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After the Habitable Zone

R. Barnes[1], R. Luger[2], H. Smotherman[1], R. Deitrick[3], and D.P. Fleming[1]

[1] Astronomy Department, University of Washington, Box 351580, Seattle, WA 98195-1580, USA, e-mail: rory@astro.washington.edu
[2] Center for Computational Astrophysics, Flatiron Institute, 162 5th Ave., New York, NY 10010, USA
[3] Center for Space and Habitability, University of Bern, Gesellschaftsstrasse 6 (G6), CH-3012, Bern, Switzerland

Abstract. All life on Earth requires liquid water, and hence the search for life beyond Earth begins with the search for stable water on the surface or in the interior of a planet or moon. The habitable zone (HZ) is traditionally defined as the region around a star in which the Earth could retain surface water based on incident stellar radiation (instellation). A terrestrial-like planet, i.e. one without a significant hydrogen envelope, in the HZ may support a surface water layer and may also support life.
However, other effects can supersede the role of current incident flux and render a planet in the HZ uninhabitable. Examples include, but are not limited to, tidal heating into a runaway greenhouse, desiccation by early high-luminosity phases, and large-amplitude eccentricity cycles induced by companion planets. With the discovery of terrestrial planets in the HZ of nearby stars, a revised and inclusive model of planetary habitability must be developed to provide robust interpretation of the history of habitable and inhabited exoplanets. We conclude with a brief description of a new computational tool, `VPLanet`, that provides a framework to couple the phenomena that affect the stability and longevity of liquid water in planetary environments.

1. Introduction

Life has been found in the boiling hot springs of Yellowstone (Brock 1978), 1 mm-wide brine tunnels in sea ice (Junge et al. 2004), near hydrothermal vent systems in the deep ocean (Corliss et al. 1979), and in driest desert on Earth, the Atacama (Navarro-Gonzalez et al. 2003). Life has been found at pressures up to 1100 bar, temperatures from -15 to +122 °C, and for water activity levels > 0.6 (McKay 2014). The diversity and resilience of Earth-based life was an important realization that underpins the new science of astrobiology because it suggests life may be found on worlds in conditions that humans might describe as "extreme". In other words, it instills confidence that life could be common in the universe.

Despite the diversity of inhabited ecosystems, all known life on Earth requires liquid water, power, and the bioessential elements C, H, N, O, P, and S (and probably Fe). The earliest evidence for life dates to 1 Gyr after the Earth formed (Schopf et al. 2007), but it may have formed within just a few hundred million years (Bell et al. 2015). Based on Earth-based life then, astronomers and astrobiologists should look for planets and moons that can colocate the essential ingredients in environments that remain within the pressure and temperature limits for at least 1 billion years.

Astronomers have scanned the Galaxy and found that the bioessential elements are some of the most plentiful, with P the least common but still the 13th most abundant element overall. Energy is also readily available in quasi-steady amounts over billions of years from stars. The water molecule is the third most abundant molecule in the Galaxy, but the liquid phase is confined to a narrow temperature range. From these general observations, the presence of liquid water is likely to be the limiting resource for biology from a cosmic perspective, and we may define a "habitable" planet to be one in which liquid water with an activity above 0.7 is present for at least 1 Gyr. With this definition, Earth, early Mars, and several icy satellites of the giant planets possess habitable environments; life *could* emerge on any of them and did on Earth.

The discovery of exoplanets renewed interest in the search for life beyond the Solar System. With only one known inhabited planet, Earth, our search is guided by its properties, directing scientists toward planets that have masses, radii, and incident stellar radiation (instellation) levels similar to Earth. A key concept in this search is the habitable zone (HZ), defined to be the shell around a star in which a terrestrial planet can maintain surface temperatures in the range for liquid water (Dole 1964; Hart 1979; Kasting et al. 1993; Kopparapu et al. 2013). Crucially, the HZ represents where a planet *might* possess habitable surface conditions as determined by current instellation — the actual composition and surface conditions are not currently known. Nonetheless, in our Solar System, surface temperature appears to be a strong function of the incident solar radiation (insolation) as demonstrated by the Earth-Venus dichotomy. Therefore, the HZ is a valuable starting point in the search for habitable worlds as it probably encapsulates the primary driver for surface habitability.

