a barrage of particles throughout the Solar System. Flares can interrupt satellite communications or knock out power grids, but these events are tame compared to some of the stars we will visit. The stability of the Sun may well have contributed to the extent and duration of life's rule on our planet.

Just as Kant and Laplace suggested, the life cycle of a star begins as a vast disk of gas. The universe is filled with elegant, glowing gas clouds called nebulae, and many of these clouds are the birthplaces of stars. Hydrogen is the most common element in the universe, so it makes sense that nebular gas is mostly hydrogen. Some nebulae incorporate the detritus of exploded stars. These nebulae also contain heavier elements such as metals, and these are the nebulae that will lead to an Earthlike world.

As drifting gas condenses into dense knots and tendrils, it begins to develop gravity. The more dense the gas, the more gravity it has. But the motion of gas moving within a cloud follows certain patterns dictated by physics, including eventually spiraling toward the center. The spinning gas flattens out into a disk. Its central bulge, where most of the mass is, pulls gas and dust in radially, becoming a globe called a protostar. The central sphere gains mass and gravity, finally collapsing in on itself and breaking atoms down in its core, triggering nuclear fusion. Within the surrounding disk, eddies and currents are also forming dense spots, and these become planets. Telescopes such as Hubble and Spitzer have resolved images of disks around stars, and in some cases have been able to actually see planets forming within those disks.

Once the star begins to burn its hydrogen fuel, it pours out a gale of particles, called the solar wind, across its planetary system. This wind clears out the gases near the star, leaving many terrestrial—or solid-surfaced rocky—planets in its wake. Giant planets form farther out, where gases are calmer and temperatures cooler, although they may not stay there (see "Arranging Planetary Families," below).

Stars spend most of their time, roughly 90 % of their lifespans, burning hydrogen into helium. This very stable time of life is referred to as the "main sequence," where stars burn steadily and brighten over time. The energy of the hydrogen fusion "holds up" the star's outer layers above its core.

Stars are classified into seven categories, according to their spectrum and from hottest to coolest. The more mass a star has, the brighter it is and the faster it burns its fuel. The first stars, inhabiting the early universe, all consisted of hydrogen and helium. But once they began to explode as novae or supernovae, the scraps of their explosive deaths resulted in heavier elements. Those elements later combined to make new generations of stars. These later-generation stars, our Sun included, still have a majority of hydrogen and helium, but also contain heavier elements such as iron, lithium and calcium. All of these elements contribute to the construction of Earthlike worlds.

Fig. 2.4 A dual planet orbiting Proxima Centauri (*star at right*) might be cool enough, and its conditions just right, to hold atmospheres and even liquid water on the surface, as seen on the distant planet. The primary stars Alpha Centauri A and B are at *left*. Alpha Centauri A, at far *left*, is Sun-like, while its companion is a cooler, K-type star. (Art © Michael Carroll)

The size of a star determines its longevity. The longer a star lives at a stable stage, the more chance Earthlike worlds have of getting started. Large suns use up their fuel quickly, burning bright and hot but not for long. The large star Spica, ten times the mass of Sol, should live "short and fast," lasting about 10 million years. Our Sun will have a lifetime spanning the course of 10 *billion* years. The small, cool dwarf star Proxima Centauri will last perhaps 90 billion years, into the old age of the universe itself (Fig. 2.4).

M Dwarfs

Proxima is among the smallest stars, called M dwarfs. These little suns boast the longest lives. Also known as red dwarfs, they range from 0.075 up to half of Sol's mass. Because of their slow-burning natures, some red dwarfs may live up to 600 billion years. While larger stars collapse after burning through the hydrogen in their cores, red dwarfs burn all of their hydrogen, from top to bottom, gradually. Instead of a deadly helium build-up like their larger siblings, M dwarfs have very energetic internal mixing. This active convection keeps the helium and hydrogen well mixed. Eventually, the helium begins to take over. Then, like their larger cousins, M dwarfs collapse into small white dwarfs.

M dwarfs are the most common stars in the galaxy, says NASA Ames Senior Research Scientist Thomas Barclay. "We have all these classes of stars, and then we put everything at the bottom—which is 70 % of the stars known—in one bin. But M dwarfs range from things smaller than Jupiter—Saturn-sized stars—all the way up to half the size of the Sun, that behave much more similarly to the Sun. If you say you study M dwarfs, it means that you study most stars."

For planet-hunters, red dwarfs present some advantages. Using the radial velocity technique, which detects changes in starlight as a planet moves its star (see Chap. 3), the presence of a small terrestrial planet is more obvious than with larger stars, because the planet's gravity will pull more markedly on the small M star. Since their HZs are closer in, the influence of nearby Earthlike worlds will tend to be more obvious than ones orbiting farther away from their parent stars. Another planet-finding approach, the transit method, also benefits from the diminutive size of red dwarfs. Detecting dips in the light of the star's surface as a planet moves in front, the small face of a red dwarf will be blocked more dramatically than the larger sphere of a Sun-sized star.

K-Type Stars

What about Earthlike worlds orbiting other types of stars? Similar to our Sun are the K-type stars, sometimes referred to as orange dwarfs. Slightly hotter than red dwarfs, these small stars burn at about three-tenths of Sol's brilliance. Their low temperature extends their lifespans, giving them 15 to 30 billion years to live out their existences. They are three to four times as common as Sun-like stars. The smaller of the two main stars in the nearby Alpha Centauri system is a K-type star. Its habitable zone will be similar to the Sun's, but the dynamics of any orbiting planets there will be skewed because of the presence of other stars next to it.

