

The Habitability of Our Earth and Other Earths: Astrophysical, Geochemical, Geophysical, and Biological Limits on Planet Habitability

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Abstract

For life-forms like us, the most important feature of Earth is its habitability. Understanding habitability and using that knowledge to locate the nearest habitable planet may be crucial for our survival as a species. During the past decade, expectations that the universe could be filled with habitable planets have been bolstered by the increasingly large overlap between terrestrial environments known to harbor life and the variety of environments on newly detected rocky exoplanets. The inhabited and uninhabited regions on Earth tell us that temperature and the presence of water are the main constraints that can be used in a habitability classification scheme for rocky planets. Our compilation and review of recent exoplanet detections suggests that the fraction of stars with planets is $\sim 100\%$, and that the fraction with rocky planets may be comparably large. We review extensions to the circumstellar habitable zone (HZ), including an abiogenesis habitable zone and the galactic habitable zone.

1. INTRODUCTION

The Sun with all those planets revolving around it and dependent on it, can still ripen a bunch of grapes as if it had nothing else in the universe to do.

—Galileo

The universe is filled with stars like our Sun (Robles et al. 2008), rocky planets like our Earth (Howard et al. 2011), water like in our oceans (Mottl et al. 2007), amino acids like those that make up our proteins, and all the other ingredients for life (Pizzarello 2007). But is the universe filled with anything we would recognize as life (Lineweaver 2006)? de Duve (1995) has argued that the initial deterministic nature of proto-biochemistry makes life a “cosmic imperative” built into the chemistry of the universe, and we should therefore expect life to be common in the universe.

Terrestrial life emerged from nonlife approximately four billion years ago (Battistuzzi et al. 2004, Sleep & Bird 2008) (**Figure 1**). Descriptions of where this happened include warm little ponds (Darwin 1871), hot hydrothermal vents (Wächtershäuser 2006, Martin et al. 2008), and cold little ponds (Bada et al. 1994). Scenarios for how life emerged include a prebiotic soup under a reducing atmosphere (Oparin 1924, Miller 1953) and some form of semi-deterministic molecular chemistry (Dyson 1999, Segre & Lancet 2000) that evolved into auto-catalytic reactions (Eigen 1971) and produced replicating molecules (Cairns-Smith 1982, Gesteland et al. 1999), proto-metabolisms (Pascal et al. 2006), and cell membranes (Deamer & Szostak 2010). Despite the variety of these scenarios, some common threads represent our best estimates of what we might expect to share with extraterrestrial life. We can expect extraterrestrial life to be based on Darwinian evolution and the most fundamental features of terrestrial biochemistry (Feinberg & Shapiro 1978, Pace 2001, Conway-Morris 2003, Benner et al. 2004, de Duve 2007, Lineweaver & Chopra 2012). Noncoincidentally, these are the same features that are often used to define life (e.g., Schrodinger 1944, Sagan 1970, Joyce 1994, and the contributions in Leach et al. 2006).

During the past few decades, the exploration of some extreme environments on Earth has uncovered extremophile microbial life in conditions previously thought to be too hostile for life. These discoveries have expanded the variety of terrestrial environments known to harbor life (Rothchild & Mancinelli 2001, Stetter 2006, Shock & Holland 2007, Baross et al. 2007, Madigan et al. 2010, Pedersen 2010). During the same few decades, progress in the characterization of the planets and moons of our Solar System, and progress in the detection of a wide variety of exoplanets in orbit around an increasingly large fraction of stars, has broadened the range of known extraterrestrial environments (Sections 3 and 4). The growing overlap of these two sets of environments suggests that habitable planets are abundant (**Figure 2**). This increases the probability of finding some kind of extraterrestrial life.

The number of papers and conferences reporting new exoplanet and extremophile discoveries, and those grappling with the issue of planetary habitability, has enormously increased. Recent reviews of habitability include Kasting & Catling (2003), Gaidos et al. (2005), Hoehler et al. (2007), and Fishbaugh et al. (2007).

This review provides an overview of habitability and focuses on what we know about the habitability of Earth, the habitability of planets orbiting other stars, and the habitability of our galaxy. It synthesizes facts and current ideas about the microbiology of the earliest terrestrial life and the latest findings of planet hunters. It is organized as follows: Section 2 reviews the limits of terrestrial life and illustrates where life is found, and is not found, on the habitable planet that we know best—Earth. We discuss energy constraints on life and how the conditions for life’s emergence may be different and more specific than the broader conditions to which life can adapt. Section 3 presents the increasingly compelling evidence that planets in general, and rocky planets

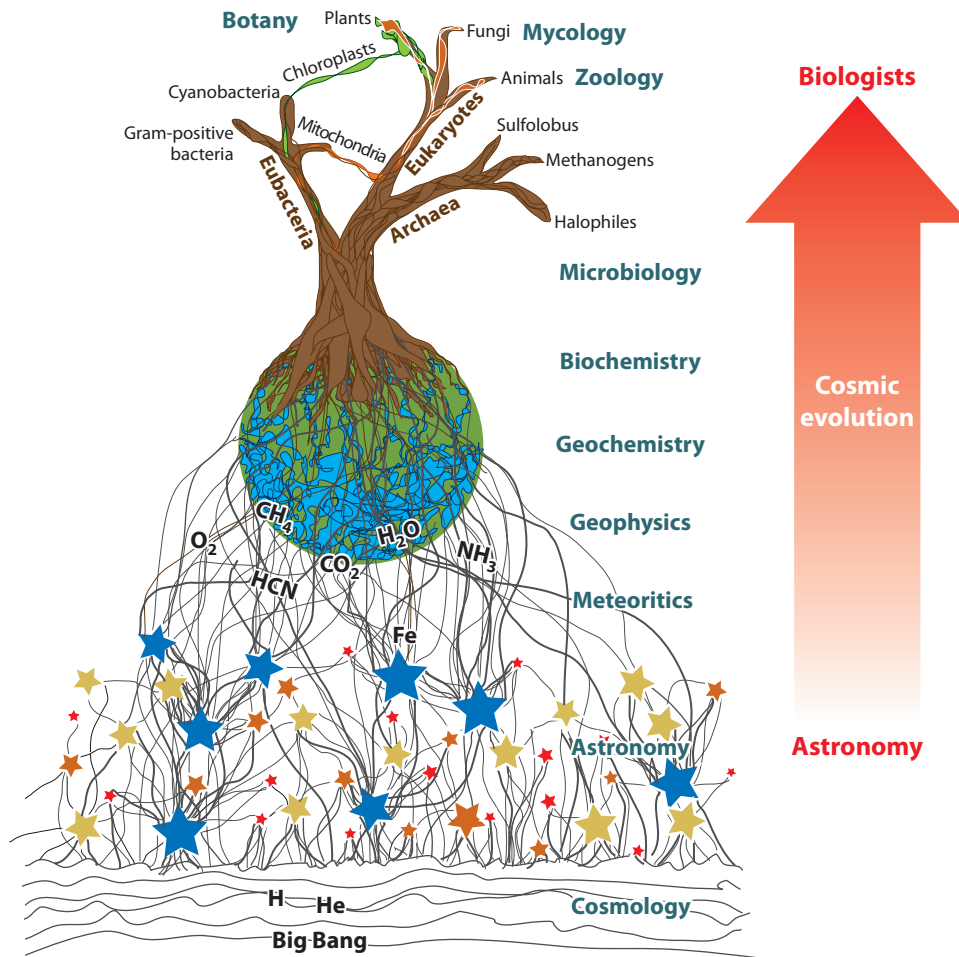


Figure 1

The emergence of biologists from astronomy. Starting from the big bang at the bottom, deterministic physical sciences set the context for the emergence of life. The resulting biologists (animals) at the top of the tree (e.g., Pace 1997, Hedges & Kumar 2009) have constructed the brown phylogenetic tree based on the molecular fossils inside the DNA of the inhabitants of the biosphere. The terrestrial tree of life took root approximately four billion years ago. We review the features of rocky planets that are implicated in the ability to give root to, and maintain, a tree of life.

in particular, are a common product of star formation. Section 4 discusses the habitability of the most Earth-like exoplanets and the traditional circumstellar habitable zone (HZ). Section 5 reviews the supply of water to terrestrial planets. Finally, Section 6 reviews work on the galactic HZ and discusses a variety of habitability issues. A list of Summary Points precedes the references.

2. THE HABITABLE ZONES ON EARTH

Because habitability is about the complex relationship between life and environment, we start close to home with a discussion of the relationship between terrestrial life and terrestrial environments. The close fit between our requirements and what Earth can provide is not coincidental. Earth

HZ: habitable zone

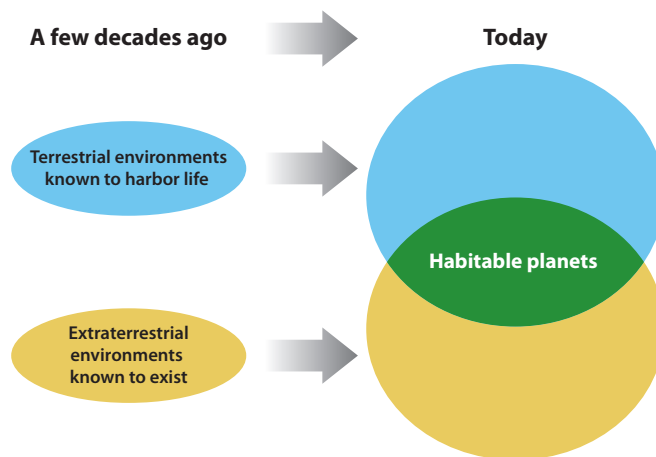


Figure 2

Emergence of habitable planets. Habitable planets are emerging from the increasing overlap of two sets of environments: the increasingly large set of terrestrial environments known to harbor life and the increasingly large set of extraterrestrial environments on the newly detected rocky exoplanets. The overlap of these research fields bolsters expectations that the universe may be filled with habitable planets.

and the life on it have coevolved. However, life is not infinitely adaptive. Some parts of Earth are habitable and some, even after approximately four billion years of evolution, are not. Life as we know it has limits, and we can explore these limits most easily on Earth.

