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A Two-Tiered Approach to Assessing the Habitability of Exoplanets

Dirk Schulze-Makuch,[1,4] Abel Méndez,[2] Alberto G. Fairén,[3] Philip von Paris,[4] Carol Turse,[1] Grayson Boyer,[5] Alfonso F. Davila,[3] Marina Resendes de Sousa António,[1] David Catling,[6] and Louis N. Irwin[7]

Abstract

In the next few years, the number of catalogued exoplanets will be counted in the thousands. This will vastly expand the number of potentially habitable worlds and lead to a systematic assessment of their astrobiological potential. Here, we suggest a two-tiered classification scheme of exoplanet habitability. The first tier consists of an Earth Similarity Index (ESI), which allows worlds to be screened with regard to their similarity to Earth, the only known inhabited planet at this time. The ESI is based on data available or potentially available for most exoplanets such as mass, radius, and temperature. For the second tier of the classification scheme we propose a Planetary Habitability Index (PHI) based on the presence of a stable substrate, available energy, appropriate chemistry, and the potential for holding a liquid solvent. The PHI has been designed to minimize the biased search for life as we know it and to take into account life that might exist under more exotic conditions. As such, the PHI requires more detailed knowledge than is available for any exoplanet at this time. However, future missions such as the Terrestrial Planet Finder will collect this information and advance the PHI. Both indices are formulated in a way that enables their values to be updated as technology and our knowledge about habitable planets, moons, and life advances. Applying the proposed metrics to bodies within our Solar System for comparison reveals two planets in the Gliese 581 system, GJ 581 c and d, with an ESI comparable to that of Mars and a PHI between that of Europa and Enceladus. Key Words: Habitability—Exoplanets—Index—Earth similarity—Complexity—Life. Astrobiology 11, 1041–1052.

1. Introduction

As of this writing, over 700 exoplanets have been detected, many in solar systems with multiple planets (for an update, see http://exoplanet.eu/). All but one of the exoplanets detected to date are larger than Earth and, for the most part, considerably closer to their central star, which, given that such planets are easier to detect, is to be expected. However, more than 20 planets with minimum masses smaller than 10 Earth masses are known, and many of them could potentially be terrestrial. Technologies already operational or under development are hastening the discovery of smaller terrestrial planets. On Hawaii, the Keck Interferometer will combine light from the world's largest optical telescopes to enable the visualization of gas clouds, including large planets within them, around distant stars. In Arizona, the Large Binocular Telescope Interferometer is currently under construction. These instruments will advance our understanding of the proportion of planets that may be smaller and more terrestrial within the coming decades, at least for neighboring systems in our own galaxy. The Kepler Mission and the Terrestrial Planet Finder (TPF) are designed to detect Earth-sized planets and directly measure gases consistent with life, such as ozone and methane, in terrestrial-like atmospheres on planets around stars up to 50 light years away (Beichman *et al.*, 2002; Basri *et al.*, 2005; Schulze-Makuch and Irwin, 2008). The possibility of Earth-type habitable planets in other solar systems has been suggested by plausible models, as was the case for the 47 UMa planetary system (Cuntz *et al.*, 2003) and Gliese 581 d (Selsis *et al.*, 2007; von Bloh *et al.*, 2007; Schulze-Makuch and Guinan, 2010; von Paris *et al.*, 2010; Wordsworth *et al.*, 2010). With a new generation of telescopes and missions on the way, the

[1]School of Earth and Environmental Sciences, Washington State University, Pullman, Washington, USA.
[2]Planetary Habitability Laboratory, University of Puerto Rico at Arecibo, Arecibo, Puerto Rico, USA.
[3]SETI Institute and NASA Ames Research Center, Moffett Field, California, USA.
[4]Institut für Planetenforschung, Deutsches Zentrum für Luft- und Raumfahrt (DLR), Berlin, Germany.
[5]Department of Chemistry and Biochemistry, Arizona State University, Tempe, Arizona, USA.
[6]Department of Earth and Space Sciences/Astrobiology Program, University of Washington, Seattle, Washington, USA.
[7]Department of Biological Sciences, University of Texas at El Paso, El Paso, Texas, USA.

discovery of many more exoplanets can be expected. That, in turn, will drive the need for a classification scheme for assigning astrobiological potential for exoplanets based on estimates derived from quantitative data of their probability for supporting life (*e.g.*, Kaltenegger *et al.*, 2010). A summary of planetary parameters that can be directly observed for exoplanets by current or proposed space mission is provided in Table 1.

Estimates of astrobiological potential in general have been dominated by the concept of the "circumstellar habitable zone" (Kasting *et al.*, 1993), which suggests that attention should be focused on those worlds that could retain an atmosphere and liquid water—the implicit assumption being that life is most likely to be found on planetary bodies with those Earth-like conditions. Many have argued, however, that focusing exclusively on a habitable zone biased by terracentric assumptions is too restrictive for the full variety of life that could exist (*e.g.*, Darling, 2001; Grinspoon, 2003; Schulze-Makuch and Irwin, 2004, 2008; Ward, 2005; Gaidos *et al.*, 2005). Therefore, the possibility that life could be found under very different conditions from those of Earth needs to be kept in mind (Schulze-Makuch and Irwin, 2002, 2006; Bains, 2004; Benner *et al.*, 2004).

As a practical matter, interest in exoplanets is going to focus initially on the search for terrestrial, Earth-like planets, as the deployment of the TPF illustrates. In a larger sense, however, the task of astrobiology is to seek out life in the Universe in all its forms. Therefore, the search for life on other worlds is really divisible into a two-part question. The first question is whether Earth-like conditions can be found on other worlds, since we know empirically that those conditions could harbor life. The second question is whether conditions exist on exoplanets that suggest the possibility of life, whether in a form known to us or not. We therefore propose two different indices for addressing each of these questions.

2. The Earth Similarity Index (ESI)

Similarity indices provide a powerful tool for categorizing and extracting patterns from large and complex data sets. They are relatively quick and easy to calculate and provide a simple quantitative measure of departure from a reference state, usually on a scale from zero to one. They are used in many fields, including mathematics (*e.g.*, set theory and fuzzy logic), ecology (*e.g.*, Sorensen similarity index), computer imaging (*e.g.*, structural similarity index), chemistry (*e.g.*, Jaccard-Tanimoto similarity index), and many others.

