REVIEW

Exoplanet Habitability

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The search for exoplanets includes the promise to eventually find and identify habitable worlds. The thousands of known exoplanets and planet candidates are extremely diverse in terms of their masses or sizes, orbits, and host star type. The diversity extends to new kinds of planets, which are very common yet have no solar system counterparts. Even with the requirement that a planet's surface temperature must be compatible with liquid water (because all life on Earth requires liquid water), a new emerging view is that planets very different from Earth may have the right conditions for life. The broadened possibilities will increase the future chances of discovering an inhabited world.

For thousands of years people have wondered, "Are we alone?" Now, for the first time in human history, the answer to this and other long-standing questions in the search for life beyond our solar system may finally be in reach through the observation and study of exoplanets—planets orbiting stars other than the Sun.

The research field of exoplanets has grown dramatically since the first planet orbiting a Sun-like star was discovered nearly 20 years ago (*1*). Nearly 1000 exoplanets are known to orbit nearby stars, a few thousand more planet "candidates" have been identified, and planets are so common that on average every star in the Milky Way should have at least one planet (*2*, *3*). The numbers of exoplanet candidates found by NASA's Kepler space telescope are high enough that robust statements of the frequency of their occurrence is possible, including the astonishing finding that small planets by far outnumber large planets in our galaxy (*3*, *4*), and the first statement about how common Earth-size planets are in the habitable zones of small stars (*5*).

The habitable zone is a region around a star where a planet can have surface temperatures consistent with the presence of liquid water. All life on Earth requires liquid water, so the planetary surface-temperature requirement appears to be a natural one. The climates of planets with thin atmospheres are dominated by external energy input from the host star, so that a star's "habitable zone" is based on distance from the host star. Small stars have a habitable zone much closer to them as compared to Sun-like stars, owing to their lower luminosity. The habitable zone was first discussed in the mid-20th century, inspired by attempts to understand the climate of early Earth and Mars (*6*, *7*), and was later brought onto a self-consistent footing when the carbonate-silicate cycle was proposed as a climate-stabilizing mechanism (*8*, *9*).

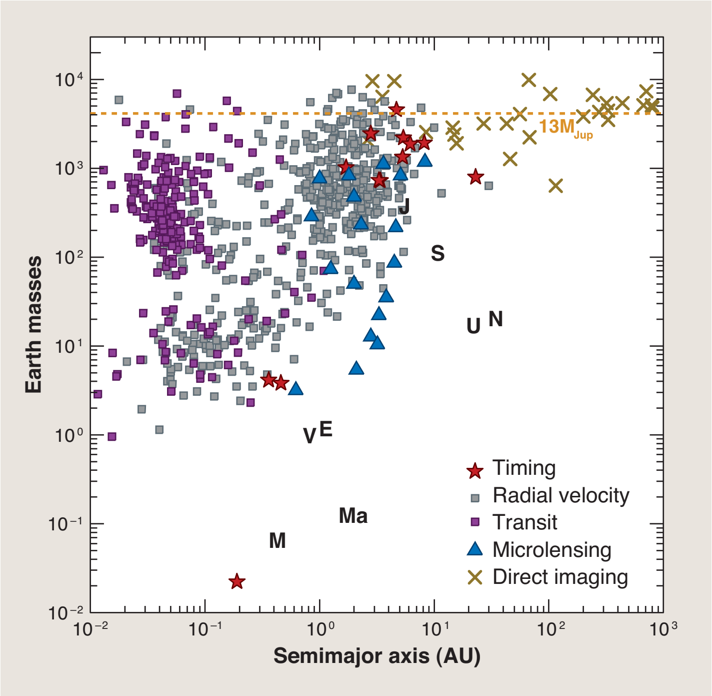

Fig. 1. Known exoplanets as of March 2013. Exoplanets are found at a nearly continuous range of masses and semimajor axes. Many different techniques are successful at discovering exoplanets, as indicated by the different symbols. The solar system planets are denoted by the first one or two letters of their name. The horizontal line is the conventional upper limit to a planet mass, 13 Jupiter masses. The sloped, lower boundary to the collection of gray squares is due to a selection effect in the radial velocity technique. Small planets are beneath the threshold for the current state of almost all exoplanet detection techniques. Data are from http://exoplanet.eu/.