The discussion of habitable exoplanets is no longer hypothetical: exoplanets with Earth-like masses, radii, and instellations are now being discovered (e.g. Borucki et al. 2013; Quintana et al. 2014; Anglada-Escudé et al. 2016; Dittmann et al. 2017; Zechmeister et al. 2019), and some may be amenable to atmospheric spectroscopy by the *JWST* (e.g. the TRAPPIST-1 planets; Gillon et al. 2017; Luger et al. 2017; Lincowski et al. 2018; Lustig-Yaeger et al. 2019). While several TRAPPIST-1 planets are in the HZ, their habitability may depend on much more than current instellation levels. As the HZ does not include second order effects that can be especially important for planets orbiting the very late M dwarf stars that are most accessible to *JWST* spectroscopy, the community must develop new models of habitable planet evolution that include many or all of the processes that affect habitability. In this chapter we review the HZ, highlight some phenomena that can destroy habitability, and describe a new model of planetary evolution that can create a comprehensive model of exoplanet habitability.

2. The Habitable Zone

The term *habitable zone* as used for the last 25 years (Kasting et al. 1993) focuses specifically on surface habitability, i.e. the water layer is in contact with the atmosphere. There are two important reasons why this definition is valuable: 1) it is the Earth's structure, and 2) any putative biosphere is also in contact with the atmosphere and hence biosignatures (observations that unambiguously reveal the presence of current or past life) may also be present in the atmosphere. Thus, the HZ is not just about habitability, but also detectability. And it's not just about detecting habitability, it's about detecting inhabitance. This marriage of a quantitative model of habitability to life detection is a central reason why the HZ has been such a powerful concept. As we move beyond the HZ, this connection should be maintained.

Traditionally the HZ has been calculated via 1-D photochemical/climate models, e.g. `ATMOS` (Kasting et al. 1993), in which the radiative transfer in atmospheric layers is calculated and the chemical composition adjusted by photolysis and recombination until the entire atmosphere reaches radiative and chemical balance. If the surface temperature is within the range of liquid water, then the planet is in the "habitable zone." This approach also produces the atmospheric composition as a function of altitude, and the output may then be used to interpret observations, a process often called "retrieval." As the modern and Archean Earth atmospheres contain(ed) biosignatures, the output can also be used to search for life as well.

Although powerful, the HZ does suffer from several shortcomings. First, it does not include all phenomena that affect habitability, including, but not limited to, stellar evolution (Luger & Barnes 2015), flaring and stellar activity (Segura et al. 2010; Garraffo et al. 2016; Airapetian et al. 2019), tidal heating (Barnes et al. 2013; Driscoll & Barnes 2015), orbital oscillations from other planets (Armstrong et al. 2014; Deitrick et al. 2018a), and even perturbations from passing stars (Kaib & Raymond 2014; Barnes et al. 2016). See Meadows & Barnes (2018) for more discussion on the factors affecting habitability.

Second, it does not include planets with subsurface biospheres that could pollute their atmospheres with biosignatures. Water-rich exoplanets may have water layers below a permeable ice crust, allowing biosignature gases to collect in the atmosphere.

Third, it cannot be used to predict the probability that a planet is habitable. Planets are either in the HZ or not. This last limitation is becoming an ever bigger issue as astronomers discover water on planets in the HZ, such as K2-18 b (Benneke et al. 2019; Tsiaras et al. 2019). As astronomers obtain more and more data on 1–2 $R_\oplus$ planets, we can begin to ask the question of habitability in a statistical sense: What is the *likelihood* that a given planet has liquid water? Only after the unification of these three features with the current HZ model will scientists possess the framework to robustly analyze exoplanet data in terms of habitability.