G-Type Stars

Our Sun is a G-type star, a type that makes up 7 % of all main sequence stars, which means that 7 out of every 100 stars has conditions favorable to hosting Earthlike planets. G-type stars range in mass from 0.8 to about 1.2 solar masses. Nearby Alpha Centauri A is a G-type star. Both it and the Sun have life expectancies of about 10 billion years. (Sol has already burned through about half of that time.)

Our Sun is a main sequence star, classified as a G2 yellow dwarf star. Nuclear fusion in its core burns hydrogen, converting it to helium and generating an incredible amount of energy. As a star ages, its hydrogen begins to run out, and what's left is a heavy shell of helium. The star's core begins to compress even more, abandoned by the supportive force of hydrogen fusion. The helium on the outside, along with leftover hydrogen, expands and heats up even further, and the star grows larger and brighter, often transforming into a red giant. During this phase, our Sun will expand to fill the orbits of Mercury and Venus, perhaps even making it out as far as Earth's orbit.

In this violent fuel-burning process, stars the size of Sol fuse heavier elements such as carbon. Larger stars generate more varied elements. Finally, when there is no more fuel for the star to burn, it departs from the "main sequence" and begins to die. Size determines the fate of a star. Medium to low-mass stars such as our Sun swell into a giant star, and eject their shell of spent hydrogen and helium into space. What's left is a "dead" star called a white dwarf. Its habitable zone shrinks down to a narrow band around the star, leaving any Earthlike worlds out in the cold.

A star with four to eight times the mass of the Sun expires in an enormous blast called a supernova. A typical supernova may put out as much power in an instant as an average star does during its entire lifetime. The resulting wave of gas expands at up to 10 % of the speed of light. Any Earthlike worlds nearby would be destroyed outright by the explosion or fried by its radiation.

F-Type Stars

F-type stars are even rarer, accounting for 2 % of the stars in the universe. These stars span up to 1.5 solar diameters, with luminosities seven times as bright and temperatures of 6500 ° C. Burning their fuel hot and fast, these stars are active for only 2 billion years. About 37 F-type stars lie within 50 light years of us. Due to their heat and radiation, the habitable zones of F stars are at a greater distance, but the short life span of F stars may preclude any stable planetary biomes.

A-Type Stars

The A-type stars make up just 1 % of the stellar population. These hot stars burn with a surface temperature of 8000 °C and a brightness of twenty times that of the Sun. Having twice the mass, they end life in about a billion years.

The brightest star in Earth's sky, Sirius A, is one of these. With an even shorter stable period than F stars, finding Earthlike worlds with active biology in these systems is unlikely.

B-Type Stars

The blue giants, classified as B-type stars, are incredibly hot. At a thousand times the luminosity of our Sun, the searing temperatures of B stars reach 15,000 °C. They contain between 2 and 16 solar masses. B-type stars rotate quickly, with equatorial speeds reaching 200 km/s. They generate fierce stellar winds of up to 3000 km/s, a deadly hurricane to any nearby planets. B stars collapse into cold, dead white dwarfs within 50 million years of their birth. Only one in every thousand stars is a B-type. In our search for Earths of distant suns, B stars are not a promising place to look.

O-Type Stars

Most scarce and deadly of all stars is the O-type, known as a blue supergiant. Supergiant surface temperatures surpass 50,000 °C. With up to 90 solar masses, they burn out in half a million years. Under the light of a million suns, the presence of an Earthlike planet is difficult to imagine.

From Supernova to Black Hole

More exotic stars lurk in the void. Most are unlikely to have anything resembling a habitable zone, so any Earth-sized world there would certainly not be Earth-like. Supernovae, exploding stars, contain cores that burn to a point at which they carry out a different type of fusion—called carbon fusion. When the core reaches this stage, the star explodes with a luminosity of 5 billion times its original brightness. Other supernovae are the result of the collision of two white dwarfs. Supernovae can also be triggered by the collapse of a star's core.

The brightest supernova on record was initially detected on June 14, 2015. Before fading again, the star fleetingly reached the brightness of 600 billion Suns. The titanic exploding sun, logged as ASASSN-15lh, was a member of a rare class of supernovae called "superluminous supernovas."

As the core of some supernovae continues to collapse, the entire star—often the mass of the Sun—shrinks to only 20 km in diameter. The core's gravity draws in upon itself, and protons and electrons clash together to make neutrons. This kind of shriveled sun is called a neutron star. The gravity of an average neutron star is 2 billion times as powerful as that of Earth. The explosion from the neutron star's collapse spins the core rapidly—up to 700 rotations per second—spewing out radiation like a lighthouse sends out beams of light. Its formative explosion would clear its inner planets of all atmosphere, and its pulses of radiation, usually X-rays and gamma rays, would leave any nearby worlds cold, barren and soaked in radiation.

If large enough to begin with, the core of a collapsing star will continue shrinking until it becomes a point in quantum space/time. This bizarre stellar phantom is called a black hole. Black holes do not generate the kind of energy that a main sequence star does, and consequently they have no habitable zones, making them a poor target in our search for Earthlike worlds.

This survey of stars shows us that not all stars are candidates for possessing Earthlike planets. Those that *are* retain varied habitable zones, dependent on the nature of their host stars. Stars must remain stable for long periods in order for an Earthlike world to arise. They must not put out too much heat or other radiation, and they must contain elements that can contribute to the building of rocky planets.

Habitable Zone Types

Since the nature and stability of a habitable zone is dependent on its host star, which are the best candidates for finding life? Types O and B stars live such short and furious lives that Earthlike planets don't get the chance to form out of the stars' accretion disks. By the time things settle down for any new terrestrial planets, O and B stars have begun their death throes.