The habitable zone for exoplanets was first presented and modeled in detail by (*9*), who also suggested an empirical version based on the concept that both Venus [0.7 astronomical units (AU) from the Sun, where an AU is the Earth-Sun distance] and Mars (1.5 AU) may have had liquid surface water at some point in the past. Most exoplanet habitable-zone research that followed continued to focus on terrestrial-like planet atmospheres orbiting main-sequence stars [see (*10*) and references therein]. This article reviews updates to the habitable zone and their rationale.

A planet in the habitable zone has no guarantee of actually being habitable. Venus and Earth may both be argued as being in the Sun's habitable zone and would appear from exoplanet discovery techniques to be the same size and mass. Yet, Venus is completely hostile to life owing to a strong greenhouse effect and resulting high surface temperatures (>700 K), whereas Earth has the right surface temperature for liquid water oceans and is teeming with life.

If there is one important lesson from exoplanets, it is that anything is possible within the laws of physics and chemistry. Planets of almost all masses, sizes, and orbits have been detected (Fig. 1), illustrating not only the stochastic nature of planet formation but also a subsequent migration through the planetary disk from the planet's place of origin [e.g., (*11*)]. The huge diversity of exoplanets and the related anticipated variation in their atmospheres, in terms of mass and composition, have motivated a strong desire to revise the view of planetary habitability. In parallel, there is a growing acceptance that even in the future, the number of suitable planets accessible to detailed follow-up observations may be very small. To maximize our chances of identifying a habitable world, a broader understanding of which planets are habitable is a necessity.

Habitable Planets, Conventionally Defined

The conventionally habitable planet is one with surface liquid water. Water is required for all life as we know it, and has motivated a mantra in astrobiology, "follow the water." Challenging the water requirement paradigm, a National Academies report (*12*) concluded that although a liquid environment is required by life, it need not be limited to water. In the search for life beyond the solar system, however, we still focus on environments that support liquid water simply because

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water is the most accessible, abundant, and common liquid in terms of planetary material (*13*).

For illustration and review, we consider water on the terrestrial planets in our own solar system. Earth is touted as the "Goldilocks planet"—not too hot, not too cold, but just right for surface liquid water (*14*). Venus, 30% closer to the Sun than Earth and receiving 90% more radiation from the Sun, may have had liquid water oceans billions of years ago, as possibly implied by the elevated deuterium/hydrogen (D/H) ratio in the venusian atmosphere (*15*). Because of warm surface temperatures, water evaporated to saturate the upper atmosphere where solar extreme ultraviolet (EUV) radiation photodissociated the H_2O, enabling H to escape to space. The increasing atmospheric water vapor further warmed the surface, creating a positive feedback loop that led to a "runaway greenhouse effect," which caused Venus to rapidly lose its oceans [but compare (*16*)]. Mars, at 1.5 AU from the Sun, is thought to have had at least episodic surface liquid water in the past, based predominantly on geomorphological features [e.g., (*17*)]. Mars was too small to hold onto a warming atmosphere and is now so cold there is no place on the Martian surface where water could be liquid. The habitable zone for terrestrial-type exoplanets with terrestrial-like atmospheres of various masses and CO_2 concentration are described in (*10*) and result in a habitable zone of 0.99 to 1.7 AU (Fig. 2). The inner edge of the habitable zone is determined by loss of water via the runaway greenhouse effect (*18*) and the outer edge by CO_2 condensation.