We propose the ESI as a measure of Earth-likeness. The basic ESI expression is constructed from a weighted reformulation of the Bray-Curtis Similarity Index (Bloom, 1981) as

$$\mathrm{ESI}_x = \left(1 - \left|\frac{x - x_0}{x + x_0}\right|\right)^w \qquad (1)$$

where x is a planetary property, x_o is a terrestrial reference value, w is a weight exponent, and ESI_x is the similarity measure as a number between zero (no similarity) and one (identical). The weighting exponent is used to adjust the sensitivity of the scale, to bring each calculated parameter equal to or above 0.8 for Earth-like conditions (see below). The ESI for each planetary property is then combined into a single ESI value by using the geometric mean as the method of aggregation.

Application of the ESI to exoplanets requires only the use of physical properties already available for many of them, such as radius, mass, and temperature. We have found it most instructive to distinguish among interior, surface, and global similarities. The interior similarity is a measure of the extent to which a planet has a rocky interior, while the surface similarity is a measure of the ability to hold a temperate surface like that of Earth. They are given by

$$\mathrm{ESI_I} = (\mathrm{ESI}_r \cdot \mathrm{ESI}_\rho)^{1/2} \qquad (2)$$

Table 1. Basic Planetary Parameters That Can Be Directly Observed for Terrestrial Extrasolar Planets by Current or Proposed Space Missions

Parameter	*Variable*	*Method*	*Missions*	*Astrobiological relevance*	*Reference*
Semimajor axis	A	DI, AM, RV, TP, GM*	Kepler, Gaia	Surface temperature	[1]
Eccentricity	ε	DI, AM, RV	Gaia	Seasonal variations	[1]
Orbital inclination	I	DI, TP (lower limit)	Kepler, Gaia, TPF	Seasonal variations	[1]
Orbital period (=semimajor axis)	T_{orb}	DI, AM, RV, TP	Kepler, Gaia	Surface pressure	[1]
Mass	M	DI, AM, RV,† GM	JWST, Gaia, TPF	Surface pressure and temperature	[1]
Radius	R	DI, TP	Kepler	Composition	[1]
Density	ρ	DI, TP	Kepler, Gaia	Seasonal variations	[1]
Mean surface temperature	T_{surf}	DI, TP*	TPF, JWST, Kepler	Stability of liquid water	[1]
Ocean areas	—	DI	TPF	Stability of liquid water	[2]
Atmospheric composition	—	DI, TP*	TPF, JWST	Bioelements	[1]
Vegetation red edge	—	DI	TPF	Habitat distribution and water cycle	[3]

*Under some conditions.
†Lower limit.
Planet detection methods are direct imaging (DI), astrometry (AM), radial velocity (RV), transit photometry (TP), and gravitational microlensing (GM).
JWST, the James Webb Space Telescope.
[1] Jones (2008).
[2] Williams and Gaidos (2008).
[3] Arnold *et al.* (2009).

$$\mathrm{ESI_S} = (\mathrm{ESI}_{v_e} \cdot \mathrm{ESI}_{T_s})^{1/2} \quad (3)$$

where the mean radius, r, and bulk density, ρ, are used to define the interior similarity, $\mathrm{ESI_I}$; while escape velocity, v_e, and mean surface temperature, T_s, are used to define the surface similarity, $\mathrm{ESI_S}$. The geometric mean is used to make the index more sensitive to lower values. The interior and surface similarities are then combined into a single value as

$$\mathrm{ESI} = (\mathrm{ESI_I} \cdot \mathrm{ESI_S})^{1/2} \quad (4)$$

where the global similarity, ESI, is a simple combined measure of the physical similarity of any planetary body with Earth.

Usually, the term "Earth-like" or "terrestrial planet" refers to a planet with similar bulk composition to Earth (*e.g.,* Gaidos *et al.,* 2005). The ESI scale can be used to quantify the concept of Earth-likeness, not only in bulk composition but also in surface properties. For the purposes of the interior ESI scale, a terrestrial planet is defined as a planet with a mass between 0.1 and 10 Earth masses and a bulk density between 0.7 and 1.5 Earth densities (4.4–8.3 g/cm^3). These conditions constrain the size of a planet. By using the mass-radius relationship for terrestrial planets of Sotin *et al.* (2007), a radius between 0.5 and 1.9 Earth radii is implied. For the surface ESI, a terrestrial planet is defined as one able to hold an atmosphere composed primarily of nitrogen but not hydrogen with mean surface temperatures between 0°C and 50°C (273–323 K). This is the temperature range tolerable by most complex life on Earth and where most phototrophic primary producers such as C3 and C4 plants are able to photosynthesize (Woodward and Smith, 1994).

Planets lose atmospheres by thermal escape, impact erosion, or nonthermal escape, where the first two processes can remove atmospheres altogether (Hunten, 1990; Catling and Zahnle, 2009). A planet that is able to thermally hold atomic nitrogen in its atmosphere will also hold heavier gases like water vapor, carbon dioxide, and oxygen, all suitable for Earth-type life. Planets sufficiently large to retain significant hydrogen may have dense atmospheres or may become gas giants. This nitrogen-hydrogen range implies that a planet should have an escape velocity between 0.4 and 1.4 Earth's escape velocity [which correspond to thermal escape velocities at Earth's equilibrium temperature of −18°C (255 K): 0.4 representing 6 times the velocity for atomic nitrogen and 1.4 representing 6 times the velocity for atomic hydrogen]. The equilibrium temperature is the temperature on the surface of a planet in the absence of atmospheric effects. For Gliese 581 g, the equilibrium temperature should vary from −64°C to −45°C assuming albedos from 0.5 to 0.3, respectively (0.3 is characteristic of the inner Solar System and Earth). Adding an Earth-like greenhouse effect would yield an average surface temperature in the range of −37°C to −12°C. Earth's present global equilibrium temperature is −18°C, which is raised to 15°C by the greenhouse effect (*e.g.,* Manabe and Wetherald, 1967).