Suns of the type A and F show more promise. With stable lifetimes of between 1 and 2 billion years, planets can form, and biomes may even become established on their surfaces. Life on Earth has left its evidence as far back as 3.8 billion years ago, less than a billion years after star birth. But because of their higher temperatures, these stars have a higher energy output, especially in ultraviolet (UV) radiation. UV radiation can be deadly to life, breaking down the bonds that hold together complex organic molecules. But it will depend on the planets circling them. UV radiation cannot penetrate deeply into soil, ice or water. Some evidence hints that life on Earth began on the ocean floors around volcanoes. Any Earthlike world with lakes, seas or oceans might provide plenty of shelter for microbes and more complex life forms. But the relatively short lifespan of A and F stars means that intelligent life may not have a chance to take hold. Humans did not arrive on the scene until Earth had been around, next to a stable Sun, for roughly 4 billion years.

Some 90 % of all stars belong to the K and M classes. K stars (the orange dwarfs) are slightly smaller than our Sun, weighing in with masses ranging from 0.45 to 0.8 the mass of our own star. They remain on the main sequence for 15–30 billion years, plenty of time for planets to form. In addition to their stability, K stars produce far less UV radiation than Sol does. Although their lower temperature means that their habitable zone is closer to the star, reduced radiation may mean that they are candidates for Earthlike conditions on nearby worlds.

The long life and low temperatures of M stars make them good candidates for finding other Earths. The habitable zone of an M dwarf forms a narrow ring around the dim orb. If our Sun were an M dwarf, its habitable zone would extend from just $^{1}/_{10}$ to ¼ the distance of Mercury. The habitable zone is so close to the star itself that any planets within it are likely to be tidally locked, always keeping one face toward their sun. Temperatures on the sunlit side might soar, while conditions on the night side would chill precipitously.

At one time, it was thought that M stars were starved of the elements that contribute to the construction of terrestrial worlds. Mercury, Venus, Earth and Mars are composed of nickel, silicon, iron, aluminum, calcium, magnesium and assorted other elements. Some early studies of stellar spectra indicated that these elements were rarer in M stars. But the Southwest Research Institute's Dirk Terrell says, "We haven't seen any red dwarfs that lack metals, the ones you'd expect to see at the earliest stages of the evolution of the universe." Research indicates that there are few major differences in elemental abundances between M stars and the Sun.

Recent work provides further hope for finding life in M-star systems. Not all planets in tight orbits need to be tidally locked. Ocean currents, large moons or thick atmospheres can provide inertia to keep a planet rotating. Additionally, even if a world becomes tidally locked so close to its star, computer models demonstrate that the circulation patterns in an atmosphere can play a critical role in subduing the wild temperature extremes from day to night. Simulations showed cloud cover developing on the day side of an Earth-mass world, keeping temperatures down and air pressure high. Winds generated by that high pressure on the lighted side redistributed the heat to the night side, raising those evening temperatures.

We see a similar situation on our own world. A constant rise and fall of currents mixes the atmosphere well in its lowest layer, called the troposphere. Solar heating and currents welling up from the warmed ground keep the air well-mixed, moderating our temperatures. Our weather is simply a mechanism in constant search of equilibrium in our planet's temperatures. On the day side of the globe, hot air forms over the region of the planet pointing most directly at the Sun, near the equator. There, hot air rises, moves away from the equator and drifts toward the poles. It cools at high altitude and sinks back down, migrating at low altitude back toward the equator. This airy conveyor-belt of atmosphere is called a Hadley cell. Planets orbiting red dwarfs may benefit from energetic Hadley cells, enabling life to take hold there.

For Earth-like exoplanets not locked in a deadly tidal dance, another roadblock to life may be the nasty red dwarf habit of flaring up. M dwarfs often send out energetic tongues of material, doubling in brightness as they discharge massive radiation, sterilizing the planetary neighborhood around them. But these flares could also trigger the production of ozone in planetary atmospheres, and this ozone would provide a shield from such radiation.

In addition, what red dwarfs lack in potential habitable real estate, they make up for in sheer numbers. Accounting for nine-tenths of the 100 billion stars in the Milky Way, M dwarfs may play host to 60 million Earthlike worlds.

Still, it seems that a complicated combination of factors contribute to Earth's own habitability. In all the millions of worlds of our galaxy alone, is it possible that Earth is unique?

Past Lives of Our Earth

Earth has not always been the life-nurturing paradise that it is today. Present-day conditions are quite different from what they were when life first arose on the planet. Temperatures and oxygen levels have ebbed and flowed. If we could travel back in time to earlier stages of our Solar System, we might not recognize Earth at all.

Earth's progression of development may well be representative of some of the Earthlike planets we will discover in other star systems. In the formative stages of our own Solar System, planets formed within the great primordial cloud from which the Sun also came. Earth was cocooned in a "reducing" atmosphere rich in hydrogen. In a phase known as T-tauri, the young Sun's solar wind cleared out the dust from the inner Solar System. It also stripped away much of our planet's first atmosphere. Comets and asteroids fell onto Earth and its fellow planets, carving out big craters and leaving behind water and minerals. Early in the process, a Mars-sized space rock slammed into the edge of Earth, creating a ring of debris that became the Moon (see "Isn't that special?" below).

Earth's first oceans appeared, but they were not oceans of water. Instead, the face of our world was awash with seas of molten rock. The great fusillade of asteroids and comets continued to rain destruction upon the glowing landscape. Their deadly salvo continued in full force until about 3.8 billion years ago. The infant Earth was a scant 4 or 5 million years old. Even then, the planet was differentiated: heavy materials had settled to the center, with lighter stuff migrating up to form a crust. Radiogenic materials within the core, along with the leftover heat from its creation, raised internal temperatures, triggering worldwide volcanic activity. These erupting mountains, in concert with materials from impacting comets and asteroids, replaced the dwindling reducing atmosphere with new gases. Carbon dioxide, nitrogen and water vapor filled the skies as Earth's second atmosphere. As they did, clouds condensed, and the first true rains fell onto cooling lava rock (Fig. 2.5).