For exoplanets, we cannot directly observe liquid surface water (*19*). Atmospheric water vapor may be used as a proxy; as long as a temperate planet is small or of low enough mass, water vapor should not be present because water will be photodissociated with H escaping to space. Atmospheric water vapor has been detected on hot giant transiting exoplanets [e.g., (*20*)] and is highly sought after for the mini Neptune GJ 1214b [e.g., (*21*)]. Both of these types of planets are too hot for surface liquid water [for a discussion of GJ 1214b, see (*22*)]; notably, water vapor will be naturally occurring on planets that are massive enough or cold enough to hold on to water vapor molecules. The detection of water vapor in the atmosphere of smaller, more terrestrial-like planets is currently out of reach.

Given the observational inaccessibility of the key habitability indicator water vapor on terrestrial-like exoplanets, the habitable zone around a star is a powerful guide for astronomers because it tells us where to focus future efforts of exoplanet discovery. We must redefine the habitable-zone concept, however, given the expected and observed diversity of exoplanets.

The Diversity of Exoplanets and the Controlling Factors of Habitability

Taking surface liquid water as a requirement, what types of planets are habitable? Water is in the liquid phase for a range of temperatures and pressures. Planets should also have a wide range of surface temperatures and pressures, expected from their diversity in mass and size and likely atmospheres. If we could connect the liquid water phase diagram with planet surface conditions, broadly speaking, we would know to first order which planets may be habitable.

The water phase diagram can be used as a qualitative guide to show that pressures thousands of times higher than Earth's 1-bar surface pressure can maintain liquid water at high temperatures (*23*). A suitable temperature for life can be considered to be between the freezing point of water and the upper temperature limits for life, about 395 K (*24*). A notable inaccuracy in the phase diagram is that the water phase boundaries at high pressures have not been studied for a variety of gas mixtures relevant for exoplanets (*25*).

The surface temperature on an exoplanet is governed by the atmosphere's greenhouse gases (or lack thereof). Specifically, the greenhouse gases absorb and reradiate energy from the host star, in the form of upwelling infrared (IR) radiation from the planet's surface. Whereas on Earth we are concerned with, e.g., parts-per-million rise in the greenhouse gas CO_2 concentrations, for potentially habitable exoplanets we do not know a priori and cannot yet measure what gases are in the atmosphere even to the tens of percent level. The atmospheric mass and composition of any specific small exoplanet is not predictable (*26*).

Nevertheless, it is worth summarizing some key factors controlling a planet atmosphere's greenhouse gas inventory. A planet's atmosphere forms from outgassing during planet formation or is gravitationally captured from the surrounding proto-planetary nebula. For terrestrial planets, the primordial atmosphere may be completely changed by escape of light gases to space, continuous outgassing from an active young interior, and bombardment by asteroids and comets. At a later stage, the physical processes operating at the top or bottom of the atmosphere still sculpt the atmosphere. These physical processes are well studied by exoplanet theorists but often with controversy or no conclusion. For example, atmospheric escape is induced by the host star's EUV flux and carried out by a number of thermal or nonthermal escape mechanisms. But the star's past EUV flux, which of the escape mechanisms was at play, and whether or not the planet has a protective magnetic field are not known [e.g., (*27*)]. As a second example, at the bottom of the atmosphere, plate tectonics and volcanic outgassing contribute to burial and recycling of atmospheric gases, but arguments as to whether or not plate tectonics will occur in a super-Earth planet more massive than Earth are still under debate (*28*, *29*). A long list of other surface and interior processes affect the atmospheric composition, including but not limited to the ocean fraction for dissolution of CO_2 and for atmospheric relative humidity, redox state of the planetary surface and interior, acidity levels of the oceans planetary albedo, and surface gravity [for