As described in Meadows & Barnes (2018), habitability may be conveniently divided into three categories: the role of the star, the role of the planetary system, and the role of the planet itself. These three components can all change the surface conditions of a planet through radiative and compositional surface fluxes. Some processes, such as those due to internal processes, are extremely difficult to constrain and will require huge resources to resolve (see e.g. Barnes et al. 2018).

3. Additional constraints on habitability

In this section, a few processes that are not part of the HZ model but nonetheless affect habitability are presented to motivate a comprehensive model of habitability. Stellar evolution can significantly change a star's luminosity over time (Hayashi 1961; Baraffe et al. 2015), and hence change a planet's instellation. Very low mass stars can require over 1 Gyr to reach the main sequence and during that time they are more luminous than their main sequence luminosities (Baraffe et al. 2015). This process causes the HZ to move inward in time, and planets that are in the main sequence HZ may have spent a long time interior to the HZ (e.g. Luger & Barnes 2015). An example of this process is shown in Fig. 1. In this case, the luminosity evolution comes from Baraffe et al. (2015), the XUV luminosity from Reiners et al. (2014) and Ribas et al. (2005). The HZ limits are from Kopparapu et al. (2013).

The bottom panels show the effect of atmospheric escape assuming it is energy-limited (Watson et al. 1981). When the planet is interior to the HZ, water may reach the stratosphere where it is photolyzed and the hydrogen may escape. Thus, water is destroyed and planets may become desiccated and sterile. This process can also result in the accumulation of oxygen in the atmosphere, if sinks are not available to absorb it all (Luger & Barnes 2015).

Close-in exoplanets are also subject to tidal heating, which is spectacularly displayed on Io (Strom et al. 1979), and planets orbiting M dwarfs may be subjected to strong tidal heating (Jackson et al. 2008; Barnes et al. 2009, 2013; Driscoll & Barnes 2015). When considering tidal heating, several benchmarks are relevant: Earth's (non-tidal) surface flux is ~ 0.08 W/m^2, Io's is approximately 2.5 W/m^2 (Veeder et al. 2015), and a runaway greenhouse begins at about 300 W/m^2 (Kasting et al. 1993; Abe 1993). In Fig. 2, the surface heat flux of a 1 Earth-mass, 1 Earth-radius planet with the

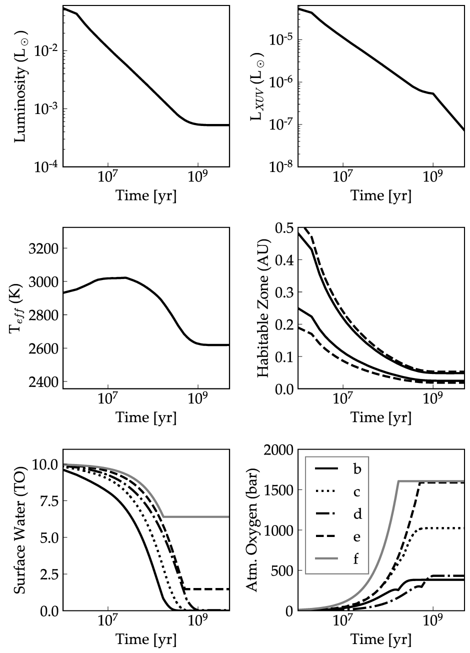

Fig. 1. Evolution of TRAPPIST-1, its HZ, and its planets' atmospheres. The evolution of the host star during the pre-main sequence can desiccate the planets that are in the main sequence HZ. *Top left:* Bolometric luminosity. *Top right:* XUV luminosity. *Middle left:* Stellar effective temperature. *Middle right:* HZ boundaries with solid lines representing the "conservative" limits and dashed the "optimistic" limits. *Bottom left:* Surface water in units of Earth's water content. *Bottom right:* Oxygen released from water photolysis.