This Dantean version of Earth gave way to another quite alien world. As the first watery oceans rolled across Earth's surface, the only upraised dry land areas were the rims of craters. But eventually, a new world-building force came into play, that of plate tectonics. Earth is like a jigsaw puzzle. Continents float on rock rafts called plates. These plates move and bump into each other on a "sea" of soft hot rock beneath Earth's crust, the mantle. As the plates ram into

Fig. 2.5 A primordial Earth peers down on a Moon still volcanic from the fires of its creation. Landmasses on Earth are limited to upraised crater rims; plate tectonics are still millions of years in the future. (Art © Michael Carroll)

each other, rock gets pushed up into mountains or melted underneath in a process called subduction. Earth's rocks soak up the gases in our atmosphere, chemically binding carbon dioxide and other gases to the surface. But the rocks eventually melt when plates collide. The trapped gases are spewed back out as volcanoes replenish our atmosphere.

This oceanic stage of Earth presented vast stretches of water where new continents rose. The landscapes of our world were barren and sterile. Craters continued to form though at a much-reduced rate, and some of the largest asteroids left scars that we still see today. South Africa's Vredefort dome, Australia's Warburton impact basins and the Yucatan's Chicxulub crater are the remnants of ancient impacts.

How hot were the ancient oceans? Initial estimates put global seas at nearly the boiling point 3.5 billion years ago, but new research indicates that this may not have been the case. Far from being a simmering inferno, early terrestrial conditions may have been downright chilly. Studies[8] of the isotope oxygen-18 in samples from South Africa's Barberton Greenstone Belt give biologists new insight into early biomes. The site contains some of the most ancient preserved rocks on Earth. Those isotopic studies have revealed that the rocks formed under cool conditions far below the boiling point of water. Additionally, researchers found the presence of clay-like diamictite, a sediment usually formed in glacial environs. Adding to the picture is 3.5 billion-year-old gypsum, which would have formed in deep, cold seawater. The samples also displayed varved sediments—seasonal bands typically laid down when standing bodies of water freeze. Even magnetic data back up the chilled scenario. Paleomagnetic data helps to lock down the location at which the rocks initially formed. The data shows that these samples formed near tropical latitudes.

Because even these near-equatorial rocks were cool, temperatures farther north or south must have been even cooler. Researchers suggest that earlier estimates of higher temperatures sampled brief periods of increased hydrothermal activity, but the new work takes into account ambient overall temperatures rather than localized ones. If the new estimates are accurate, our planet has hosted conditions amenable to life for far longer than originally thought.

Earth continued to change and shift. Continents rearranged themselves, prompting changes in sea currents and weather patterns. Craters came and went as weather and mountain-building eroded the terrain. Minerals from highlands washed into the ocean basins, where they were recycled back to the continents by the subduction and uplift of plates. But on the microscopic

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[8] See *3.5-Ga hydrothermal fields and diamictites in the Barberton greenstone Belt* by Maarten J. de Wit and Harald Furnes; *Science Advances*, February 26, 2016.

level, something remarkable was taking place, something that would eventually transform our alien Earth into the world we inhabit today.

Within puddles and tidal pools at the ocean's edge, life began. How did it happen? What do we find in the chemistry of the rocks and in the fossil record? Life's origin is a rich area of research for biologists today, and a topic for theologians and philosophers as well. One thing is certain: over 3.8 billion years ago, Earth's chorus line of life took to the stage. Single-celled microbes appear as fossils from about that time, but these little creatures are complex, with delineated internal structures and varied outer membranes. Apparently, life had been around for some time before these fossils were put down. Microbial life transformed the atmosphere of Earth, pumping O_2 into the air. Many researchers consider this a third atmosphere of Earth, one that enabled life forms with oxygen-friendly metabolisms to thrive.

At some point, life came ashore, but the world was a changeable, dangerous place. Earth's toxic atmosphere was laced with lightning and furious winds. Meteors continued to fall. Eventually, new life forms such as the plankton and plants brought an influx of oxygen into the air. Global temperatures varied dramatically. During the age of the dinosaurs, high temperatures may have prevented any extensive ice—even at the poles—but the planet has also undergone radical temperature swings into the cold. Some geologic and isotopic studies[9] indicate that our world may have suffered a planet-wide deep freeze. Temperatures fell to well below 0 °C across the map, resulting in a complete glaciation from pole to pole. The world's oceans would have frozen over in episodes that lasted approximately 100 million years. These events are referred to as Snowball Earth ice ages. How Earth pulled out of such an environmental catastrophe is not clear, but the timing of Snowball Earth glaciations seems to coincide with several mass extinctions, along with the advent of oxygenating organisms long before life came on land.

Between the planet's ice ages, ocean temperatures were actually substantially higher than they are today, with ocean levels some 200 m higher than we currently see. Global temperatures may have clocked in at 8 to 10° warmer than today, which probably resulted in higher humidity. Further back, between 3 and 3.5 billion years ago, ocean temperatures may have topped 85 °C, deadly by today's standards. The fossil record shows us that during that time, life inhabited the oceans. These "unearthly" swings in temperatures and gasses, combined with the extreme biomes in which life thrives here, may indicate that the current environment of Earth is not, in fact, the best model to use in the search for extraterrestrial life.

[9] Hoffman and Schrag, 2000.