In a specific region, when some requirement for life is outside the optimal range for life, the total biomass in that region is low (**Figure 3** presents these regions). We generically call such regions deserts. Low rainfall makes water deserts. Low temperatures make low-temperature deserts at Earth's poles. Far from land, in mid-oceanic gyres [where windblown dust and aerosols are at a minimum (Duce & Tindale 1991)], low nitrate levels produce nitrate deserts.

Chlorophyll maps of the ocean (McClain et al. 2006) show regions where, despite ample water, photons, and nitrates, there are low concentrations of chlorophyll. Iron fertilization experiments in these enigmatic high-nitrate-low-chlorophyll regions found that the biomass was iron limited, rather than phosphate limited or limited by some other nutrient (Falkowski et al. 1998, Smetacek & Naqvi 2008). Such iron deserts have been identified in the Southern Ocean, the northwest Pacific, and the eastern equatorial Pacific. Low-phosphate regions overlap significantly with nitrate deserts (Garcia et al. 2006). Because the elements H, O, C, N, P, and S make up ~98% (by mass) of life (Lineweaver & Chopra 2012), one might expect analogous C and S deserts.

The subtle variations of biomass over the horizontal surface (**Figure 3**) are dwarfed by the nonsubtle variations of biomass in the vertical direction. The terrestrial biosphere is a thin bioshell whose thickness (~10 km) is ~1/600 of Earth's ~6,400 km radius. **Figure 4** is a vertical profile of terrestrial biomass. Low temperatures and low densities prevent life from living permanently in air or on the highest mountains (low-temperature deserts). High temperatures prevent life from existing more than ~5 kilometers underground, because the average continental geothermal gradient of 20–30° per km reaches the upper temperature limit of life [122°C, Takai et al. (2008)] at approximately that depth. (Shield gradients and those above subduction zones can be as low as ~10°C per km.) Thus, the interior of Earth is a spherical high-temperature desert. The bioshell is thin because life is kept squeezed into a narrow HZ between a high-temperature desert below and a low-temperature desert above (**Figures 4** and **5**).

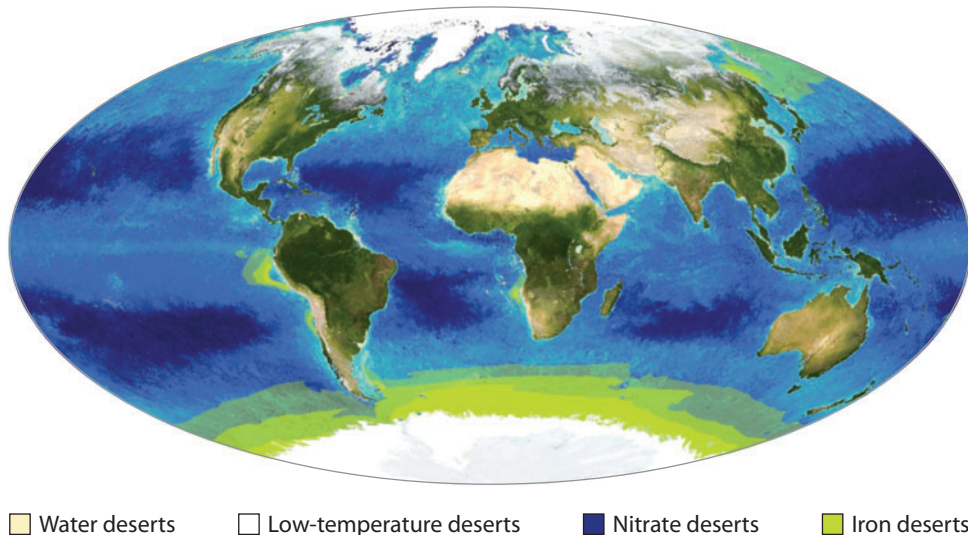


Figure 3

Four deserts on Earth's surface. Life is not evenly distributed over the surface of Earth. There are water deserts (*sandy brown*), low-temperature deserts (*white*), nitrate deserts (*dark blue*), and iron deserts (*light green*), where the abundance of life is significantly lower than in surrounding regions. This map was constructed with data from Stockli et al. (2005) and McClain et al. (2006).

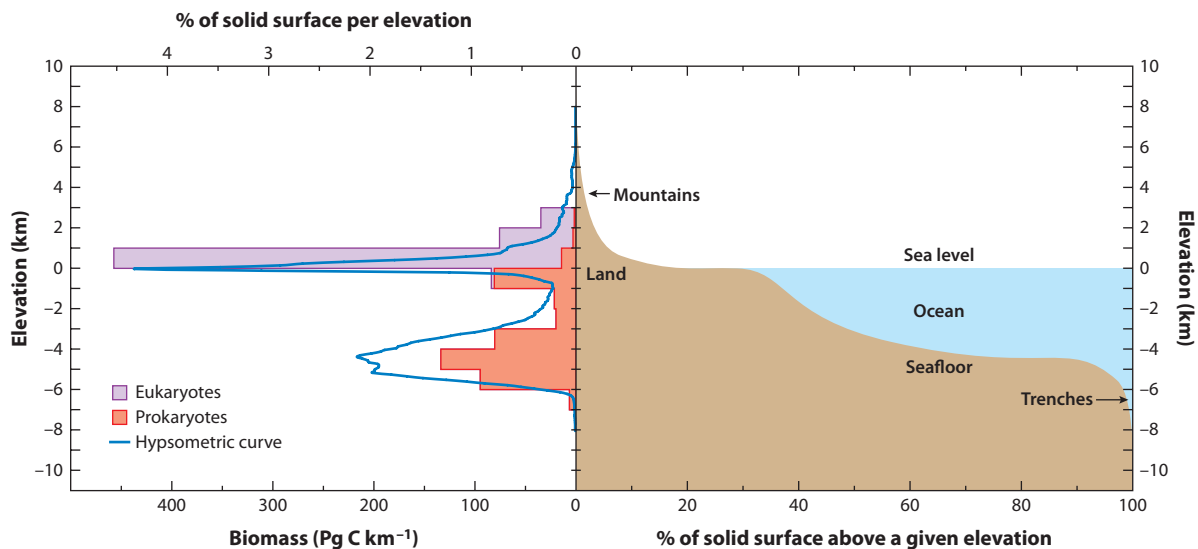


Figure 4

Vertical profile of biomass in the thin terrestrial bioshell (± 10 km). The hypsographic curve on the right shows the fraction of Earth's solid surface above a given elevation. For example, 30% of the solid surface is above sea level, whereas the remaining 70% is below sea level. The hypsometric curve on the left (*blue line*) (Perotti & Rinaldi 2011) shows the fraction of Earth's solid surface at any given elevation. The histogram on the left shows our estimate of the vertical profile of terrestrial biomass (total carbon in terrestrial life forms) derived from combining data from Whitman et al. (1998) and Houghton (2003).

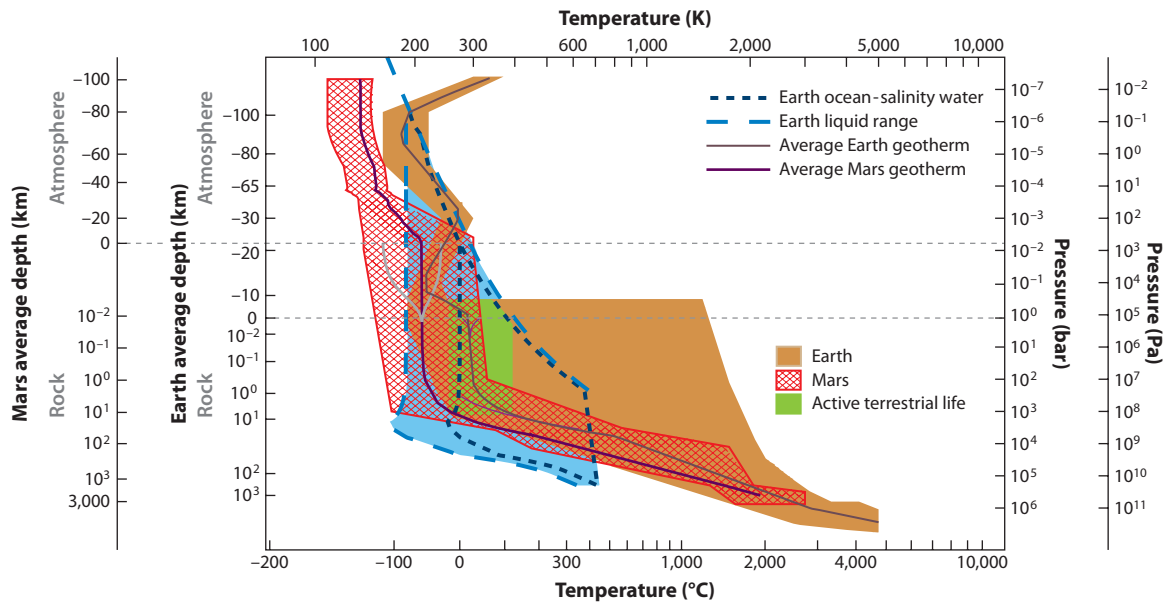


Figure 5

Uninhabited water on Earth and the potential biosphere of Mars. This pressure-temperature phase diagram is a superposition of the region where H₂O is liquid (*blue*), all terrestrial environments (*brown*), inhabited terrestrial environments (*green*), and all Martian environments (*hatched red*). Notice the large regions of uninhabited terrestrial liquid water that is either too cold ($-80^{\circ}\text{C} < T < -20^{\circ}\text{C}$) or too hot ($122^{\circ}\text{C} < T < 400^{\circ}\text{C}$) for life. The ± 10 km vertical extent of the green area corresponds to the elevation range of the biomass profile in **Figure 4**. The shape of the green area shows that the presence of liquid water and the -20°C to $+122^{\circ}\text{C}$ temperature range are the dominant variables determining habitability. These inhabited and uninhabited terrestrial environments, set by the need for liquid water and a specific range of temperature, are our best guides to exoplanet habitability. Figure from Jones et al. (2011). See also Mottl et al. (2007), Jones & Lineweaver (2010, 2012), and Cockell (2011).