We have defined an Earth-like planet, for both the interior and surface ESI scale, as one for which each planetary property is weighted to give an ESI value above 0.8. The definitional limits were substituted in Eq. 1 for each planetary property, along with the corresponding reference values for terrestrial mean radius, bulk density, escape velocity, and surface temperature. The weighted exponents were then solved for each planetary property by using the 0.8 ESI value as a threshold. A geometric mean was used to average the weight exponents corresponding to the minimum and maximum limits for each property. This resulted in weighted exponents of 0.57 for the mean radius, 1.07 for the bulk density, 0.70 for the escape velocity, and 5.58 for the surface temperature. Accordingly, the respective ESI values should be raised by these exponents (see Appendix for an example calculation).

Table 2 shows a list of the reference values used to define the ESI scale for each planetary property, based on data from the Extrasolar Planets Encyclopedia (http://exoplanet.eu/), the Exoplanet Data Explorer (http://exoplanets.org/), and from NASA JPL Solar System Dynamics (http://ssd.jpl.nasa.gov/). Only five parameters were necessary for the ESI calculations: the planet's mass, radius, and semimajor axis; and the parent star's radius and effective temperature [the effective temperature of a star is a single temperature at which a blackbody spectrum (*i.e.,* a smooth, continuous spectrum defined solely by temperature) would produce the same total energy flux as the real star; for our Sun the effective temperature is about 5777 K (*e.g.,* van't Veer-Menneret and Megessier, 1996)]. Bulk density and escape velocity were calculated from the mean planetary radius and mass. The radius was estimated for those not known by using the mass-radius relationship of Sotin *et al.* (2007) for planets with less than 10 Earth masses or assuming a density of 1.4 g/cm^3 (similar to Jupiter) for more massive planets. Mean surface temperatures were used for Solar System objects, and the equilibrium temperatures plus 30 K for greenhouse warming (similar to the terrestrial value) were used for exoplanets. Figure 1 plots the surface ESI against the interior ESI for familiar Solar System objects and 258 exoplanets.

3. The Planetary Habitability Index (PHI)

For assessing the possibility that life in some form could be present on another world, we propose a PHI, based on the essential requirement that all life has for a stable and protected substrate, energy, polymeric chemistry, and a liquid medium. To avoid a terracentric bias, we do not consider the presence of water, *per se,* as a relevant criterion for the PHI.

We propose the following calculation for the PHI, as a measure of the probability that life in some form will exist on another world:

$$\mathrm{PHI} = (S \cdot E \cdot C \cdot L)^{1/4} \quad (5)$$

The PHI is the geometric mean of separate values related to the presence of a stable substrate (S), available energy (E), appropriate chemistry (C), and a liquid solvent (L) on the world of interest. The parameters relevant for constructing a metric for each of these variables, and the way in which those parameters could be measured or detected from Earth at a distance many light years away, will be considered individually.

3.1. Substrate (S)

Life appears to thrive particularly at discrete interfaces (Norde, 2003), which occur most notably on rocky

Table 2. Data and Calculations for the Determination of the ESI, as Applied to Selected Solar System Planets and Satellites, and Exoplanets

Planet	*Radius (EU)*	*Density (EU)*	*Escape velocity (EU)*	*Surface temperature (K)*	*Interior ESI*	*Surface ESI*	*Global ESI*
Earth	1.00	1.00	1.00	288	1.00	1.00	1.00
Mars	0.53	0.71	0.45	227	0.82	0.60	0.70
Mercury	0.38	0.98	0.38	440	0.84	0.42	0.60
Moon	0.27	0.60	0.21	220	0.67	0.46	0.56
Venus	0.95	0.95	0.93	730	0.98	0.20	0.44
Io	0.29	0.64	0.23	130	0.69	0.19	0.36
Callisto	0.38	0.33	0.22	134	0.58	0.20	0.34
Jupiter	10.97	0.24	5.38	152	0.36	0.24	0.29
Ganymede	0.41	0.35	0.25	110	0.60	0.14	0.29
Ceres	0.08	0.36	0.05	167	0.41	0.18	0.27
Europa	0.25	0.55	0.18	102	0.64	0.11	0.26
Saturn	9.14	0.12	3.23	134	0.28	0.22	0.25
Titan	0.40	0.34	0.24	94	0.59	0.10	0.24
Uranus	3.98	0.23	1.91	76	0.46	0.077	0.19
Neptune	3.87	0.30	2.11	72	0.51	0.067	0.18
Titania	0.12	0.31	0.07	60	0.43	0.025	0.10
Enceladus	0.04	0.31	0.02	75	0.32	0.028	0.094
Pluto	0.18	0.37	0.11	40	0.51	0.011	0.075
Triton	0.21	0.38	0.13	38	0.54	0.010	0.074
GJ 581 g	$\geq$1.36	1.22	1.51	277	0.90	0.88	0.89
GJ 581 b	$\geq$3.97	0.25	1.98	499	0.47	0.36	0.41
GJ 581 c	$\geq$1.60	1.36	1.87	380	0.85	0.58	0.70
GJ 581 d	$\geq$1.60	1.36	1.87	232	0.85	0.64	0.74
GJ 581 e	$\geq$1.16	1.10	1.21	591	0.95	0.30	0.53
GJ 581 f	$\geq$2.16	0.70	1.80	139	0.79	0.27	0.46
HD 69830 d	4.19	0.25	2.10	312	0.47	0.77	0.60
55 Cnc c	5.68	0.25	2.84	310	0.43	0.72	0.56

EU = Earth Units, where Earth's radius is 6371 km, density is 5.51 g/cm^3, and escape velocity is 11.19 km/s.

and icy planetary bodies. Habitability is further favored on substrates that are protected from shortwave radiation by an atmosphere (Frederick and Lubin, 1988) and from excessive charged particle radiation by a magnetosphere (Curtis and Letaw, 1989).

Solid surfaces. A solid substrate promotes habitability by providing a larger degree of stability, a higher density of chemical compounds, a surface for chemical reactions, and, for life beneath the surface, protection from various types of radiation. Rocky planets provide interfaces between their solid features and any liquids or atmospheres that may be present. Planets with frozen layers in contact with atmospheres and liquids also provide an interface where organisms and nutrients can be concentrated in a two-dimensional plane. Solid planetary cores with sufficient density to generate internal heat from radioactive decay favor habitability because plate tectonics recycles elements essential for a regenerative biosphere (Kasting 1993; Sundquist, 1993). Also, on Earth-like planets, geochemical recycling of carbon by tectonic processes is generally considered essential for stabilizing the planetary climate against variations in stellar luminosity (Kasting and Catling, 2003). Thus, habitability correlates positively with solidity, which can be predicted from density values derived from measurement of size and mass. We assign a value of 1 for the presence of either a rocky or frozen substrate.