The Great Dyings

Many of the planet's species disappeared during the Permian extinction, the largest extinction event yet detected. Life on our planet did not arise in a steady progression. It accelerated and diversified, only to be beaten back again or to stabilize at a balance. Earth has been subjected to several mass extinction events. Topping the list, the Permian extinction may have wiped out 90 to 96 % of all species on land and in the oceans.[10] The Cretaceous-Paleogene (or K-T) event is the most famous, as it ended the reign of the dinosaurs. But life on this planet was nearly wiped out multiple times (see Fig. 2.6). What this means in our search for other Earths is that although we may find sister planets, any past life there may have been snuffed out in a Permian-event-on-steroids. The same fate could very probably befall Earth. Many see this as an impetus for humanity to spread to other worlds. In fact, astronomer Carl Sagan saw this fact as one reason that advanced civilizations must travel among the stars. In his book *Pale Blue Dot*, Sagan asserted, "Since, in the long run, every planetary society will be endangered by impacts from space, every surviving civilization is obliged to become spacefaring—not because of exploratory or romantic zeal, but for the most practical reason imaginable: staying alive."

The Earth's roller-coaster story of planetary evolution and life enables us to imagine what various forms Earths of distant suns may take. But the cosmos has provided us with other insights very close to home.

Earthlike Planets in Our Solar System

One way to gain understanding about potential distant exo-Earths (Earthlike exoplanets) is by studying the worlds near us. With Earth as the primary example for imagining habitable planets in other star systems, early astronomers struggled to envision what other Earths might look like. They had two other specimens of somewhat Earthlike worlds just next door. Earth is bracketed by two planets that can be considered somewhat "Earthlike," Venus and Mars. Even small Mercury has a similar internal structure. Each of these three terrestrial, or Earth-similar, planets has an outer crust overlaying a lithosphere (or upper shifting mantle), a deeper silicate mantle and a metallic core.

[10] Recent controversial research suggests that the Permian die-off was not as widespread as once thought. Land species believed to have gone extinct during the event have been found later in the fossil record. For more, see Gastaldo, et al. "Is the vertebrate-defined Permian-Triassic boundary in the Karoo Basin, South Africa, the terrestrial expression of the end-Permian marine event?" *Geology*, October 2015.

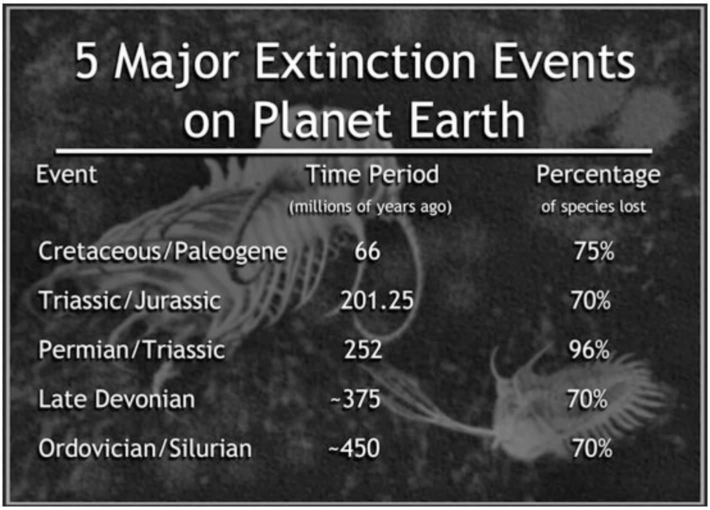

Fig. 2.6 Planet Earth has endured many major extinctions throughout its history, as shown in this table. Exoplanets undoubtedly suffer the same events. How do these influence the likelihood of life on other worlds?

As for planetary interiors, we know the most about Earth's. We know what the surface is made of, and we've had tastes from the deep interior by way of lava eruptions and deep drilling projects. The planet gives us an added bonus. Seismic activity (volcanic eruptions, earthquakes) sends shockwaves through the planet's subsurface. Because we have deployed seismometers around the globe to monitor such waves, we can chart the subtle movement and arrangement of the interior. Like a bat using echolocation in the dark, the way seismic waves bounce around inside Earth reveals its structure. Just 4/1000th of our planet's mass resides in its crust, a hide that varies in thickness from about 6 km in the oceans to 50 km at the continental mountains. Since the crust makes up such a small amount of the planet's mass, it does not figure into calculations of distant Earths.

Next down is the upper mantle, a layer of olivine, pyroxenes and garnet. It is within this region where plate tectonics take place. Below this layer lies the lower mantle, dominated by silicates in various forms. At the planet's center, a solid iron core 2400 km in diameter floats within a molten iron outer core.

Venus is likely similar in structure, as it is Earth's twin in size. Mars affords another example that can be applied to exo-Earths (Earth-like exoplanets). Current models of the Martian interior suggest that its core region is roughly 3590 km across. Data and models imply that the core consists primarily of iron and nickel, with a bit more than 15 % sulfur thrown in. This iron sulfide core is partially fluid, and contains a larger component of lighter elements than Earth's core. A silicate mantle surrounds the Martian core. As on Earth, that mantle is responsible for many of the tectonic and volcanic features on the planet, but it now appears to be dormant. In addition to silicon and oxygen, the most abundant elements in the Martian crust are iron, magnesium, aluminum, calcium and potassium. The average thickness of the planet's crust is about 50 km, thick compared to the overall planet. In contrast, Earth's crust is just one-third as thick—compared to the planet—as the Martian crust.

In the case of Earth, the solid iron core is surrounded by a molten outer region of liquid iron. This liquid metal moves with the turning of Earth and with inner convection, setting up magnetic fields around the planet. These fields, called collectively the magnetosphere, form a protective bubble around Earth, staving off the barrage of radiation pouring from the nearby Sun. The magnetosphere also protects the atmosphere from being stripped away by solar wind (Fig. 2.7).