Terrestrial biomass is approximately evenly divided between eukaryotes (55%; **Figure 4**, light purple) and prokaryotes (45%; **Figure 4**, orange). Biomass is also roughly evenly divided between above sea level (56%) and below sea level (44%). Of Earth’s eukaryotic biomass, 99.5% is on land (Sundquist & Visser 2003). About 96% of prokaryotic biomass is below sea level, mostly in seafloor sediments (Whitman et al. 1998). The oxygenic photosynthesis that powers most of the eukaryotic life on land was a relatively late adaptation (Kiang et al. 2007, Sleep & Bird 2007), as was the ability to colonize the land (Battistuzzi et al. 2004). Five hundred million years ago, there was land but little eukaryotic life on it. Thus, for approximately the first three billion years, the profile of terrestrial biomass may have resembled the current prokaryotic profile (**Figure 4**, orange).

2.1. The Abiogenesis Habitable Zone and Habitable but Uninhabited Planets

As we learn more about the origin of life, we can start to define an abiogenesis habitable zone (AHZ) where the requirements for life’s emergence are met. The habitability requirements for the origin of life may be substantially different from, and more specific than, the requirements to maintain life on a planet—think of the difference between a spark plug to start an engine and a carburetor to supply it with fuel. If you shine light onto a vat of HOCNPS, or bubble molecular hydrogen through a flask of amino acids, life does not spontaneously emerge. For a planet to

AHZ: abiogenesis habitable zone

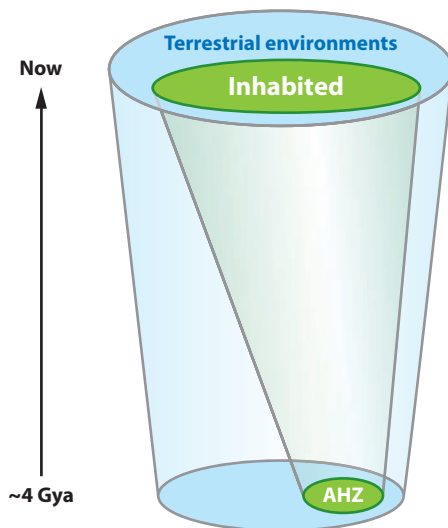


Figure 6

Abiogenesis habitable zone (AHZ). The conditions needed for the origin of life (before life could adapt) are narrower than the broader conditions to which life can adapt.

manage the transition from the nonliving to the living—to qualify as an AHZ—juxtapositions and flows of specific combinations of molecules are needed to produce auto-catalytic reactions and proto-metabolisms that can tap into either the flow of redox pairs or photons (de Duve 1995, Lane et al. 2010).

Once life begins, organisms do not just passively adapt to preexisting environments. They actively change and construct the world they live in (Odling-Smee et al. 2003). The evolutionary history of life on Earth can be written in terms of how organisms have modified their environments. From the oxygenation of the atmosphere to the creation of beaver dams, life modifies its environment. But life also modifies itself and adapts to fit the environment—evolving, for example, spores to survive dry conditions, antifreeze for survival at low temperatures, and salt pumps to survive at high salinity. Whether life adapts to fit an environment or modifies an environment to be able to survive, the result is the same: The initial specific AHZ is widened (**Figure 6**). Through its management of the greenhouse and its partitioning of reductants and oxidants, the activity of life increases the range of inhabited environments (Nisbet et al. 2007, Hazen et al. 2008).

Environments change life-forms, and life-forms change environments. This feedback between life and environment may be so strong that, for a planet to be habitable, it might have to be inhabited. Thus, planetary habitability becomes a dynamic concept with different stages. Habitability begins as a relatively narrow AHZ, completely dependent on the chemistry and other physical characteristics of the planet. Once life emerges and passes the “Darwinian threshold” (Woese 2002) habitability shifts to a dependence on both the characteristics of the planet and the adaptability of its life-forms. Finally, habitability becomes predominantly dependent on the ability of the inhabitants to regulate their environment. The thermoregulation of Earth over the past four billion years, despite a 30% increase in solar luminosity, is a possible example of such Gaian regulation (Lovelock 1965, 1979; Lovelock & Margulis 1974; Schneider & Boston 1991; Schneider et al. 2004). It may be that natural negative-feedback processes, such as the carbon-silicate cycle (Walker et al. 1981), without Gaian regulation, are not conducive to life any more

than a nonevolving body would be (Schwartzman & Volk 1989). Thus, eventually, habitability becomes a property of life, as much as, or perhaps more than, it is a property of a planet.

The persistence of life requires liquid water, an appropriate temperature range, nutrients, and an energy source. Self-assembly is an example of an additional requirement for abiogenesis that would be relaxed once life got started (making the AHZ narrower than the HZ). For example, origin-of-life chemists are trying to understand how RNA could self-assemble in the presence of water (e.g., Szostak et al. 2001). To self-assemble, dehydration reactions are needed. Cyclic evaporative dehydration could happen near continental hot springs or in warm tidal pools as the kilometer-high tides came in and out every few hours (e.g., Lathe 2004). On ocean planets (Section 4), there could be no dehydration reactions because there would be no evaporation from solid surfaces. Thus RNA would not self-assemble and life might not be able to get started on ocean planets. If the self-assembly of RNA required cyclic evaporation, and this assembly was critical to the emergence of life, ocean planets would be lifeless. They would be habitable but uninhabited planets.

2.2. Habitable Energies

On Earth today, ~60% of the biomass is phototrophic and ~40% is chemotrophic (**Figure 4**). Thus, the dominant energy source for life is the solar photon flux. However, when life emerged approximately four billion years ago there may have been much less dry land (Taylor & McLennan 2009) and no eukaryotes. The terrestrial biomass distribution thus may have more closely resembled the current prokaryotic distribution in which the majority of the biomass is not necessarily in the photic zone but at hydrothermal vents at various depths, which were more common approximately four billion years ago (Southam et al. 2007, Sleep 2010). Studying the earliest and most fundamental metabolisms of terrestrial life is our best hope for understanding how likely such energy-transducing metabolisms (and thus life) are to emerge elsewhere. Candidates for the earliest metabolisms include two broad categories of primary producers: anoxygenic phototrophs and chemolithotrophs. Chemolithotrophs live off inorganic redox pairs supplied by chemical disequilibria at hydrothermal vents (Nisbet & Sleep 2001, Kelly & Wood 2006).

Hyperthermophiles are the deepest- and shortest-branched organisms on the phylogenetic tree of life (e.g., Pace 1997, Lineweaver & Schwartzman 2003). Hyperthermophiles gain energy by inorganic redox reactions employing compounds such as H_2 , CO_2 , S^0 , Fe^{2+} , and Fe^{3+} (Stetter 2006). Redox reactions in hydrothermal vents and hot springs probably played a dominant role in early metabolism. The earliest life forms were probably chemoheterotrophs that evolved in high-temperature, low-pH, and high-salinity environments resembling hydrothermal vents (Martin et al. 2008) or hot springs. The transition of life from a redox-only energy source to a redox and photon energy source is suggested by comparing the energies of different metabolic reactions in **Figure 7** (Sleep & Bird 2008). The earliest redox reactions—pyrite formation, sulfur reduction, methanogenesis, and acetogenesis (Wächtershäuser 1998, Martin & Russell 2007, Blank 2009, Ljungdahl, 1986)—provide less energy than photosynthesis. However, these early reactions do provide enough energy to charge transmembrane potentials in a chemiosmotic coupling and convert low-energy molecules such as ADP, NAD^+ , and NADP^+ to higher-energy molecules such as ATP, NADH, and NADPH (Mitchell 1961). These molecules are universal energy currencies and likely to have been adopted by the earliest organisms.