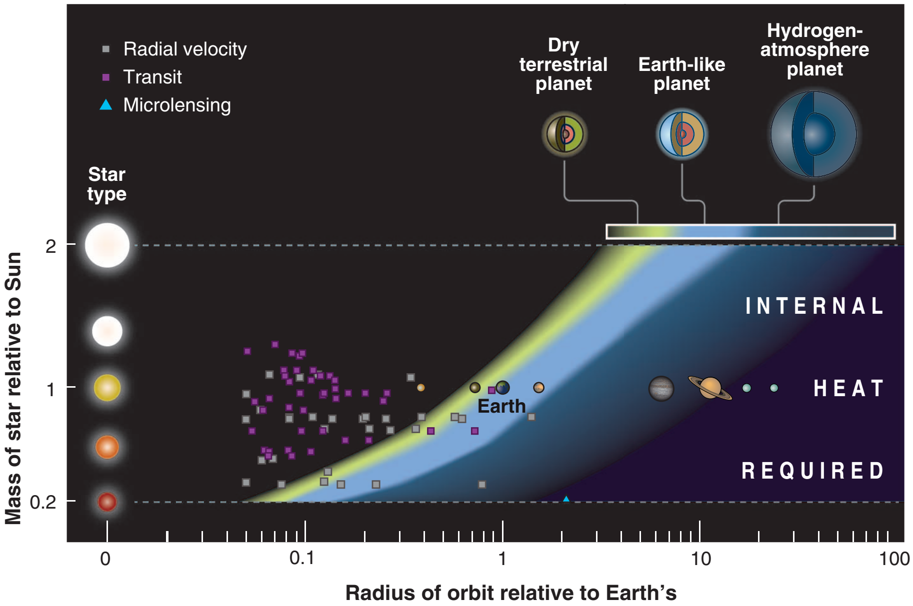

Fig. 2. The habitable zone. The light blue region depicts the "conventional" habitable zone for planets with N_2-CO_2-H_2O atmospheres (*9*, *10*). The yellow region shows the habitable zone as extended inward for dry planets (*36*, *37*), as dry as 1% relative humidity (*37*). The outer darker blue region shows the outer extension of the habitable zone for hydrogen-rich atmospheres (*34*) and can extend even out to free-floating planets with no host star (*35*). The solar system planets are shown with images. Known exoplanets are shown with symbols [here, planets with a mass or minimum mass less than 10 Earth masses or a radius less than 2.5 Earth radii taken from (*66*)].

a more detailed list, see (*30*)]. Many other factors are relevant to habitability, including the radiation environment from the star, especially the energy distribution as a function of wavelength and the EUV radiation that destroys molecules and determines their atmospheric lifetime, and x-ray fluxes that could be detrimental to surface life (*27*). In some cases, planets have been found to orbit one or both stars of a binary star system, complicating the influence of stellar radiation.

A Major Extension of the Habitable Zone

For our qualitative assessment of habitability, we therefore focus on the dominant planetary atmospheric greenhouse gases and how they delimit the habitable zone (Fig. 2).

The most important atmospheric greenhouse gas that extends the habitable zone to large planet-star separation is molecular hydrogen (H_2). Planets are expected to form with some primordial light gases, either H_2 (from interior outgassing) (*26*, *31*) or H_2 and He (from gravitational capture of gas from the surrounding protoplanetary disk). Although small planets like Earth, Venus, and Mars are unable to retain these light gases, more massive or colder exoplanets are expected to be able to do so. H_2 is a formidable greenhouse gas, because it can absorb radiation over a wide, continuous wavelength range. Most molecules absorb in discreet bands. As a homonuclear molecule, H_2 does not have a dipole moment and therefore lacks the typical rotational-vibrational bands that absorb light at near-IR wavelengths. However, a momentary dipole is induced by collisions, and thus at high enough pressures, frequent collisions induce very broadband absorption (*32*, *33*). Furthermore, H_2 does not condense until tens of kelvin at 1- to 100-bar pressures (in comparison, CO_2 condenses at about 190 to 250 K for 1- to 10-bar pressures and is therefore a cutoff for the cold end of conventional planet habitability). The potency of H_2 as a greenhouse gas means that planets can have surface liquid water at a factor of several times larger planet-sun separations than planets with CO_2 atmospheres (*34*) and even possibly extending to rogue planets that were ejected from their birth planetary system and are now floating through the galaxy (*35*).