Venus, Mercury and Mars have far weaker magnetic fields, in varying strengths and locations. The metallic cores of both Mercury and Mars likely cooled early in their histories, freezing into solid rock as the hot young planets settled into their more sedate modern forms. While Venus is a twin to Earth in size, its rotation is very slow, turning one lazy day each 243 Earth days. Since its year lasts for 224 days, its longer daily turn means that the planet

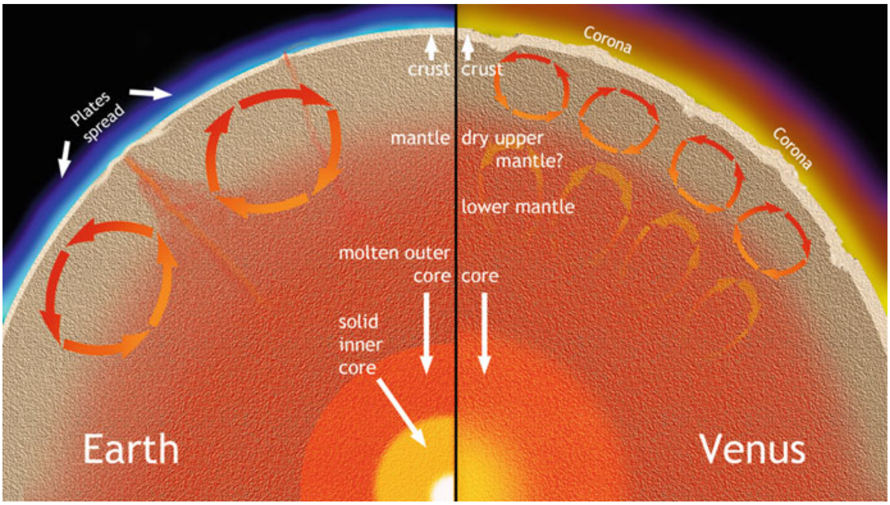

Fig. 2.7 The interior plumbing of Earth (*left*) and its Earthlike sibling, Venus (*right*). (Art © Michael Carroll)

rotates in the opposite direction to most things in the Solar System, in a retrograde motion.[11] The lack of a Venusian magnetosphere may be due, in part, to the planet's slow rotation.

Although a planet's magnetosphere has a dramatic effect on its atmosphere, other factors come into play. In the case of the terrestrial planets, their atmospheres came late. Unlike the gas and ice giants, which drew their atmospheres from the surrounding solar nebula in the Solar System's formative years, the terrestrials lost their early atmospheres as the nearby Sun formed and blew its furious solar winds outward, clearing the inner Solar System of its primordial hydrogen-rich gases. Hydrogen and helium still rule our outer system, but the inner worlds have secondary atmospheres made up of different gases: nitrogen, oxygen and carbon dioxide (in fact, carbon dioxide makes up the majority of gas on both Mars and Venus). As on primordial Earth the new gases of the other terrestrials came from volcanoes, and from the impacts of asteroids and comets. Once in place, the second-chance atmospheres changed and morphed, sculpted by sunlight, chemical interactions with the surface, and loss from solar wind. Earth's third atmosphere, unique in its rich oxygen (O_2) levels, has been altered by biology. As we will see, oxygen may be a "marker" of biology on exo-Earths.

A planet's day/night cycle, seasonal tilt and nearness to the Sun also affect its gas blanket. The slow rotation and dense air of Venus produce high temperatures and pressures. The Venusian proximity to Sol may have triggered a greenhouse effect, vaporizing the extensive oceans it may have had and roasting carbon dioxide from its rocks, adding it to the expanding atmosphere. Mercury and Mars, on the other end of the atmospheric scale, both have low gravity and little in the way of protective magnetic fields, so they have lost more atmosphere over their lifetimes. Their smaller masses meant smaller cores, and as those cores cooled, they shut down the protective magnetic fields. Both planets have had extensive volcanic outgassing, but with little gravity to hang on to what was left, the air around Mercury and Mars drifted away on the solar winds. Venus, Mars and Mercury undoubtedly represent some number of relatively Earthlike exoplanets (Fig. 2.8).

In our search for Earthlike worlds, the past events and climates of our planet inform us that life can exist in extreme conditions, perhaps in exotic locations of other star systems. Nevertheless, the most familiar, Earthlike worlds will be found in a star's habitable zone. Each star type has its own unique habitable zone.

[11] Seen from above their north pole, the planets all tend to orbit the Sun in a counterclockwise—or prograde—direction, and they spin in the same counterclockwise motion. Any body moving in the opposite direction has a motion called retrograde.

Fig. 2.8 The most "Earthlike" planets in our Solar System may provide glimpses into what we can expect on some Earths of distant suns. Here, we see three typical surface views of (l to r) Venus, Earth and Mars. (*Left:* Digital revamp of Soviet Venera image courtesy of Don Mitchell and the author. *Center:* Death Valley, California, Earth, photo by the author. *Right:* Curiosity rover image of Gale crater, NASA/JPL/Caltech)

Some HZs are narrow and close in, while others are wide and spread out. The main thrust of our search for Earths of distant suns will focus there. But not all HZs are created equal.

Isn't That Special?

The rich and varied history that our planet has undergone demonstrates a small sampling of the variety we may find among Earthlike planets of other systems. And while much of what we witness in the ancient record here may apply to other earthlike planets, some features may be unique to Earth. For example, the rejuvenating power of plate tectonics, with its recycling of minerals in the rock and gases in the air, does not seem to occur on planets with thicker crust. Our twin in scale, Venus, has no hint of plate tectonics, although it may have a less efficient type of movement within its dense crust. This movement appears to present in a columnar migration of material. Crust moves up and recirculates down in oval regions, as if limited to the outer edge of a pillar.