Atmosphere. The presence of an atmosphere promotes habitability by protecting the surface from biologically damaging shortwave radiation, stabilizing surface liquids by way of a greenhouse effect in planets with global equilibrium temperatures below the freezing point, shielding surface liquids against photolysis, maintaining barometric pressure against boiling, and perhaps allowing an exchange medium for gaseous metabolites (Frederick and Lubin, 1988; Kasting and Siefert, 2002; Lammer *et al.*, 2010). Except for runaway greenhouse gases, an atmosphere, through its general radiative structure, also provides a tropopause cold trap, which prevents loss of water through upward transport followed by photolysis and escape of hydrogen to space (Catling and Kasting, 2007). Depending on its composition and mass, the amount and nature of stellar radiation admitted, reflected, and retained can be predicted to a first approximation, further defining the characteristics of the biosphere and the stability of the surface. Evaluating the dimensions of an atmosphere on many exoplanets should be within the capability of the TPF and can be aided as well by albedo measurements with enhanced imaging technologies. Long-term photometric observations of transiting exoplanets that sample many phases of its eclipse can be used to determine the planetary bond albedo (Rowe *et al.*, 2008; Cowan and Agol, 2011). We assign a value of 0.1, 0.5, or 1.0, depending on the presence of a trace, thin, or dense atmosphere, respectively.

Magnetosphere. Magnetic fields promote habitability on terrestrial surfaces by deflecting harmful radiation and provide a source of energy that theoretically could be harvested by living organisms, though the yield of free energy would

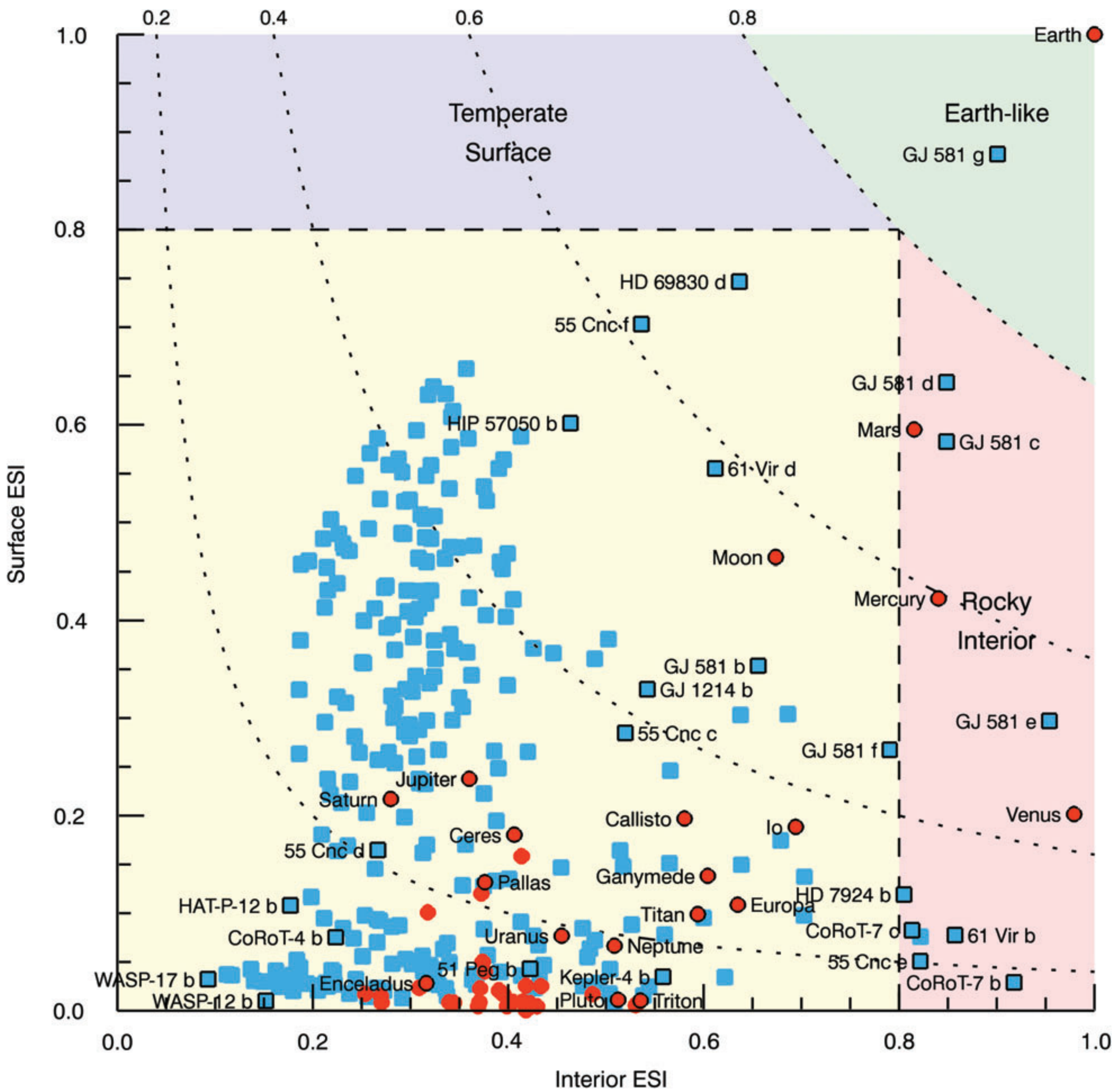

FIG. 1. Earth Similarity Index (ESI) for 47 Solar System bodies with radius greater than 100 km (red circles) and 258 extrasolar planets (blue squares). Only some of the most notable bodies are labeled. The ESI scale makes a distinction between those rocky interior (light red area) and temperate surface (light blue area) planets. Only planets in these two categories can be considered Earth-like planets (light green area). The dotted lines represent constant ESI values. If confirmed, only Gliese 581 g is in the Earth-like category together with Earth. Color images available online at www.liebertonline.com/ast

be extremely small (Schulze-Makuch and Irwin, 2008; Lammer *et al.*, 2010). Thus, the presence of a magnetic field should correlate positively with habitability. The ability to measure magnetospheres at great distances may be challenging for the near future, though promising techniques have been proposed recently (*e.g.*, Ekenbäck *et al.*, 2010; Vidotto *et al.*, 2010). We assign a value of 0.5 or 1.0, depending on the presence of a moderate or strong magnetosphere, respectively.