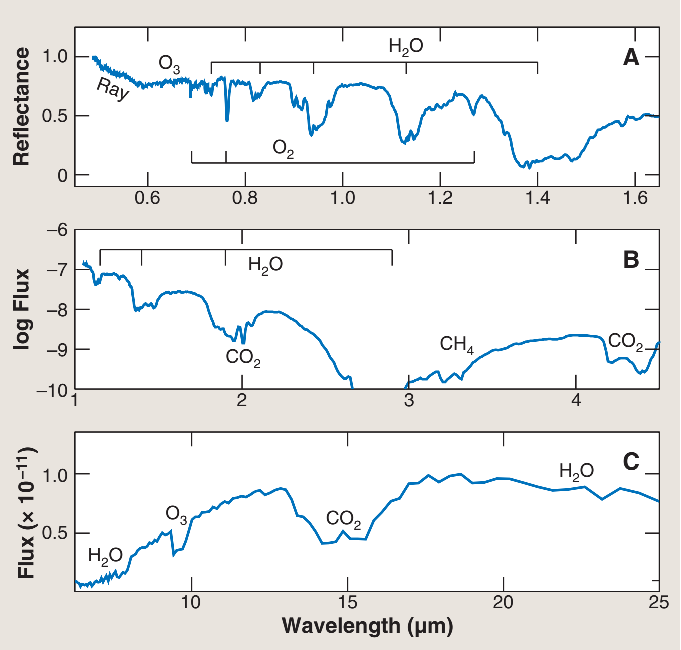

Fig. 3. Earth as an exoplanet, via observed disk-integrated spectra. (A) Visible-wavelength spectrum from Earthshine measurements plotted as normalized reflectance (*67*). (**B**) Near-infrared spectrum from NASA's EPOXI mission with flux in units of W m^{-2} µm^{-1} (*68*). (**C**) Mid-infrared spectrum as observed by Mars Global Surveyor enroute to Mars with flux in units of W m^{-2} Hz^{-1} (*69*). Major molecular absorption features are noted, including Rayleigh scattering. Only Earth's spectroscopically active, globally mixed gases would be observable from a remote space telescope.

The inner edge of the habitable zone is controlled by the strong greenhouse gas H_2O, which is fundamentally unavoidable on habitable worlds. Surface liquid water—the adopted requirement for habitability—gives rise to atmospheric water vapor. The habitable planets closest to their host stars must therefore be relatively dry (*36*, *37*)—that is, with a smaller ocean-land fraction than Earth—so the atmosphere will have less water vapor than Earth's. But the putative inner-edge habitable-zone planet must not be too dry; otherwise, CO_2 cannot be washed out of the atmosphere, which would lead to a buildup of CO_2 and subsequent warming. Theoretical simulations of planet formation indicate that dry planets are possible [e.g., (*38*)].

Pockets of small areas of habitability on an individual exoplanet are usually disregarded for exoplanets (*39*); the concern is that they will not lead to any detectable atmospheric signatures. Although large planetary moons of giant planets may be habitable (some might even have interior energy generated by planet-moon tidal friction), detectability of the moon's atmosphere is a concern because of severe contamination from the adjacent larger, brighter planet.

We have seen that planetary habitability is very planet-specific. The habitable zone has been defined with an inner edge of about 0.5 AU around a solar-like star, for a dry rocky planet (*37*), out to 10 AU around a solar-like star for a planet with an H_2 atmosphere and no interior energy (*34*), and even possibly out to free-floating planets with no host star, for planets with thick H_2 atmospheres (*35*) (Fig. 2).

Ideally, we would triage each planet first by the planet's bulk density, using a measured mass and radius, to screen planets for those that have thin atmospheres. Next, we could use the star's luminosity and planet-star separation, as well as model possibilities of the planet's interior, to assess whether the likely surface temperatures are conducive to support liquid water. For planets that pass the tests, telescopic observations of the planet's atmosphere to identify water vapor as a proxy for surface liquid water would be a definitive step for identifying a habitable world. However, for most exoplanets, such fundamental measurements will not be possible. In some cases, a planet's mass but not size can be measured; in other cases, the size but not mass can be measured, and the atmosphere will be accessible only for a few small planets orbiting nearby stars.