As evidence of this new type of tectonics, some researchers point to the coronae, vast oval mounds hundreds of km across. Typically, concentric troughs surround the coronae, perhaps formed as upwelling mantle material forces the crust upward. Rather than a surface in constant movement, Venus may endure periodic global resurfacing events. The liquid water on Earth may lubricate the process of plate migration. Without liquid water, Venus is doomed to simmer under a dense atmosphere, warmed not only by greenhouse effects from above but also from trapped heat below, where interior energy is unable to escape. What's left is a world pockmarked by volcanoes, the only clear escape route for its internal heat. The slow spin of Venus also contributes to its alien nature. Without the currents of molten metal sloshing around in its core, Venus lacks a magnetic field. To add insult to injury, its lazy day/night cycle combines with hurricane force winds that blow heated daylight air onto the night side, fostering its global blast-oven conditions.

Unlike Earth, Venus has no moon. Although this might not disturb any Venusian romantic poets, the lack of a moon may actually be an important barrier to life. In fact, our Earth's large natural satellite has a profound effect on the uniqueness of our planet.

Earth's Moon is so large—compared to its primary—that Earth essentially qualifies as a double planet.[12] Luna may have helped to draw away early greenhouse gases, something Venus would have benefited from. It regulates Earth's spin and dampens the wobble of its axial tilt.

Ironically, a violent impact gave birth to our beneficent Moon. Shortly after our planet became differentiated, a cataclysm nearly put an end to the world we inhabit today. The event transpired some 4.2 billion years ago, in the midst of the asteroid demolition derby. Earth's mass became large enough—and radioactive materials abundant enough—to heat the core. But before Earth could settle down into a respectable planet, a Mars-sized behemoth sped out of the darkness. If the angle of impact had been slightly steeper, Earth would have shattered like a dropped wineglass. Instead, the stray planet hit a glancing blow. The colossal collision peeled away the lighter material from Earth's crust. For a brief time in geologic history, the again-molten Earth had a ring to rival even Saturn. Within less than a million years, though, that ring of debris had become our Moon.

The Moon not only keeps our environment stable, it also raises the tides. Many biologists believe the Moon played a critical role in the rise of life. Earthlike worlds lacking a large natural satellite—like Venus—may be at a disadvantage in developing a biome.

One such world is Mars. In many ways, Mars is the most Earthlike world in our Solar System. The planet's tilt is similar to Earth's, providing it with comparable seasonal changes. Its day is only a few minutes longer than Earth's, and daytime temperatures, while chilly, are close to the melting point of water. Mars orbits just at the outer edge of the Sun's habitable zone. But its two moons, Phobos and Deimos, are so small as to have no effect on the

[12] While the Moon orbits Earth, the center of rotation for the entire Earth/Moon system is just inside the surface of Earth. The only other two-body system that comes close to this scenario is Pluto, which orbits a point between itself and its large moon Charon.

stability of the Red Planet. This means that over time, the Martian spin axis tips wildly. About 50,000 years from now, the axial tilt of Mars will roll over to the point where the planet spins nearly on its side, creating dramatic—and possibly lethal—seasonal changes. Additionally, Mars' small size means that its core has cooled. Liquid metal in the center has, for the most part, frozen into solid iron, leaving the planet without a substantial magnetic field. Some evidence suggests that the planet once had a robust field, and something like plate tectonics. Because of Earth's tectonics, new rocks are generated on the floor of the Atlantic Ocean, moving away from a central ridge like two conveyor belts sliding away from each other. These rocks retain a record of Earth's magnetic fields, their patterns creating a mirror image of each other. On Mars, hints of this kind of mirror image show up in some areas of the crust, ancient traces of magnetism from long ago. But the core's magnetic field is essentially gone today.

Mars has another problem in the Earth-similarity-department. Its low gravity is unable to hold onto a substantial atmosphere. In similar fashion to Earth and Venus, Martian volcanoes replaced its initial reducing atmosphere with carbon dioxide, nitrogen and water. Because the little world has no shifting plates, some volcanoes became giants, building over a geological heat source for over a billion years. But eventually, the volcanoes all died out, and today so much of the original Martian air has drifted away that pure water cannot exist on the surface; the pressure is so low that it boils away instantly as vapor.[13]

Our Solar System possesses four terrestrial (rocky) planets: Mercury, Venus, Earth and Mars. Of those, only Venus, Earth and Mars could have become habitable. Mercury is not in the habitable zone; it orbits so close to the Sun that daytime temperatures reach 427 °C. On the other hand, both Venus and Mars travel along the inner and outer edge of the zone, affording them the possibility of liquid water under the right conditions. However, they have both lost their magnetospheres, those protective magnetic bubbles surrounding some planets. Without the protection of a magnetosphere, Mars has lost most of its atmosphere, leaving it cold and geologically quiet, too small to have remained active. With its overgrown atmosphere, Venus broils in conditions too hot for life. So although we have three terrestrial planets within a habitable zone, it appears that only one—Earth—sustains a biome.[14]

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[13] In some of the lowest-lying areas on Mars, liquid water may persist close to the surface, and impurities like ammonia may enable water to retain a liquid state on the surface itself.

[14] Here, we are speaking of life as we know it from the only sample we have: Earth's. Extremophiles living in drastic conditions on our own world demonstrate that life may take many forms in quite hostile environments. The search for life on our nearby worlds, active or in the fossil record, continues.

A Really Big Habitable Zone?