Energy sources based on a redox gradient may have been ubiquitous on the early Earth, particularly because hydrothermal activity may have been more widespread than it is today (Sleep 2007). The similar energies of the earliest metabolic pathways and the availability of the reactants in environments such as hydrothermal vents bolster the case that life began by using energy

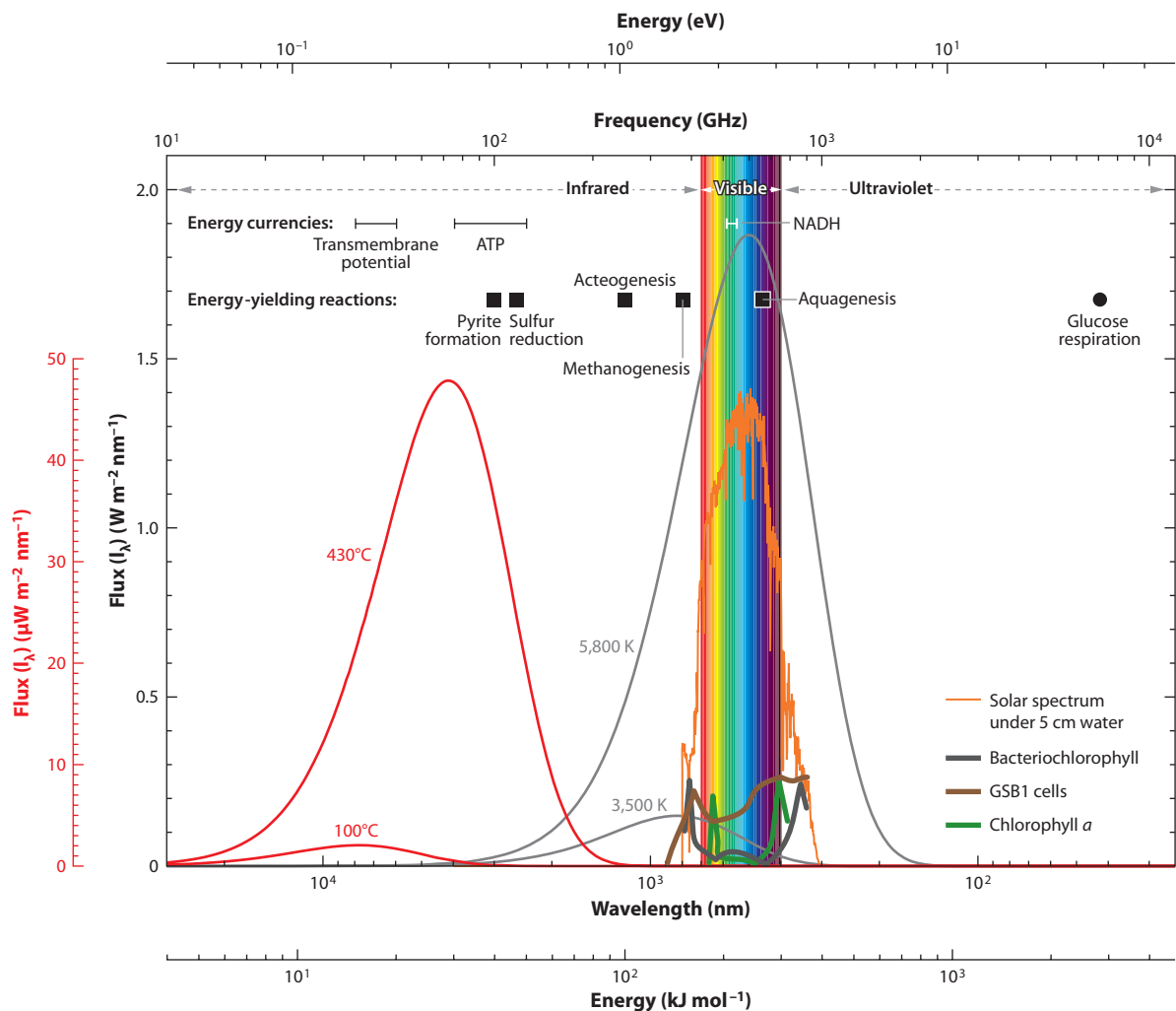


Figure 7

Comparison of the photon and redox energy sources of early life with the dominant energy currencies of life. The two sources of energy available to early life were solar photons [represented by the solar spectrum as seen from beneath 5 cm of water (*orange*)] and inorganic redox pairs available at hydrothermal vents (*black squares*). The energy obtained from both these sources was converted into the currencies life uses to store or circulate energy (transmembrane potential, ATP, and NADH). Uncertainties indicate the common range of energies associated with these currencies under physiological conditions. Five redox reactions are shown that are candidates for the sources of energy for the first chemolithotrophs [see **Supplemental Table 1** (follow the **Supplemental Materials link** from the Annual Reviews home page at <http://www.annualreviews.org>) and Blank 2009]. Blackbody curves are shown for Sun-like G stars and for the most common star in the universe, low-mass M stars such as Gl581 (Section 4). On the left, using a different y-axis, the blackbody spectra of a 430°C hydrothermal vent (or hot spring) fluid and a 100°C fluid represent the native environment of hyperthermophiles. Absorption spectra are shown for two candidates for the earliest anoxygenic photosynthesis: bacteriochlorophyll (Frigaard et al. 1996, Madigan 2006) and the spectra of intact cells of an obligately photosynthetic bacterial anaerobe (green sulfur bacterium, GSB1) isolated from a deep-sea hydrothermal vent environment (Beatty et al. 2005). The absorption spectrum of eukaryotic chlorophyll *a* (Cinque et al. 2000) and the maximum energy available from oxic glucose respiration are shown for comparison.

sources based on redox gradients and over time evolved to perform higher-energy reactions such as oxygenic photosynthesis and oxic respiration. Canfield et al. (2006) claim that the most-active, earliest ecosystems were probably driven by the cycling of H_2 and Fe^{2+} through primary production conducted by anoxygenic phototrophs.

The absorption spectra of bacteriochlorophylls, which are considered to be more ancient than chlorophylls, and the photosynthetic pigments in green sulfur bacterium (GSB1) peak outside the visible region of the spectrum in the near-IR, where photons can penetrate to some degree through murky water. Although the blackbody emission of hot hydrothermal fluids has far fewer photons in the near-IR than in the mid-IR, they are in sufficient numbers and of high enough energy that GSB1 can photosynthesize and live in a dark environment. Photons of even lower energies ($\sim 1,000$ nm) are used by purple anoxygenic bacteria (Kiang et al. 2007). Note that all redox reactions in **Figure 7** are above the peak energy of the $100^\circ C$ ambient temperature of a hyperthermophile environment. Any redox reaction that is used by life must satisfy the constraint that the activation energies must be higher than what is available as background energy in the environment (Shock & Holland 2007). An upper limit for the temperature at which metabolic activity can take place is set by the temperature at which the molecular dissociation of proteins and membranes takes place.

If the conditions that permitted terrestrial abiogenesis based on energy-yielding metabolic reactions, such as those plotted in **Figure 7**, are not available on other planets, then the search for life elsewhere in the universe may yield the discovery of numerous habitable planets that have remained uninhabited. This is one possible outcome of Mars exploration. The search for life elsewhere in our Solar System has focused on Mars because it is relatively close and because Mars probably contains a lot of subsurface water (Jones et al. 2011). In **Figure 5**, the substantial overlap of the green and red areas represents extensive water at habitable temperatures on Mars. This, combined with much other evidence for water on Mars, suggests that we will find liquid water in the Martian subsurface at temperatures compatible with terrestrial life. If appropriate redox pairs exist, psychrophilic terrestrial life should be able to live between tens of centimeters and ten kilometers beneath the Martian surface (Jones et al. 2011). However, Mars exploration has not yet found any life. In 1976, two Viking spacecraft landed on Mars with life-detection instruments, which returned ambiguous results that have been interpreted as offering no evidence for life (Klein 1979, Klein 1999, Navarro-Gonzalez et al. 2010; see, however, Levin & Straat 1981). Although the Viking mission only attempted to search for active life on the surface (and not in the region below 10 cm where liquid water might be present), there are other potential biosignatures of subsurface life that may be detectable on the surface. One such potential biosignature was recently detected as transitory faint traces of methane (Formisano et al. 2004, Krasnopolsky et al. 2004, Mumma et al. 2009, Lefevre & Forget 2009). The debate about whether this methane could be biotic or abiotic seems to be leaning toward an abiotic explanation: Hot olivine exposed to water and CO_2 undergoes serpentinization and produces methane (Kasting 2010, Webster & Mahaffy 2011).

NASA's Mars Science Laboratory, launched on November 26, 2011, has 10 instruments to help determine if life did, or does, exist on Mars. The ongoing exploration of the Martian subsurface is one of the most promising fields where progress in our understanding of habitability can be made. Other promising destinations include Jupiter's moons Europa, Ganymede, and Callisto and Saturn's moons Titan and Enceladus. These large moons may have provided wet incubators where life could have emerged (and might still exist). Evidence from the Galileo mission (Spohn & Schubert 2003) suggests that Europa, Ganymede, and Callisto contain a combined volume of liquid water 30–35 times that of Earth's oceans. For reviews of the habitability of our Solar System, see Shapiro & Schultze-Makuch (2009) and McKay (2011). There are also specific papers on the

habitability of Europa (Chyba & Phillips 2001, Hand et al. 2007), Enceladus (McKay et al. 2008), Titan (Benner et al. 2004, McKay & Smith 2005, Raulin 2008), and Venus (Grinspoon 1997, Svedhem et al. 2007).

3. WHAT FRACTION OF STARS HAVE TERRESTRIAL PLANETS

Outside our own Solar System, terrestrial planets or large rocky moons in the circumstellar HZs around other stars are the most likely habitable places. Since 1995, when the first exoplanet was detected around a Sun-like star (Mayor & Queloz 1995), the fraction of stars with planets has been periodically reported. These are plotted in **Figure 8** (see **Supplemental Table 2**). The values depend on what fraction of the mass-period parameter space of **Figure 9** has been sampled or extrapolated over. Because no technique can sample the entire space, coverage is always incomplete and any reported value such as “10% of stars have planets” is a lower limit—the actual value is larger. Because of this incompleteness, the data are, and always have been, consistent with 100% of stars having planets. This is represented in **Figure 8** by the blue arrows extending from the reported lower limits to 100%. See Cassan et al. (2012) for supporting evidence from microlensing observations.