Biosignature Gases

The main interest in defining a habitable planet is to identify an inhabited one, via remote-sensing observations of biosignature gases. Biosignature gases are gases produced by life that accumulate in a planetary atmosphere to high enough levels for remote detection by futuristic space telescopes. The underpinning assumption is that life uses chemical reactions to extract, store, and release energy, such that biosignature gases are generated as by-products somewhere in life's metabolic process.

Atmospheric biosignature gases have been studied theoretically as indicators of life for nearly half a century (*40*, *41*), with the proposed concept that a favorable biosignature gas is one that is many orders of magnitude out of thermochemical equilibrium with the planetary atmosphere.

Not all biosignature gases will be detectable from afar. Only globally mixed, spectroscopically active gases will be visible in an exoplanet spectrum. On Earth, the dominant global biosignature gases are O_2 (and its photolytic product O_3) produced by plants and photosynthetic bacteria, N_2O, and for early Earth possibly CH_4 (*42*) (Fig. 3).

The microbial world on Earth is incredibly diverse, and microorganisms produce a broad range of gases (*43*). Some of these gases, such as CO_2, are not unique to life as they occur naturally in the atmosphere. Other biosignature gases may be negligible on present-day Earth but accumulate to relevant levels in an environment substantially different from Earth's. Some examples that have been studied for terrestrial-like atmospheres include organosulfur compounds, particularly methanethiol (CH_3SH, the sulfur analog of methanol) (*44*); CH_3Cl, a hydrogen halide (*45*); and sulfur biogenic gases on anoxic planets (*46*).

A major highlight from the last decade of biosignature gas research is the realization that low-EUV radiation environments, compared to solar radiation levels, lead to a much higher concentration of biosignature gases. This is because the stellar EUV radiation creates the radical OH (in some cases O), which destroys many gases in the atmosphere and thus reduces the gas lifetime (*45*). In an H_2-rich atmosphere, the same result holds with H as the major reactive species. Low-EUV radiation environments, compared to solar radiation levels, are found around inactive M dwarf stars (*47*).

Many biosignature gases have a "false positive" interpretation because they can be produced abiotically. False positives can, it is hoped, be identified by other atmospheric diagnostics. For example, photodissociation of water vapor in a runaway greenhouse with H escaping to space could lead to detectable O_2 levels. This situation could be identified by an atmosphere heavily saturated with water vapor. O_2 could also accumulate in a dry, CO_2-rich planet with weak geochemical sinks for O_2, a case that could be identified through strong CO_2 and weak H_2O features (*48*, *49*).

A sobering thought usually left unacknowledged is that when we finally discover biosignature gases, it may be not with a triumphant 100% certainty but rather with an assigned probability, depending on the level at which the false positive likelihood can be ascertained.

How to Find and Identify a Habitable World

In parallel to developing the theoretical foundation for planetary habitability, astronomers are developing instruments, telescopes, and space mission concepts to find and identify habitable or inhabited worlds. There are two ways to observe exoplanet atmospheres, and this leads to a "two-pronged approach."