Another limitation to Earthlike worlds may exist: location in the galaxy. It seems that our Milky Way has a habitable zone of its own. The great spiral of stars making up our galaxy spans some 120,000 light-years across, inhabited by 100 to 400 billion stars. Within this structure, interstellar gas and dust drift among the star-birthing nebulae. Young and middle-aged stars glow throughout, but the stars in the central bulge tend to be more geriatric. A supermassive object at the galactic center, known as Sagittarius A*, attracts a maelstrom of gases and stars around it. The object pumps out prodigious amounts of X-rays and may well be a massive black hole.

Our planet orbits the galaxy far enough from the center to have access to the heavy elements coming from exploding stars. Older stars near the center lack many of the heavier elements, while stars out in our neighborhood benefit from heavy elements generated in the explosions of supernovae. This is good fodder for the rich terrestrial planets in our Solar System. At the same time, Earth orbits 28,000 light years from the center, far enough away to elude the lethal gamma radiation coming from the galaxy's heart. Just 5 % of stars in our galaxy fall within this zone.

The Solar System's orbit around the galaxy is also fairly circular, so that it avoids the galaxy's dangerous spiral arms. We have seen that those starry lanes are high-radiation neighborhoods, making them bad territory for life, but there is more to the story. Within those arms, interstellar gas gives birth to new stars whose intense radiation could destroy life on Earth. But our location lets us keep pace with the arms. As a communications satellite orbits far enough from Earth to remain over the same spot, turning at the same rate as the planet, so the Sun orbits at the right distance from galactic central to remain in between spiral arms. Sol's family is also far enough away from the galactic center to miss the disruptive gravitational forces and intense radiation nearer the central hub (Fig. 2.9).

Location of the neighborhood is critical to the existence of Earth-like worlds, but so are the details of each individual planet. What we have learned about our own planetary system can be applied to Earths of distant suns.

Applying Lessons to Exo-Earths

Our studies of members in our own Sun's family make it clear that a planetary interior has a profound effect on the nature of a world. But how can we tell about the interior structure of an Earthlike world we can't even directly see?

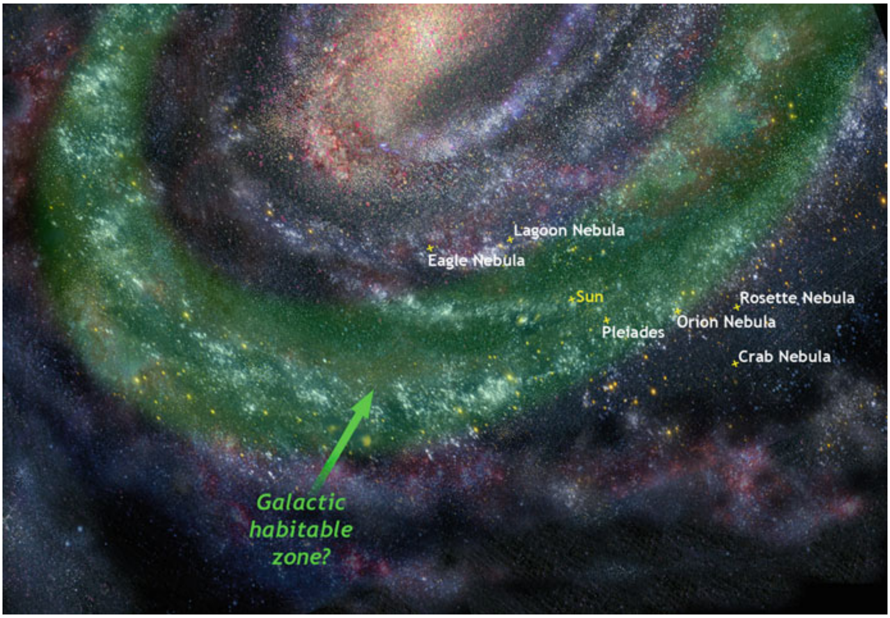

Fig. 2.9 Our place in the Milky Way Galaxy may be particularly well-suited for life, between spiral arms and away from the radiation-filled heart. (Art © Michael Carroll)

A recent study by Caltech's Christophe Sotin et al. indicates that only a few elements are needed to determine the total mass of a planet. It turns out that oxygen, iron, magnesium and silicon together make up 95 % of Earth's bulk. Combined ratios of these elements, compared to the planet's known mass, provide observers with a yardstick for an approximation of masses of distant worlds.

Technology is nearly to the point where we may be able to spectrally tell what these exoplanets are made of, but while we wait for those advances, we can use their estimated masses (found by other techniques such as transits and radial velocity) to approximate the makeup of these faraway worlds. When we do this, we can also make an educated guess as to what the interiors of these exoplanets are like, which tells us about possible magnetospheres, volcanic contributions to their current atmospheres, etc.

Building a model of an exoplanet interior is not as easy as it sounds (and it doesn't sound easy). Adding sulfur, nickel and aluminum to the mix introduces complexities, shifting the melting points and crystalline structure, and changing the model's extent and location of crust, mantle and core. Still, theorists have come up with models that work well with the few terrestrial planets we have as examples. Using only the elements as a guide to the size of Venus, Earth and Mars, the models come within 1 % of predicting how large the planets should be.

We cannot yet determine the specific elements within the crust and interior of exoplanets, but their nearby stars provide clues. Abundances of rock-forming elements such as iron, magnesium and silicon within stars can be calculated by the light spectrum coming from the parent stars themselves. Just how close is that relationship between the makeup of a star and the composition of orbiting planets? The issue is still under debate.

These compositional models supply us with estimates about the three Earthlike worlds of our own system. As we establish how close they come, we can then apply that knowledge to the study of exoplanets. And, as we determine the composition of exoplanets, these models will help us to fill in the blanks, giving us an approximation of what may be going on within these worlds.

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