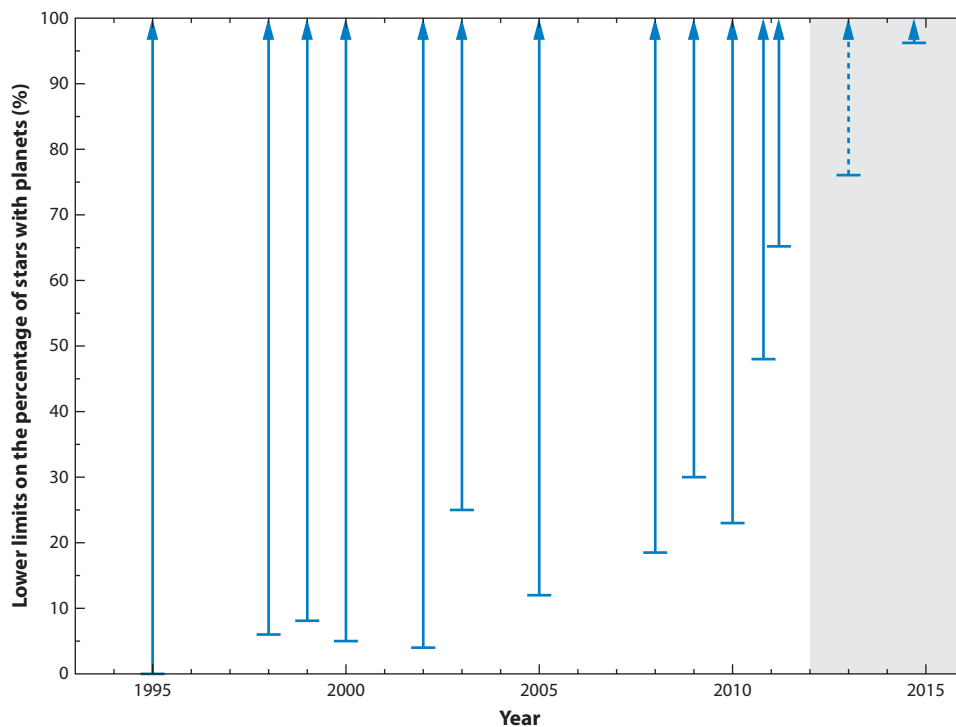


Figure 8

Lower limits to the fraction of stars with planets as a function of time. Because published values are based on limited ranges in mass or period (i.e., small areas in the parameter space of **Figure 9**), they are not estimates of the real fraction of stars with planets but are lower limits. These lower limits have been rising as the durations of surveys increase and detection sensitivity improves. The predicted lower limits at 2013 and 2015, suggesting that 100% of stars have planets, are based on the trends seen in the past three years and the plausible range over which these trends can be extrapolated.

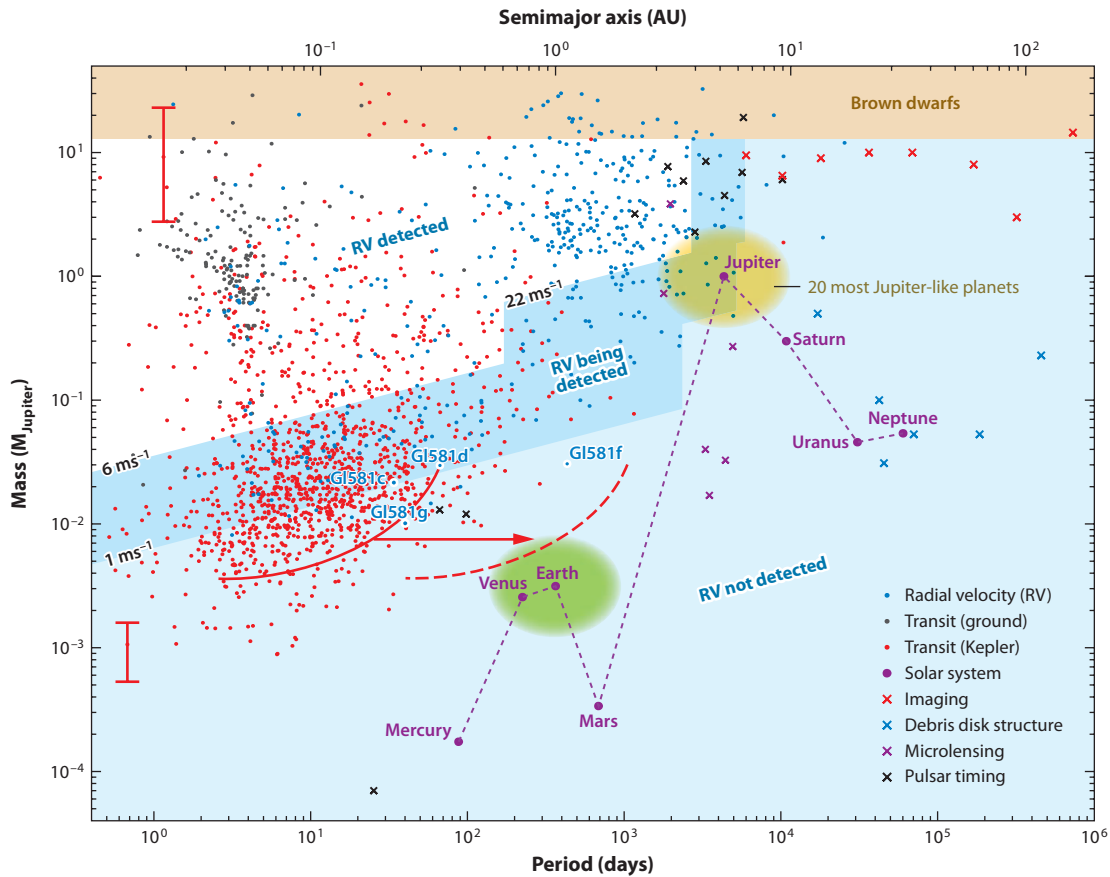


Figure 9

Our Solar System compared to $\sim 1,870$ exoplanets detected using various techniques. The region around our planetary system and to the lower right has not been well explored. The red cloud of points in the lower left represents the $\sim 1,200$ Kepler planet candidates from Borucki et al. (2011). The other ~ 670 exoplanets were detected by other instruments. After the nominal approximately four-year Kepler mission, the red curve, approximating the limit of the Kepler cloud, will have moved to the dashed red curve. At least a few Earth-mass planets in Earth-like periods around Sun-like stars are expected within the green oval surrounding Earth. If the Sun were removed to some typical distance (~ 30 light years) and were on the target list of our planet-hunters, it would probably still be listed as having no planets. The yellow oval contains the 20 most Jupiter-like planets, which are plotted separately in **Figure 11**.

Figure 8 refers to reported values from surveys of Sun-like stars of spectral type FGK. All are radial velocity (RV) surveys with the exception of Howard et al. (2011), which is based on Kepler transits. Planets orbiting substantially smaller M stars probably have smaller masses (Johnson et al. 2010) and smaller semimajor axes. [See Gould et al. (2010) and Cassan et al. (2012) for microlensing results with predominantly M star hosts. For disk imaging results from A stars, see Bowler et al. (2010).]

Planet detections have technique-dependent limits (Cumming 2010). **Figure 9** shows how the eight planets of our Solar System (dashed purple line) compare to the $\sim 1,870$ exoplanets compiled from six detection techniques listed in the lower right. The estimated masses of the planets are plotted as a function of their orbital periods.

The most important take-home message is: Yes, there are planets around other stars. The second message is that most of the patterns in the data tell us more about instrument sensitivity

and survey durations than about the underlying real distribution of planets. Thus, the relatively empty region in the lower right (low mass, long period) appears empty because it has not been well explored. And the blob of dark gray points in the upper left, from ground-based transit searches, is concentrated at high mass and short period because that is where this technique has the highest sensitivity, not because there is a natural concentration of planets there.

The left edge of the red cloud of Kepler points is a real edge due to the underlying distribution of planets and tells us that planets with orbital periods less than a couple of days are rare. The lower right edge of the red cloud (indicated by the red curve) is a result of instrument sensitivity and the duration of observations (only 90 days). At the end of the nominal Kepler mission in 2014, Kepler's region of sensitivity will have extended to the dashed red curve, much closer to the region of Venus- and Earth-like planets.

The background of **Figure 9** is color-coded to show the sensitivity of the RV technique to planets orbiting solar-mass stars. The ability of the RV technique to detect planets is 100% in the white region in the upper left, decreases across the "RV being detected" region, and sinks to near 0% in the "RV not detected" region. Thus, in the white "RV detected" region, any observed pattern of RV planets (blue dots) is a real pattern and is not due to instrument sensitivity or survey duration. The most obvious pattern is that in the high-mass region ($1\text{--}10 M_{\text{Jupiter}}$), as periods increase (approaching Jupiter's 12-year period), the number of planets increases dramatically. Thus, Jupiter-mass planets become more numerous as we look in more Jupiter-like orbits.

Because the RV technique is most sensitive in the upper left of **Figure 9**, **Figure 8** is predominantly telling us about the fraction of stars with massive Jupiter-, Saturn-, Uranus-, and Neptune-sized planets that have been scattered or have migrated from their region of formation (farther from the host star) into a region closer to their host star where they could be detected with the RV technique. However, we are more interested in exoplanets that are more similar to Earth in both mass and period. In **Figure 9**, planets indicated by the red Kepler dots are the most similar to Earth in mass. If the fraction of stars with large planets is $\sim 100\%$, what about the fraction of stars with low-mass rocky planets like Earth? Based on extrapolation of RV data, Howard et al. (2010) report "23% of stars harbor a close-in Earth-mass planet (ranging from 0.5 to 2.0 Earth masses)." Wittenmyer et al. (2011) report 17% for planets with mass $< \sim 13 M_{\text{Earth}}$.