3.2. Energy (E)

We have shown that, for planetary bodies in reasonable proximity to a sun and those on which cyclic oxidation-reduction chemistry is possible, sunlight and chemistry are the most effective sources of free energy for driving biological processes (Irwin and Schulze-Makuch, 2001; Schulze-Makuch and Irwin, 2004; Schulze-Makuch and Grinspoon, 2005). While heat is probably the most commonly available source of energy in the Universe, free energy yields from thermal gradients are inefficient and non-regenerative (Schulze-Makuch and Irwin, 2008). Nonetheless, heat is a key contributor to habitability through the effects of temperature on living components and processes. A common source of heat on solid bodies is tidal flexing, because cyclic variations in the effects of gravity generate kinetic energy and recycle materials between the surface and the interior. Hence, tidal flexing could be a significant contributor to habitability in its own right.

Light. The stellar flux received by a planet is an inverse function of the square of the distance of that body's orbit from its central star and depends further on the luminosity of the star. We assume that light up to a distance of 2.5 AU from our Sun can support photosynthesis well and that photosynthesis can be driven to some degree at distances at least up to 10 AU (Wolstencroft and Raven, 2002). We therefore assign values of 2, 1, and 0 respectively to planets up to 2.5, 10, and beyond 10 relative AU, where the relative AU distance for a planet in another system is adjusted for the luminosity of its central star.

Heat. On worlds where more efficient forms of energy are not available, heat could be harvested directly for living processes (Muller, 1995; Schulze-Makuch and Irwin, 2008). But even where heat is not the primary bioenergetic source, it factors into the habitability of the environment, since very low temperatures dampen the rate of chemical reactions, while temperatures too high destabilize the complex molecules on which living processes depend. We thus assign a value of 1 to bodies on which the mean surface temperature lies between 200 and 400 K. Surface temperatures should be detectable on planets such as Mars or Earth, where there are atmospheric windows that allow surface emission to be seen remotely. For thick, opaque atmospheres, such as on Venus, the remote spectrum is characteristic of temperatures at altitude, and surface radiation generally cannot get through directly to space. On Venus, near-infrared windows between 0.8 and 2.5 μm have surface emission contributions only on the nightside (Meadows and Crisp, 1996; Mueller *et al.*, 2008), but these would be too narrow and too low in flux to detect at an interstellar distance.

Redox chemistry. Spectrophotometry can detect a sufficient variety of compounds to indicate whether energy-yielding reactions in a regenerative cycle would be possible. The TPF should be able to provide this information (Schindler and Kasting, 2000).

Tidal flexing. This major source of internal heating is significant wherever orbital trajectories introduce cyclic variations in gravitational interactions between a planet and its central sun(s), other planets, or satellites. It can be predicted from the mass, orbital characteristics, and proximity of the world in question to other planetary bodies and its central star(s). An important consideration is whether an exoplanet or exomoon might be tidally locked, likely a common occurrence for planets around M stars due to the smaller distance to their central star. Prospects for habitability are expected to be lower on tidally locked planetary bodies since benign enough environmental conditions might only occur in a small sliver of the planetary surface that separates extremely hot and light conditions on one side from cold and dark conditions on the other side of the body. On the other hand, Joshi *et al.*, (1997) showed that atmospheric circulation can transfer heat to the dark side of a tidally locked planet around an M star and widen the area of habitability. Remote sensing techniques, such as direct observations targeted to compute the rotation rate of planets from light curves (*e.g.*, Pallé *et al.*, 2008; Kawahara and Fujii, 2010), should allow for determination of whether a planet is within a tidally locked zone.

3.3. Chemistry (C)

Polymeric chemistry appears to be an essential requirement for life (Westall *et al.*, 2000). For a variety of reasons, carbon has the most desirable chemical properties and molecular bonding characteristic for the formation of biopolymers (Schulze-Makuch and Irwin, 2008). The flexibility of carbon is enhanced considerably by its ability to form covalent bonds with other common elements essential to biological systems—in particular nitrogen, sulfur, and phosphorus—as well as oxygen (Pace, 2001). Silicon can also form polymers, though these tend to be either too stable or too unstable over a great range of temperatures at which carbon polymers are stable but not inflexible. At very low or very high temperatures, some silicon-based polymers could be effective, and organosilicates are a known component of living systems (Bains, 2004; Benner *et al.*, 2004; Schulze-Makuch and Irwin, 2004).

The chemical composition of distant bodies should eventually be detectable through spectrophotometry (Schindler and Kasting, 2000). The detection of organic compounds, including organosilicates or silicon polymers, is a positive indicator of the possibility that biomolecules can exist. We assign a value of 2 for the known presence of polymeric molecules, 1.5 for the presence of organic molecules in abundance, 1 for detectable organic molecules other than atmospheric gases, and 0.5 for trace or suspected amounts of organic compounds, including atmospheric gases.

The presence of nitrogen, sulfur, and phosphorus further enhances the probability of organic heteromolecules, which makes the presence of complex chemistry more likely. We assign a value of 1 for the detectable presence of any molecules containing one of these atoms.

3.4. Liquids (L)

The presence of liquids—in the atmosphere, on the surface, or beneath the surface—is a function of chemistry, pressure, and temperature.

If clouds are detected by direct imaging, information on their chemical content and temperature, along with pressure deduced from planetary mass, can suggest what liquids might be airborne in the atmosphere. A general contribution of clouds to the signal may be discernable (Pallé *et al.*, 2008; Cowan *et al.*, 2009), if a planet's broadband visible spectrum can be recorded with a time resolution better than $\sim 1/10$ of its rotation period.