The first approach is direct imaging [reviewed in (*50*)]. Here, the planet is observed as a point source (not spatially resolved like the beautiful Apollo images of Earth), and with the appropriate instrumentation, the light could be dispersed into a spectrum. The two objectives are to spatially separate the planet and star on the sky and to observe the planet literally within the glare of the host star. The limiting challenge for a planet like Earth is not its faintness—a relatively nearby Earth would not be fainter than the faintest galaxies ever observed by the Hubble Space Telescope—but the planet's proximity to a bright host. The Sun is 10 billion times as bright as Earth at visible wavelengths. The low-luminosity M stars are even more challenging to observe because of the smaller planet-star angular separation on the sky for the habitable zone. The use of a space-based telescope to image these planets is essential, both to get above the blurring effects of Earth's atmosphere and to avoid having to contend with the presence of these gases in our own atmosphere during an Earth-based hunt for biosignatures [compare (*51*)]. Implementation of the optical mathematics and engineering for blocking out starlight for planet finding is a subfield that has proceeded at a breathtaking pace (*50*), culminating in many concepts described under the umbrella term "Terrestrial Planet Finder" (TPF) (named after a cancelled set of missions under study by NASA in the early 2000s; the European Space Agency had a version called "Darwin"). Although a spectroscopically capable direct-imaging space mission to survey the 100 nearest Sun-like stars is now out of reach owing to an estimated cost of more than 5 billion dollars, technology development is still ongoing (*52*). A prescient saying in the exoplanet community Is that "all roads lead to TPF," because space-based direct imaging is the prime way to find and identify a true Earth twin.

The second approach is transit finding [reviewed in (*53*)] and transit spectroscopy. When a planet goes in front of its host star as seen from a telescope, some of the starlight will pass through the planet's atmosphere, and the atmospheric features will be imprinted on the starlight. In addition, when the planet goes behind the star (called "secondary eclipse"), the planet light will disappear and then reappear. For such transit and eclipse observations, the planet and star are not spatially separated on the sky but are instead observed in the "combined light" of the planet-star system: Using the starlight as a calibration tool enables the high-contrast measurements. Atmospheres of dozens of hot Jupiter exoplanets have been observed in this way. Although the Earth-Sun analog signal is still too small for observation, Earth-size and larger planets transiting M stars are suitable (*54*). M stars are favorable in many ways, from detectability to characterization, because the small star makes relative planet-to-star measurement signals larger than for Sun-like stars (*55*).

The obstacle to observing transiting planets is that the required orbital alignment will be fortuitous and infrequent, limiting the numbers of transiting planets accessible for study. The good news is that for planets orbiting quiet M stars, biosignature gases will accumulate, and simulations show that several such objects should exist and will be available for study with the under-construction James Webb Space Telescope [e.g., (*56*)]. First, we need a pool of suitable transiting planets orbiting quiet M stars (*57*) and next, a large amount of telescope time, perhaps tens of hours or more per planet. This scenario represents our nearest-term chance of identifying a habitable world.

Epilogue

Planet habitability is planet specific, even with the main imposed criterion that surface liquid water must be present. This is because the huge range of planet diversity in terms of masses, orbits, and star types should extend to planet atmospheres and interiors, based on the stochastic nature of planet formation and subsequent evolution. The diversity of planetary systems extends far beyond planets in our solar system. The habitable zone could exist from about 0.5 AU out to 10 AU for a solar-type star, or even beyond, depending on the planet's interior and atmosphere characteristics. As such, there is no universal habitable zone applicable to all exoplanets.

Many questions related to physical processes that govern the atmosphere, which itself controls habitability, may remain unanswered owing to a lack of observables. For example, which planets have plate tectonics and which have protective magnetic fields? Either there are no connections to observables or the observables are too weak for current and future instrumentation to measure.

Research strides are currently being made with statistical assessments of the occurrence rate of different sizes and masses of planets. This statistical phase of exoplanet research is moving toward estimates of the frequency of habitable planets with a handful of habitable-zone candidates tentatively identified. This statistical phase of exoplanets is expected to continue to flourish and dominate exoplanet science until the next generation of ground- and space-based telescopes.

Ultimately, a return to study of compelling individual objects is required—at any cost—if we want to assess a planet's habitability or attain the goal of identifying signs of life via biosignature gases. Is there any hope that the next space telescope, the James Webb Space Telescope, could be the first to provide evidence of biosignature gases? Yes, if—and only if—every single factor is in our favor. First, we need to discover a pool of super-Earths transiting in the "extended" habitable zones of nearby, quiet M stars. Second, life must not only exist on one of those planets, but must also produce biosignature gases that are spectroscopically active. Regardless of the search for life, the field of exoplanet characterization is on track to understand habitability and to find habitable worlds.

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