Catalogs of exoplanet detections can be found in Schneider (2011) and Wright et al. (2011). The Kepler planet candidates are from Borucki et al. (2011) (http://archive.stsci.edu/kepler/planet_candidates.html). The radii of Kepler candidates have been converted to masses using the average radius-dependent density of the dozen or so least massive exoplanets detected by the transit and radial velocity techniques. Representative uncertainties on this conversion are given in **Figure 9** by the size of the vertical error bars on two red points on the far left.

The radii of planets can be extracted from small dips in Kepler's precision photometry of $\sim 150,000$ stars. **Figure 10** is a recent result (Howard et al. 2011). As the fraction of stars with planets approaches its maximum value of 100% (**Figure 8**), this fraction becomes uninformative about the average number of planets per star, which is the y -axis in **Figure 10**. The two bins in the region to the left of the dashed gray line ($1 < R < 2 R_{\text{Earth}}$) are incomplete because planets that small are harder to detect and need to transit more times for their signal to emerge out of the noise. These incomplete bins were not used to produce the red dashed fit.

On the left side of **Figure 10** notice that the dashed red line crosses $R = R_{\text{Earth}}$ at 0.4 planets per star. Because there are many more single-planet stars than multiple-planet systems in the Kepler database, this 0.4 means that $\sim 35\%$ of stars are expected to have planets with radii $0.8 < R < 1.2 R_{\text{Earth}}$ and with orbital periods $P < 50$ days. That is a large fraction for such a small range of radii and periods. Adding up the values of the red points for the entire range of radii yields the average number of planets (with radii $1 < R < 23 R_{\text{Earth}}$ and $P < 50$ days) per star: 0.6. When

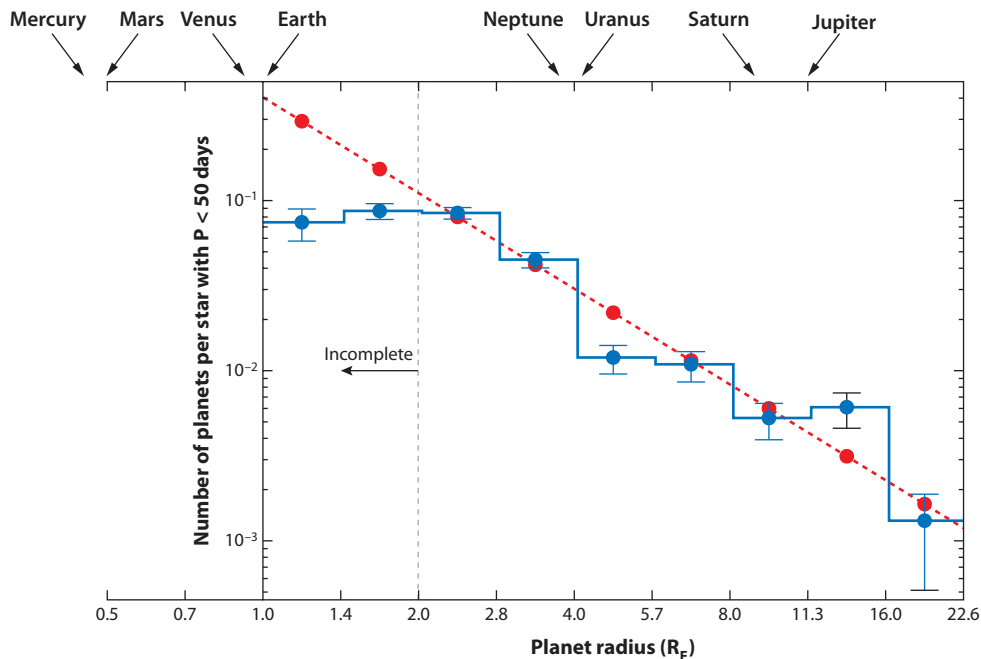


Figure 10

Recent Kepler results. The amplitude of the red line tells us that there are many planets close to stars ($P < 50$ days; for comparison, $P_{\text{Mercury}} = 88$ days). The slope of the red line tells us that there are approximately ten times as many Earth/Venus-sized planets as there are Uranus/Neptune-sized planets and approximately ten times as many Uranus/Neptune-sized planets as there are Jupiter-sized planets. Figure modified from the top panel of figure 6 in Howard et al. (2011).

converted to the fraction of stars with a planet, this becomes the 48% plotted in **Figure 8**. Adding up only the values for rocky planets (the three bins with radii $1 < R < 2.8$) yields more than 0.5 rocky planets per star. This high frequency within such a small region close to the star (< 0.25 AU) indicates that rocky planets are extremely common.

After Kepler detects more planets with $R \sim R_{\text{Earth}}$, if the trend of the red line accurately describes the next smaller bin, the vast majority (perhaps 90%) of planetary systems may be found to have an Earth-size planet with an orbital period $P < 200$ days. With Venus's 224-day orbital period and radius $R = 0.95 R_{\text{Earth}}$, and Mercury's $P = 88$ days and $R = 0.38 R_{\text{Earth}}$ (too small to detect), such a high observed frequency of close-in exoplanets would make our planetary system unusual for having relatively fewer Earth-sized planets, or having them unusually distant from the host star, or both.

The data collected in **Figures 8** and **9** illustrate that as stars are monitored for longer periods of time, and as we extend our detection sensitivity to Jupiter-like periods, we detect more planets and require less extrapolation to reach the conclusion that $\sim 100\%$ of stars have massive planets. In addition, as we extend our observations to smaller planets (left side of **Figure 10**, $0.5 < R < 2 R_{\text{Earth}}$) the numbers increase and again suggest that $\sim 100\%$ of stars have at least one Earth-sized planet.

Other evidence that the fraction of stars with planets is $\sim 100\%$ is that protoplanetary accretion disks are ubiquitous in young star clusters. The observed fraction of young stars with protoplanetary disks approaches 100% for star-forming regions less than ~ 0.5 million years old

(Mamajek 2009, Fedele et al. 2010). Also, there are no large planets without a retinue of rocky/icy moons. Many of the moons of Jupiter, Saturn, Uranus, and Neptune are part of miniature planetary systems formed from their planet's miniature accretion disk. "Planets around every star. Moons around every large planet" is probably the most reasonable position from which to ponder habitability. Soon we will have detected so many Earth-like planets that our efforts will have to be focused on determining which ones are the most habitable (Horner & Jones 2010).

4. HABITABLE TEMPERATURES: CIRCUMSTELLAR HABITABLE ZONES

If they be inhabited, what a scope for folly; if they not be inhabited, what a waste of space.

—Thomas Carlyle

Exoplanet research is moving beyond counting planets and plotting their masses and orbital periods. We are beginning to study their temperatures, densities, compositions, tectonic regimes, atmospheric chemistries, and albedos—all factors that can influence habitability. **Figure 11** shows that there are several dozen known planets in circumstellar HZs. The least massive are three to five times the mass of Earth. Because the mass of moons seems to scale with the mass of the host planet, the most massive planets in the HZ could harbor habitable moons.

For each planet in our Solar System (**Figure 11**), notice the difference between the computed effective temperature (T_{eff} , small light purple dots) and the actual surface temperatures T_{Surf} (larger purple dots). We have plotted error bars around T_{Surf} , indicating the range of surface temperatures on Mercury, Venus, Earth, and Mars. Because $\Delta T = T_{\text{Surf}} - T_{\text{eff}} > 0$ for all eight planets of our Solar System, all experience some kind of warming.

For Earth we have $\Delta T_{\text{Earth}} = 33^\circ$, but the thick 90 bar Venutian CO_2 atmosphere produces $\Delta T_{\text{Venus}} = 440^\circ$. The variation of ΔT values within our Solar System is large: $15^\circ < \Delta T < 440^\circ$, due to differences in albedos and greenhouse gas (CO_2 , H_2O) column densities. This range gives us an idea of the expected range of exoplanet ΔT s that will shift exoplanets to the left in **Figure 11**. Thicker atmospheres provide more greenhouse warming and larger ΔT s (Marcus et al. 2010). Because we expect $\Delta T_{\text{Super-Earths}} > \Delta T_{\text{Earth}}$, the shift of the HZ to be centered on the T_{eff} of Earth represents a minimal correction. Thus super-Earths, such as Gl581d just to the right of the HZ, should be considered the best candidates for habitable planets.

A reasonable assumption is that super-Earths ($3 < M < 10 M_{\text{Earth}}$) are probably endowed with a mass of greenhouse gases, M_g , proportional to the mass of the planet, M : $M_g \sim M$. Thus, the column density Σ responsible for greenhouse warming would be $\Sigma \sim M_g/\text{surface area} \sim M/R^2 \sim R \sim M^{1/3}$. With this plausible scaling we would expect the ΔT s of super-Earths to be, very roughly, twice as large as the ΔT s of our Solar System's planets. Thus, it may be that the half-dozen planets in the middle and left side of the most habitable exoplanets region of the HZ of **Figure 11** are greenhouse heated too far to the left to support life.