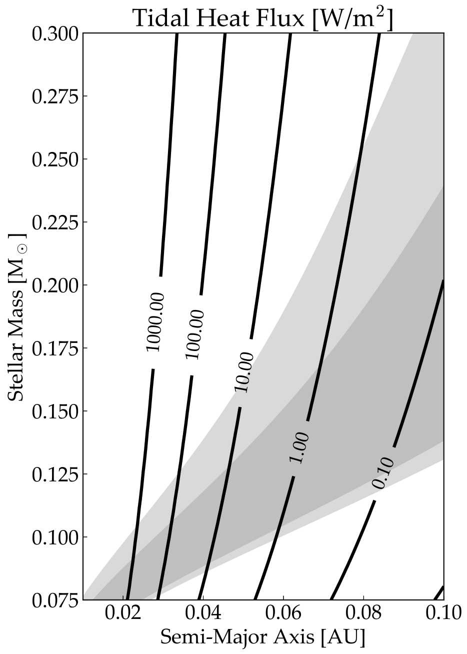

Fig. 2. Surface energy flux of an Earth-mass, Earth-radius planet with the modern Earth's tidal response and an eccentricity of 0.05. The light grey is the "optimistic" HZ; dark grey the "conservative" HZ. Planets with surface energy fluxes greater than 300 W/m^2 are likely to be in a runaway greenhouse even though they are in the classic HZ.

same tidal response as Earth (Williams et al. 1978) and an orbital eccentricity of 0.05 is shown. Planets in the HZ of the lowest mass stars may be tidally heated into a runaway greenhouse at even this modest eccentricity (note that many observed exoplanets have eccentricities 10x larger). For larger stars, tidal heating may still be significant in their HZs.

In some planetary systems, orbital oscillations caused by gravitational perturbations between worlds can be very large. For example, Barnes et al. (2015) showed that planets in mean motion resonances with significant eccentricities and inclinations can enter a chaotic evolution that drives eccentricities to over 0.99, see Fig. 3. Despite these extreme orbital variations, the system is stable for 10 Gyr. A planet with a semi-major axis in the HZ of its host star is not likely to remain habitable under such orbital conditions as at epochs of high eccentricity the incident flux can easily exceed the threshold for a runaway greenhouse.

Figs. 1–3 represent a non-exhaustive set of demonstrations of how the HZ does not include all the possible processes that can sterilize a planet. For a given planet, its semi-major axis and host star's luminosity may place it in the HZ, but other factors that can be measured can preclude habitability. Thus, a broader framework must be envisaged that can account for the breadth of sterilizing phenomena.

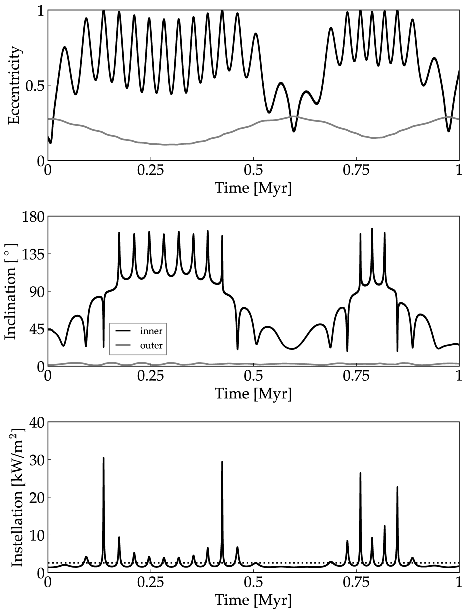

Fig. 3. Orbital evolution of a hypothetical system consisting of solar mass star, a 1 Earth-mass planet with a semi-major axis of 1 AU, and a 22 Earth-mass planet in the 3:1 mean motion resonance. *Top:* Eccentricity. Note that the inner planet reaches values larger than 0.99. *Middle:* Inclination. *Bottom:* Instellation of the inner planet, with Venus' current insolation shown by the dotted line. At those times the planet is likely in a runaway greenhouse even though its orbit places it in the classic HZ.