Temperature and pressure values, along with chemical information, can also suggest the possibility of liquids on the surface. It was deduced, for instance, that liquid hydrocarbons probably existed stably on the surface of Titan (Lunine *et al.*, 1983), before they were confirmed by direct radar imaging (Campbell *et al.*, 2003). It may also be possible to use direct imaging to detect surface liquids on exoplanets.

Subsurface liquids are more difficult to detect. Techniques such as asynchronous rotation of magnetic fields with planetary rotation, as used to infer the presence of subsurface oceans on icy satellites like Europa (Anderson *et al.*, 1998), may be tricky to apply at a great distance. Geysers, as observed on Enceladus (Porco *et al.*, 2006), give evidence of subsurface liquids, but they too may be difficult to detect by direct imaging until telescopes become much more powerful. Indirect inference from data on density, chemical composition, surface temperature, and, if possible, surface pressure may be the best hope for estimating the possibility of subsurface liquids.

We assign a value of 1 for liquids known or inferred to be present on the surface or within the subsurface. For atmospheres known to hold droplets of liquid, we assign a lesser value of 0.5, on grounds that liquid droplets in the atmosphere could host living organisms but present a greater challenge to habitability than standing liquids on the surface or beneath it.

3.5. Calculation of the PHI

Within each parameter category—for substrate, energy, chemistry, and liquids, respectively—the values assigned to each parameter are summed to give the value that will be substituted into Eq. 5:

$$\mathrm{PHI_{rel}} = (\mathrm{PHI}/\mathrm{PHI_{max}}) \tag{6}$$

Dividing by the maximum value that could be obtained normalizes the PHI to a scale between 0 and 1.0. Values assigned for planets and satellites in our Solar System, along with several exoplanets to the extent of our current knowledge, are given in Table 3.

4. Discussion

The ultimate mission of astrobiology is the search for life on other worlds. In this paper, we argue that such a search can be distinguished by two strategies. The first is a search for planets similar to Earth, on grounds that life as we know it is most likely to be found on a planet like our own. The second is consideration of life as it could exist in either known or unknown forms, whether or not on planets like our own. We have proposed two different indices—an Earth Similarity Index (ESI) for the first and a Planetary Habitability Index (PHI) for the second.

The ESI is based on planetary parameters that can easily be determined via remote sensing. It can thus be calculated for most of the exoplanets detected to date. It does have some important limitations, however. Many exoplanet masses are only established as minimum values. Higher values will generally decrease the ESI values. We used equilibrium temperatures for exoplanets in the absence of surface temperatures. The equilibrium temperatures were calculated assuming a bond albedo of 0.3, which is typical of planets in the Solar System but is unknown for exoplanets. Actual surface temperatures also depend on the greenhouse effect and will significantly change the ESI numbers.

Note that the ESI can only be used to compare planetary bodies with Earth, not with one another. For example, the ESI values for Mars and Gliese 581 c are very close, but this does not necessarily mean that they are similar—only that they are equivalently dissimilar from Earth, just as northern and southern latitudes can vary to the same magnitude but in opposite directions. Thus, Mars and Gliese 581 c are equally dissimilar from Earth but for very different reasons: one is much bigger and hotter, the other much smaller and colder.

The extension of the ESI formulations to other planetary parameters in future work would be straightforward. Other scales could be constructed for assessing the similarity between ocean-like or Jupiter-like planets in a similar way by using appropriate reference values and weighted exponents. The presence or abundance of biologically relevant gases such as water vapor, oxygen, methane, carbon dioxide, and nitrogen could be used to further constrain the index calculations. Also, other important planetary parameters such as a magnetic field, internal differentiation, and plate tectonics could also be included into an expanded ESI formulation.

It must be noted that the ESI implies only one type of habitability—the type we are most familiar with on our home planet. Habitability in a wider sense is not necessarily restricted to water as a solvent or to a planet circling a star. For example, the hydrocarbon lakes on Titan could host a different form of life (McKay and Smith, 2005; Schulze-Makuch and Grinspoon, 2005; Shapiro and Schulze-Makuch, 2009). Analog studies in hydrocarbon environments on Earth, in fact, clearly indicate that these environments are habitable in principle (Marcano *et al.*, 2002; Ali *et al.*, 2006, Schulze-Makuch *et al.*, 2011). Orphan planets wandering free of any central star could likewise conceivably feature conditions suitable for some form of life (Debes and Sigurðsson, 2007).

Thus, when evaluating habitability on exoplanets, terracentric thinking needs to be avoided. The disadvantage of this approach is that it is intrinsically more speculative. The alternative, however, to miss habitable worlds due to restricted assumptions would be self-defeating. Our proposed PHI is informed by chemical and physical parameters that are conducive to life in general. It relies on factors that, in principle, could be detected at the distance of exoplanets from Earth, given currently planned future (space) instrumentation. And like the ESI, its value is cumulative, in the sense that it can be updated and refined as new information is obtained. Indeed, the relative PHI values for several of the exoplanets in Table 3 will probably rise as more information becomes available.

We emphasize that the values presented here are not intended to be viewed either as absolute probabilities or as definitive conclusions about either planetary similarity or habitability. Rather, our intention is to suggest a template for evaluating both. We give the values that we have assumed in making our calculations. Other investigators may substitute their own values for alternative estimates. As new and better information becomes available, the calculations can and should be updated.