Gliese 581 is an M star approximately 20 light years away, with a mass $M = 0.31 M_{\text{Sun}}$ and $\sim 1\%$ of the Sun's luminosity. Gliese 581's planetary system contains several rocky planets whose habitabilities are being debated (Udry et al. 2007, Selsis et al. 2007, von Bloh et al. 2008, Mayor et al. 2009, Wordsworth et al. 2011, Kaltenegger et al. 2011a). The system contains four confirmed planets (Gl581b, -c, -d, -e) and possibly two more unconfirmed planets (Gl581f, -g) (Vogt et al. 2010). With poor signal to noise at the edge of RV sensitivity, the fitted eccentricities can vary between 0 and as much as 0.4. Of the four confirmed planets, Gl581d looks like the best current candidate for being a rocky habitable planet (see also Kaltenegger et al. 2012). Its mass is $M = 10_{-3}^{+4} M_{\text{Earth}}$. It receives 35% less stellar energy than Mars, and its orbital eccentricity is ~ 0 . Its

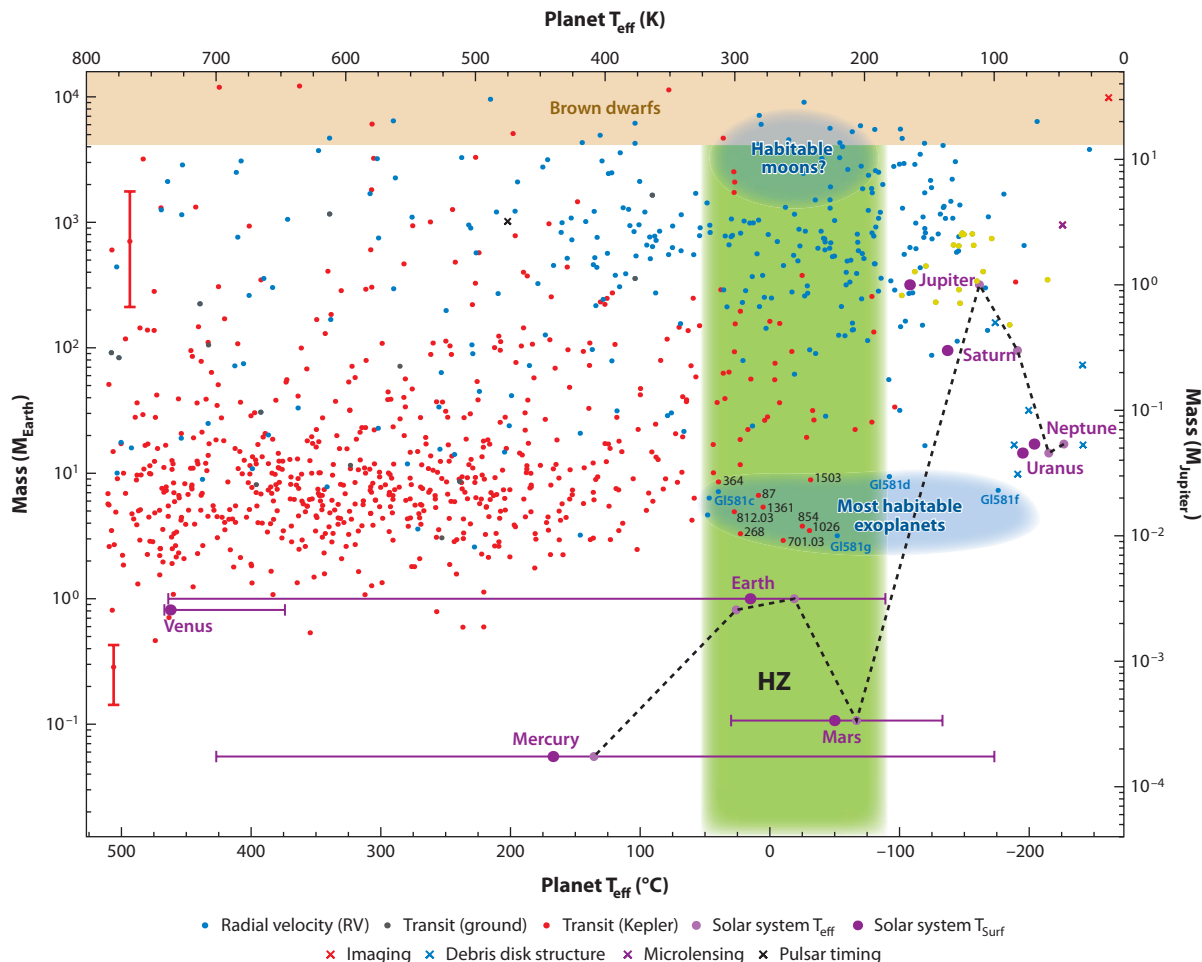


Figure 11

Planet temperatures and the circumstellar habitable zone (HZ). This figure is essentially the same as **Figure 9** except we have used our knowledge of the luminosity of the host stars to convert orbital periods into effective temperatures (T_{eff}) at the planet’s distance from its host. To obtain T_{eff} values for exoplanets and the planets of our Solar System in the same way, we have followed the appendix of Borucki et al. (2011, v1 only, but using $\text{albedo} = 0.3$, $\epsilon = 1$, $\beta = 1$). Because we are trying to evaluate the habitability of exoplanets for which we have only T_{eff} values (not actual surface temperatures), we have shifted the habitable temperature range ($+122^{\circ}\text{C}$ to -20°C) by 80° (keeping the 144° width) to be centered on the T_{eff} of Earth. This allows for a more direct comparison of the HZ with exoplanet T_{eff} values and is the simplest way to make a first-order minimal correction for the poorly known extent of exoplanet greenhouse gases and albedos. Because the planets of our Solar System orbit the same star, the dashed lines connecting their (M, T_{eff}) coordinates here mirror the dashed lines in **Figure 9** connecting their (M, P) coordinates. This is not the case in general. For example, the most Jupiter-like planets (within the *yellow oval* in **Figure 9**) are indicated here with yellow dots.

period is ~ 66 days and it is tidally locked. It has a radius of $\sim 2 R_{\text{Earth}}$, and its surface gravity is approximately twice that of Earth’s. Using a global climate model designed for exoplanets, with CO_2 and H_2O as greenhouse gases, Wordsworth et al. (2011) find that the range of possible atmospheric pressure is 5–30 bars.

The importance of Gl581 is based on the proximity of its planets to its circumstellar HZ. Kasting (2010, ch. 10) gives an informed review of the history of the circumstellar HZ and discusses

the details of the most cited HZ paper, Kasting et al. (1993). For details of how the inner and outer limits of the circumstellar HZ are computed, see Forget & Pierrehumbert (1997) and Abe et al. (2011). The idea of a circumstellar HZ is based on the scenario of surface life kept warm and powered by stellar photons. In the context of the present Earth, this is a reasonable scenario because solar photons control the temperature of the ocean and the top few meters of the continental crust and power most of current life (**Figure 4**). But Earth's AHZ may not have been powered by the Sun. If life emerged from a dark hydrothermal vent, vent redox chemistry and the plate tectonic regime that drives it may have more to do with whether life can emerge on a planet than whether the planet is in the circumstellar HZ and has liquid water on its surface.

Moving beyond the circumstellar HZ, planets not bound to any star, drifting around between the stars, seem to be the abundant remnants of the gravitational free-for-all in the earliest stages of planet formation in dense star clusters. Using microlensing observations Sumi et al. (2011) report nearly twice as many unbound Jupiters as there are main sequence stars in the galaxy. If there are super-Earths among them with enough hydrogen in their atmospheres (Pierrehumbert & Gaidos 2011), and if life can emerge and persist without photons from a star, then there may be no outer limit to the circumstellar HZ. There may be life-sustaining planets in interstellar space (Stevenson 1999).

5. WATER AND TEMPERATURE

Because life as we know it is water-based carbon chemistry, the processes that control the supply of water and carbon to a planet control its habitability. Water is also essential to aid the continual tectonic reworking and erosion that supply key redox gradients and biochemical substrates to sustain habitability (**Supplemental Table 1**; Nisbet et al. 2007). Morbidelli et al. (2000) and Mottl et al. (2007) summarize our understanding of the origin of water on Earth. D/H ratios (Robert 2001) and much other evidence suggest that the sources of terrestrial water were hydrous bodies such as carbonaceous chondrites (5%–20% water) from the outer part of the main asteroid belt. An alternative wet accretion model has between one and three oceans of water accreting with the planetary embryos that formed the bulk Earth (Drake & Righter 2002, Drake 2005). A third possibility discussed by Mottl et al. (2007) is the acquisition of hydrogen and water directly from the solar nebula by adsorption onto accreting material and dissolution into a magma ocean.

Because variations in temperature and water content are the two most important variables in delimiting the habitability of Earth, they should be the basis of any classification scheme for the habitability of planets. The green circumstellar HZ in **Figure 11** is based on effective temperature computed from stellar type and semimajor axis. To obtain more accurate surface temperatures, we need to know more about planetary greenhouse gas content and albedos. The amount of water on a rocky planet can depend on the C/O ratio of the star (because C/O controls the amount of water in the protoplanetary disk), but like T_{surf} , water content depends on many variables. Numerical simulations that take into account the notionally most important parameters indicate that water content on a terrestrial planet can vary typically by factors of a few (Raymond et al. 2007) and probably much more (perhaps an order of magnitude) when more parameters are allowed to vary. Variations in water supply are caused by variations in the number of impacts with water-rich planetesimals. The number of impacts is a function of planetary position (proximity to the snowline) and planetary mass (to gravitationally focus the impactors). Impacts also depend on the mass, eccentricity, and orbital evolution of the Jupiter analog in the system (if there is one) (Levison & Agnor 2003, O'Brien et al. 2006).