4. A comprehensive model of habitability

To move beyond the HZ, a model that connects all relevant processes must be created, including those shown in Figs. 1–3. One step toward this inclusive model was recently taken with the creation, validation, and release of the new software package `VPLanet` (Barnes et al. 2019). This model connects simple models of terrestrial planet interiors (Driscoll & Bercovici 2014), atmospheric escape (Watson et al. 1981; Murray-Clay et al. 2009; Luger & Barnes 2015), orbital evolution (Ellis & Murray 2000), tidal evolution (Ferraz-Mello et al. 2008; Leconte et al. 2010), climate (North & Coakley 1979; Huybers & Tziperman 2008), stellar evolution (Baraffe et al. 2015), rotational effects (Kinoshita 1977), and galactic processes (Ricker et al. 2014). This code generated the results presented in Figs. 1–3, and has been used to study climates of planets on dynamically active orbits (Deitrick et al. 2018b,a), binary stars and their planets (Fleming et al. 2018, 2019a), and the plausible range of histories of the star TRAPPIST-1 (Fleming et al. 2019b).

The `VPLanet` code is designed to be modular and expandable, as described in more detail in Barnes et al. (2019). This functionality is key as it allows the model to grow in complexity and be tailored to individual systems as they are discovered, as well as identify generic feedbacks that may affect any planet. An open source development strategy enables community vetting of the model and the opportunity to contribute new functionality to the code.

Although the `VPLanet` model includes substantially more processes than previous models of planetary habitability, it is still incomplete as it ignores key processes like geochemistry (e.g. Walker 1981; Foley & Smye 2017), photochemistry (e.g. Kasting 1988), and physical oceanography (e.g. Auclair-Desrotour et al. 2018; Green et al. 2019). Nonetheless, this framework provides the opportunity to combine the relevant physics and chemistry to simulate the stability and lifetimes of liquid water layers on the surfaces and interiors of planets and moons, i.e. habitability. As more processes are coupled, we can begin to paint more and more realistic pictures of planetary evolution and ultimately understand how planets can sustain habitable conditions in any astrophysical setting.