The value of indices is further increased if the data set to which they refer can be simply and easily expressed in graphic form. A plot of the surface ESI versus the interior ESI provides an overview of the extent to which other Solar System bodies and a large number of exoplanets resemble Earth, and how they do so (Fig. 1). Objects that lie further to the right more nearly resemble Earth's rocky nature, while those that plot higher on the graph have surface temperatures closer to Earth's. Note that only Gliese 581 g falls into the Earth-like category. However, the existence of Gliese 581 g still needs to be independently confirmed after its apparent initial discovery by Vogt *et al.* (2010), as later reanalysis of the discovery data suggests that Gliese 581 g does not exist (Tuomi, 2011). It will be interesting to see where the

Table 3. Factors That Affect the Probability That Life Could Exist on Any Planetary Body, as Applied to Planetary Bodies and Satellites in Our Solar System and to Selected Exoplanets

	Substrates			Energy				Chemistry				Liquids				
Body	*Solid or Frozen*	*Atmosphere*	*Magnetosphere*	*Light*	*Heat*	*Redox chemistry*	*Tidal flexing*	C_{org}	*N*	*S*	*P*	*Atmospheric*	*Surface*	*Sub-surface*	*PHI*	PHI_{rel}
Mercury	1	0	0.1	2	0	0	0	0	0	1	0	0	0	0	0.00	**0.00**
Venus	1	1	0	2	0	1	0	0.5	1	1	0	0.5	0	0	1.65	**0.37**
Earth	1	1	1	2	1	2	0.2	2	1	1	1	0.5	2	1	4.37	**0.96**
Moon	1	0	0	2	0	0	0.2	0	0	1	0	0	0	0	0.00	**0.00**
Mars	1	0.5	0	2	1	1	0	0.5	0	1	1	0	1	1	2.66	**0.59**
Ceres	1	0	0.1	1	0	0.5	0	0.5	1	0	0	0	0	0.5	1.05	**0.23**
Jupiter	0	1	1	1	0	1	0	1	1	1	1	0.5	0	0	1.68	**0.37**
Io	1	0.1	0.5	1	0	1	1	0.5	0	1	0	0	0.5	0	1.38	**0.30**
Europa	1	0.1	0.5	1	0	0.5	1	0.5	1	1	0	0	0.5	1	2.22	**0.49**
Saturn	0	1	1	1	0	1	0	1	1	1	1	0.5	0	0	1.68	**0.37**
Titan	1	1	1	1	0	1	0	1.5	1	0	0	0.5	2	1	2.89	**0.64**
Enceladus	1	0.1	0	1	0	0.5	0.5	0.5	1	0	0	0	1	1	1.60	**0.35**
Uranus	0	1	1	0	0	1	0	1	1	0	0	0.5	0	0	1.19	**0.26**
Titania	1	0	0	0	0	0.5	0.5	0.5	1	0	0	0	0	0.5	0.93	**0.21**
Neptune	0	1	1	0	0	1	0	1	1	0	0	0.5	0	0	1.19	**0.26**
Triton	1	0.1	0.1	0	0	0.5	0	1	1	0	0	0	0.5	0.5	1.05	**0.23**
Pluto	1	0	0	0	0	0.5	0	1	1	0	0	0	0	0.5	1.00	**0.22**
GJ 581 b	0	1	1	2	0	?	1	?	1	?	?	0.5	0	?	1.19	**0.29**
GJ 581 c	1	1	1	2	1	?	1	?	1	?	?	0.5	0.5	?	1.73	**0.41**
GJ 581 d	1	1	1	2	1	?	0.5	?	1	?	?	0.5	0.5	?	1.57	**0.43**
GJ 581 g	1	1	1	2	1	?	1	?	1	?	?	0.5	1	?	1.73	**0.45**
HD69830 d	0	1	1	2	1	?	0	?	1	?	?	0.5	0	?	1.32	**0.29**
55 Cnc c	0	1	1	1	0	?	1	?	1	?	?	0.5	0	?	1.32	**0.26**
MAX	1	1	1	2	1	2	1	2	1	1	1	0.5	2	1	4.53	**1.00**

The PHI is calculated from Eq. 5 and divided by the theoretically maximum PHI (derived from values in the bottom line) to give a relative PHI (PHI_{rel}, Eq. 6), shown in the rightmost column in bold.
Substrate: solid (rocky) or frozen; present = 1, absent = 0.
Atmosphere: dense = 1, thin = 0.5, trace = 0.1.
Magnetosphere: strong = 1, moderate = 0.5, little or none = 0.
Light: based on equivalent AU (adjusted to luminosity of central star); equivalent AU of 0–2.5 = 2, equivalent AU of 2.5–10 = 1, equivalent AU > 10 = 0.
Heat: average surface temperature of 200–400 K = 1.
Redox chemistry: presence of oxidant and reducer = 1, suspected presence = 0.5, clear abundance of both = 2.
Tidal flexing: severe = 1, substantial = 0.5, small effect = 0.2.
Organics: presence of complex organic molecules (biomarkers) = 2, presence of organic compounds in abundance = 1.5, detectable = 1, or in trace or suspected amounts = 0.5.
Compounds of N, S, P: known to be present = 1.
Liquids, atmospheric: liquids possible at known temperatures in atmosphere = 0.5.
Liquids, surface: known to be present = 2, known to be emitted or transiently present = 1, possibly present = 0.5.
Liquids, subsurface: liquid solvents beneath the surface; known or likely to be present = 1, possibly present = 0.5.

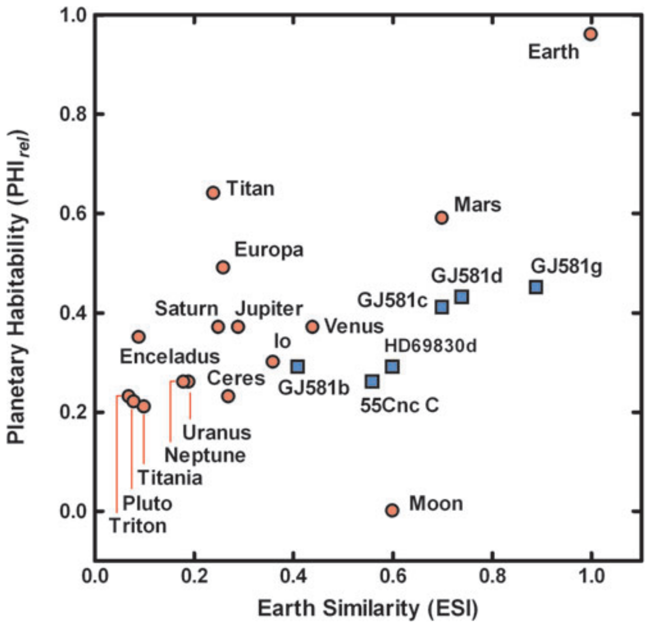

FIG. 2. Values for the global ESI and the relative PHI of Solar System bodies (red circles) and selected exoplanets (blue squares). Color images available online at www.liebertonline.com/ast

candidate planets recently detected by the Kepler mission will fall on the ESI scale.