Another complication is that Earth may have acquired far more water during its formation than exists in its ocean and mantle today (Abe et al. 2000). Variations in the ability of a planet

Table 1 Rocky planet classification according to water content

Name	% surface liquid water	Features
Ocean planet	~100%	Hydrothermal vents, little erosion (Kuchner 2003, Leger et al. 2004)
Earth-like planet	1%–99%	Continental and oceanic crust, surface erosion, fresh water
Desert planet	~0%	Wider habitable zones? (Abe et al. 2011)

to hold onto the supplied water depend on planetary mass, temperature (through thermally induced hydrodynamic escape), atmosphere, the amount of collisional erosion (Genda & Abe 2005, O'Neill & Palme 2008), and the degree of differentiation of the impacting planetesimals. In the first few million years, ^{26}Al (half-life 0.7 million years) provides much of the radiogenic heat (in addition to the heat of accretion) responsible for the density segregation of planetesimals, exposing water on the outside while sequestering iron on the inside (Grimm & McSween 1993, Hester & Desch 2005). Importantly, the ^{26}Al content of a protoplanetary disk can vary by several orders of magnitude since it depends on how close the disk is to the closest supernovae produced by the largest stars in the birth cluster (Bizarro et al. 2004, Gaidos et al. 2009, Gilmour & Middleton 2009, Adams 2010). Because of the large variation possible in the water content of rocky planets, it makes sense to classify them by water content and by the phase of that water (solid, liquid, or gas) (see **Table 1**).

Ocean, Earth-like, and desert planets will each have low-, moderate-, and high-temperature versions. For example, a low-temperature ocean planet will be covered with ice (Europa-like), possibly because it is too small to maintain ongoing volcanism, or too poor in the four long-lived radiogenic isotopes to recover from episodes analogous to snowball Earth (Hoffman & Schrag 2002). A high-temperature version of an ocean planet would be a steam planet. Desert planets, low in H_2O owing to a small amount of radial mixing of material beyond the snowline, would also be low in carbon. Low carbon could also be a factor limiting the habitability of planets orbiting stars with low C/O ratios. See Bond et al. (2010) and Delgado-Mena et al. (2010) for a discussion of how stellar variation in C/O and Mg/Si can affect the mineralogy and habitability of rocky planets. For example, they find that stars with $\text{C/O} > 0.8$ will host reduced carbide planets with little water.

6. THE GALACTIC HABITABLE ZONE

Life is embedded in a hierarchy of supporting environments that provide the requirements for habitability. Estimation of a circumstellar HZ assumes the presence of a star and a planet and addresses the question, Where can the planet be located such that its surface is at the right temperature for life? The galactic HZ is a similar idea but on a much larger scale: Given an 11-billion-year-old galaxy, where can you find a star, a rocky planet, and clement conditions that last long enough to maintain life? The idea of a galactic HZ was intimated by Lem (1986), clearly articulated by Gonzalez et al. (2001), extended and more carefully quantified by Lineweaver et al. (2004) (**Figure 12**), and refined spatially to individual stars in a Monte Carlo simulation by Gowanlock et al. (2011) (see, however, Prantzos 2008).

Stars in our galaxy are not distributed uniformly in either space or time, nor do they all have enough metallicity (elements excluding H, He) to accrete rocky planets. And some are dangerously close to supernovae that disrupt habitability. Lineweaver et al. (2004) mapped the distribution in space and time of four prerequisites for complex life: the presence of a host star, enough heavy

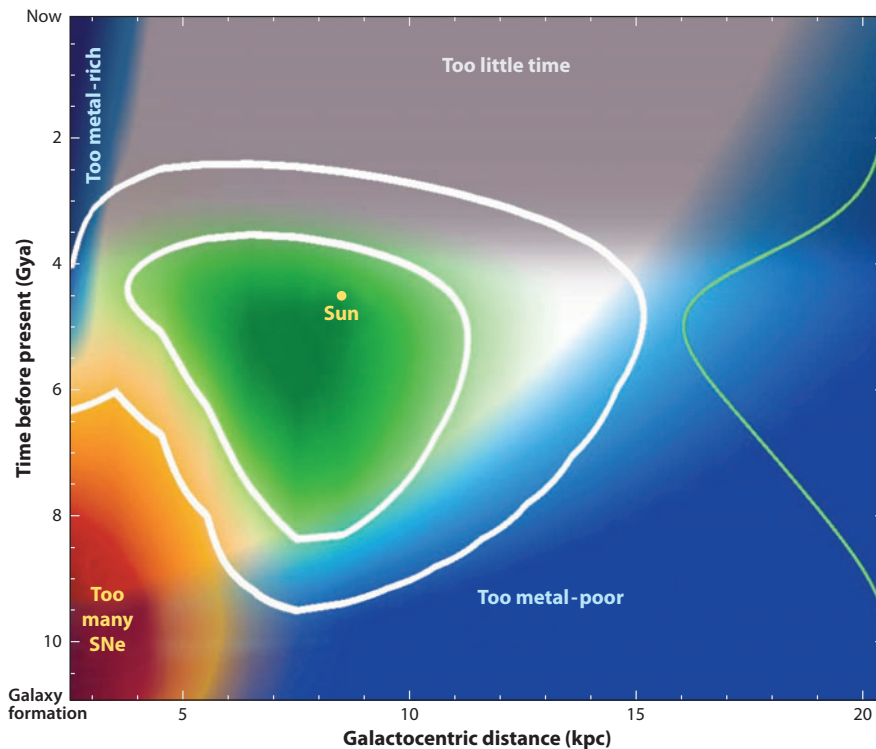


Figure 12

Galactic habitable zone (HZ) of our Milky Way Galaxy (Lineweaver et al. 2004). “Too many SNe” indicates the region where the supernovae (SNe) rate is probably too high to be compatible with the evolution of life. Abbreviation: kpc, kiloparsecs.

elements to form terrestrial planets, sufficient time for biological evolution (~4 billion years), and an environment free of life-extinguishing supernovae. We identified the galactic HZ as an annular region between seven and nine kiloparsecs from the galactic center that widens with time and is composed of stars that formed between eight and four billion years ago. Similar to the boundaries of the circumstellar HZ, these limits are not sharp, but do indicate where the potential for complex (= 4 billion years old) life may be the highest. This galactic HZ yields an age distribution for the complex life that may inhabit our galaxy: 75% of the stars in the galactic HZ are older than the Sun.

One can extend the concept of HZ beyond the galaxy to the universe. For example, a cosmic temporal HZ can be constructed from the age distribution of terrestrial planets in the universe (Lineweaver 2001). There are times that are habitable and times that are not. In the first two to three billion years after the big bang, there were no terrestrial planets because there was not enough condensable material to make them. There are also many other features of our universe that play a role in its habitability. These are discussed insightfully elsewhere (Dicke 1961, Carter 1974, Barrow & Tipler 1988, Bostrom 2002, Carroll 2006, Barrow et al. 2006).

Following Lovelock’s (1965) idea that the simultaneous presence of oxygen and reduced gases (e.g., CH₄, H₂) is unlikely without life, Sagan et al. (1993) analyzed a spectrum of Earth taken by the Galileo probe, searching for signatures of life. They concluded that the large amount of O₂ and the simultaneous trace amounts of CH₄ are strongly suggestive of biology. This has been a model of how we might be able to remotely detect life elsewhere (Leger et al. 1999). However, oxygen can

be produced abiotically by photolysis of water with subsequent hydrogen escape and photolysis of CO₂ with subsequent burial of carbon. The future search for extraterrestrial life will rely on our improved ability to understand and spectrally characterize the abiotic and potentially biotic contributions to atmospheric chemical disequilibria (Kasting et al. 2009, Catling & Bergsman 2010, Seager 2010, Vazquez et al. 2010, Kaltenecker et al. 2011b).

The study of habitability, habitology, is a new, immature cross-disciplinary synthesis of facts and theory from Earth and planetary sciences, biology, and astronomy. As new data come streaming in from these disparate disciplines, the preliminary steps of their integration is exhilarating and confusing. We can only find out who we are and how we fit into the universe by studying and interpreting these data with the goal of finding other life-forms. Our search for extraterrestrial life is a search for ourselves and our place in the universe. If we cannot find extraterrestrial life-forms that fit our definition of life, perhaps we will have to broaden our definition until we do. Even if we fail to find life elsewhere, we will soon find the closest uninhabited habitable planet. That will be crucial, sooner or later, for our survival as a species.

SUMMARY POINTS

1. The increasingly large overlap between terrestrial environments known to harbor life and the surface environments of newly detected rocky exoplanets bolsters expectations that the universe may be filled with habitable planets.
2. The inhabited and uninhabited regions on Earth (thin bioshell, deserts, uninhabited water) tell us that the presence of water and the temperature range (−20°C to 122°C) are the two most important parameters controlling habitability.
3. Earth was able to get life started and keep life going. There may be a large number of planets that have been unable to get life started and thus do not belong to the AHZ. They are habitable but uninhabited.
4. The fraction of stars with planets is approximately 100%. The fraction of stars with a rocky planet in the HZ could be comparably large.
5. The water content of rocky planets is highly variable. This variability can be used to classify their habitability, e.g., ocean planets, Earth-like planets, and desert planets. Each class would have high-, medium-, and low-temperature versions.
6. The future of studies in habitability is in the exploration of the Martian subsurface and in the detailed characterization of Earth-like exoplanets, specifically in using IR spectrographs to distinguish biotically and abiotically produced atmospheric chemical disequilibria on the nearest terrestrial exoplanets.

DISCLOSURE STATEMENT

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