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References

Abe, Y. 1993, Lithos, 30, 223
Airapetian, V. S., Barnes, R., Cohen, O., et al. 2019, arXiv e-prints, arXiv:1905.05093
Anglada-Escudé, G., Amado, P. J., Barnes, J., et al. 2016, Nature, 536, 437
Armstrong, J. C., Barnes, R., Domagal-Goldman, S., et al. 2014, Astrobiology, 14, 277
Auclair-Desrotour, P., et al. 2018, A&A, 615, A23
Baraffe, I., et al. 2015, A&A, 577, A42
Barnes, R., et al. 2009, ApJ, 695, 1006
Barnes, R., Mullins, K., Goldblatt, C., et al. 2013, Astrobiology, 13, 225
Barnes, R., et al. 2015, ApJ, 801, 101
Barnes, R., Deitrick, R., Luger, R., et al. 2016, ArXiv e-prints, arXiv:1608.06919
Barnes, R., Shahar, A., Unterborn, C., et al. 2018, ArXiv e-prints, arXiv:1801.08970
Barnes, R., Luger, R., Deitrick, R., et al. 2019, arXiv e-prints, arXiv:1905.06367
Bell, E. A., et al. 2015, Proceedings of the National Academy of Sciences, 112, 14518
Benneke, B., Wong, I., Piaulet, C., et al. 2019, arXiv e-prints, arXiv:1909.04642
Borucki, W. J., Agol, E., Fressin, F., et al. 2013, Science, 340, 587
Brock, T. D. 1978, Thermophilic Microorganisms and Life at High Temperatures (Springer, New York)
Corliss, J. B., Dymond, J., Gordon, L. I., et al. 1979, Science, 203, 1073
Deitrick, R., Barnes, R., Bitz, C., et al. 2018a, ArXiv e-prints, arXiv:1805.00283
Deitrick, R., Barnes, R., Quinn, T. R., et al. 2018b, AJ, 155, 60
Dittmann, J. A., Irwin, J. M., Charbonneau, D., et al. 2017, Nature, 544, 333
Dole, S. H. 1964, Habitable planets for man (Rand Corp., Santa Monica, CA)
Driscoll, P. & Bercovici, D. 2014, Physics of the Earth and Planetary Interiors, 236, 36
Driscoll, P. E. & Barnes, R. 2015, Astrobiology, 15, 739
Ellis, K. M. & Murray, C. D. 2000, Icarus, 147, 129
Ferraz-Mello, S., Rodríguez, A., & Hussmann, H. 2008, Celestial Mechanics and Dynamical Astronomy, 101, 171
Fleming, D. P., et al. 2018, ArXiv e-prints, arXiv:1804.03676
Fleming, D. P., et al. 2019a, ApJ, 881, 88
Fleming, D. P., et al. 2019b, arXiv e-prints, arXiv:1906.05250
Foley, B. J. & Smye, A. J. 2017, ArXiv e-prints, arXiv:1712.03614
Garraffo, C., Drake, J. J., & Cohen, O. 2016, ApJ, 833, L4
Gillon, M., Triaud, A. H. M. J., Demory, B.-O., et al. 2017, Nature, 542, 456
Green, J. A. M., Way, M. J., & Barnes, R. 2019, ApJ, 876, L22
Hart, M. H. 1979, Icarus, 37, 351
Hayashi, C. 1961, PASJ, 13, 450
Huybers, P. & Tziperman, E. 2008, Paleoceanography, 23, n/a
Jackson, B., Barnes, R., & Greenberg, R. 2008, MNRAS, 391, 237
Junge, K., Eicken, H., & Deming, J. W. 2004, Applied and Environmental Microbiology, 70, 550
Kaib, N. A. & Raymond, S. N. 2014, ApJ, 782, 60
Kasting, J. F. 1988, Icarus, 74, 472
Kasting, J. F., Whitmire, D. P., & Reynolds, R. T. 1993, Icarus, 101, 108
Kinoshita, H. 1977, Celestial Mechanics, 15, 277
Kopparapu, R. K., Ramirez, R., Kasting, J. F., et al. 2013, ApJ, 765, 131
Leconte, J., et al. 2010, A&A, 516, A64
Lincowski, A. P., Meadows, V. S., Crisp, D., et al. 2018, ApJ, 867, 76
Luger, R. & Barnes, R. 2015, Astrobiology, 15, 119
Luger, R., Sestovic, M., Kruse, E., et al. 2017, Nature Astronomy, 1, 0129
Lustig-Yaeger, J., Meadows, V. S., & Lincowski, A. P. 2019, AJ, 158, 27
McKay, C. P. 2014, Proceedings of the National Academy of Science, 111, 12628
Meadows, V. S. & Barnes, R. K. 2018, Factors Affecting Exoplanet Habitability, in Handbook of Exoplanets, Deeg H., Belmonte J. eds (Springer, Cham), 57
Murray-Clay, R. A., Chiang, E. I., & Murray, N. 2009, ApJ, 693, 23

Navarro-Gonzalez, R., Rainey, F., Molina, P., et al. 2003, Science, 302, 1018
North, G. R. & Coakley, J. A. J. 1979, J. Atm. Sci., 36, 1189
Quintana, E. V., Barclay, T., Raymond, S. N., et al. 2014, Science, 344, 277
Reiners, A., Schüssler, M., & Passegger, V. M. 2014, ApJ, 794, 144
Ribas, I., et al. 2005, Astrophys. J., 622, 680
Ricker, G. R., Winn, J. N., Vanderspek, R., et al. 2014, Proc. SPIE, 914320
Schopf, J. W., et al. 2007, Precambrian Research, 158, 141
Segura, A., et al. 2010, Astrobiology, 10, 751
Strom, R. G., et al. 1979, Nature, 280, 733
Tsiaras, A., et al. 2019, Nature Astronomy, 451
Veeder, G. J., Davies, A. G., Matson, D. L., et al. 2015, Icarus, 245, 379
Walker, A. R. 1981, MNRAS, 195, 1029
Watson, A. J., Donahue, T. M., & Walker, J. C. G. 1981, Icarus, 48, 150
Williams, J. G., Sinclair, W. S., & Yoder, C. F. 1978, Geophys. Res. Lett., 5, 943
Zechmeister, M., Dreizler, S., Ribas, I., et al. 2019, A&A, 627, A49