Planetary similarity to Earth and potential for habitability are shown by plotting the ESI and the relative PHI on two axes of the same graph in Fig. 2. Thus Earth, which has an ESI of 1 by definition and the highest PHI, lies in the upper right of the graph, at or near the maximum point on both the x and y axes. Mars and the planets of the Gliese 581 system that appear to be most similar to Earth likewise plot to the right on the ESI axis but well below Earth on the PHI axis. Titan and Europa have less similarity to Earth than Venus, but their potential for habitability is greater than that for Venus and, in the case of Titan, even than for Mars.

Some interesting anomalies are also apparent in Fig. 2. First, the PHI values for the gas giants are surprisingly large, which reflects their abundance of energy and organic constituents. While the origin of life on gas giant planets lacking a solid substrate is problematic, the possibility cannot totally be excluded. In the case of Jupiter, life originating elsewhere, as for example on Europa early in its history, could have been transported to the atmosphere of a gas giant where the abundant sources of energy and organic chemistry may have provided for sustained viability at appropriate levels in its cloud layers. The plausibility of life reaching the gas giants and surviving in their atmospheres is discussed by Irwin and Schulze-Makuch (2011, Chapter 7). Though the chances for life within a gas giant seem very remote, current knowledge does not let us conclude that the PHI of a gas giant should be zero.

Second, the PHI for Venus is also surprisingly high, given the consensus view that life on or beneath the surface is extremely unlikely on such a hot planet. However, liquid droplets at benign temperatures in the upper cloud layers could harbor microscopic forms of life, evolved from ground-dwelling organisms earlier in the planet's history (Grinspoon, 1997; Schulze-Makuch *et al.*, 2004; Irwin and Schulze-Makuch, 2011). This points to the fact that planetary history should be an integral part of any calculation for the probability of life, if that history could be determined. It is also interesting to note that current Earth has not a perfect PHI of 1.0 but a PHI of 0.96. Tidal flexing was much more dominant in early Earth history, at a time when the origin of life likely occurred on our planet. More stark are the differences in PHI between current and ancient Mars, which was exposed to much more liquid water in its past, more than 4 billion years ago, than it is today (not shown). Again, this reiterates the point that the history of a planet is critical to the presence of life. If we base the PHI on current Mars conditions only (as we have done), we may underestimate its ability to host life. In regard to exoplanets, this critical piece of information will likely remain unknown for a long time. Perhaps at least the age of the exoplanets, based on the apparent age of their central stars, should be considered, though we have not done so in this initial proposal.

Third, the PHI is surprisingly higher for Titan than it is for Europa, largely on the basis of confirmed organic chemistry, surface liquids, and an atmosphere on the former. Any life that might exist on Titan, however, would most likely differ more greatly from life as we know it than would any life that might be found on Europa. This reinforces the point that life need not necessarily be expected to fall within a "habitable zone" of Earth-like conditions.

Whether these anomalies call into question the underlying assumptions on which our calculations are based or point to new ways of thinking about the distribution of life in the Universe is a matter to be decided ultimately by more and better data. In the meantime, seeming anomalies such as these can serve to question our intuitive opinions about habitability, as well as prompt us to reexamine the strategy on which the indices are based.

5. Conclusions

The two-tier classification scheme offered here proposes an Earth Similarity Index (ESI), which provides a quick screening tool with which to detect exoplanets most similar to Earth, and an independent Planetary Habitability Index (PHI), which attempts to rate the probability that life of some form could exist on any given world. These two indices represent a first attempt to categorize the many exoplanets and exomoons that are expected to be discovered in the near future with regard to their potential for harboring life. These metrics are clearly useful only in direct proportion to the quality of information we have for exoplanets. As technology improves, the values generated by the indices proposed here will likely rise and become more realistic, until direct evidence for life on other worlds confirms their utility in the future. Meanwhile, as information on more exoplanets and exomoons accumulates, perhaps the point will be reached at which a sufficiently large sample of extrasolar bodies can be evaluated for potential habitability to make possible a more accurate assessment of the overall distribution of life in the Universe.

Appendix A. Sample Calculation for Mars

A.1. ESI_x—calculations using Equation 1

$$ESI_r = (1 - |3376.63\ \text{km} - 6371\ \text{km}| / |3376.63\ \text{km} + 6371\ \text{km}|) = 0.6928$$

$$r_{Mars} = 0.53 \times 6371 \text{ km} = 3376.63 \text{ km}$$

$$ESI_{\rho} = (1 - |3.9121 \text{ g/cm}^3 - 5.51 \text{ g/cm}^3| / |3.9121 \text{ g/cm}^3 + 5.51 \text{ g/cm}^3|) = 0.8304$$

$$\rho_{Mars} = 0.71 \times 5.51 \text{ g/cm}^3 = 3.9121 \text{ g/cm}^3$$

$$ESI_{v_e} = (1 - |0.45 - 1\ | / |\ 0.45 + 1|) = 0.6207$$

$$v_{e_{Mars}} = 0.45 \text{ EU} \quad (\text{calculation done in Earth Units})$$

$$ESI_{T_S} = (1 - |227 \text{ K} - 288 \text{ K}\ | / |\ 227 \text{ K} + 288 \text{ K}|) = 0.88155$$

$$T_{S_{Mars}} = 227 \text{ K}$$

A.2. Calculation of ESI_I using Equation 2

$$ESI_I = (0.6928^{0.57} \times 0.8304^{1.07})^{0.5} = 0.8154 \sim 0.82$$

A.3. Calculation of ESI_S using Equation 3

$$ESI_S = (0.6207^{0.70} \times 0.88155^{5.58})^{0.5} = 0.5953 \sim 0.60$$

A.4. Calculation of the global ESI using Equation 4

$$\text{Global ESI} = (0.8154 \times 0.5953)^{0.5} = 0.6967 \sim 0.70$$

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Abbreviations

ESI, Earth Similarity Index; PHI, Planetary Habitability Index; TPF, Terrestrial Planet Finder.

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Address correspondence to:
Dirk Schulze-Makuch
School of Earth and Environmental Sciences
Washington State University
P.O. Box 642812
Pullman, WA 99164-6376
USA

E-mail: dirksm@wsu.edu

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