THE DIVERSITY AND DISTRIBUTION OF HABITABLE WORLDS. A. Méndez, Planetary Habitability Laboratory, University of Puerto Rico at Arecibo (abel.mendez@upr.edu).

Introduction: There are about four thousand known exoplanets but only a few of those might have the conditions necessary to support life [1]. However, we do not have enough information about them to fully assess their potential for life. Our current criteria for habitability mostly consist on simple estimates on their potential to be rocky and support surface liquid water [2]. Additional factors include the age of the system [3, 4], the activity of the star, which might work in favor or against habitable conditions [5, 6], orbital dynamics [7], and tidal effects [8]. Therefore, we do not know yet the diversity of habitable worlds in the universe.

In this study we model the potential diversity and distribution of habitable worlds based on their global surface habitability. Subsurface biospheres will be considered in a future study. The model was applied to solar and extrasolar planetary objects. In principle, it is expected that future measures of both habitability and biosignatures are correlated, given the presence of life. This is true for Earth but not necessarily for other worlds.

Global Habitability: Habitability is generally defined as the suitability of an environment for life. It is formally known as *habitat suitability* in biology [9, 10, 11]. The habitability H of a system bounded by a space s and time t of interest can be calculated from

$$\frac{\partial^2 H}{\partial s \partial t} = \left(\frac{1}{q}\frac{\partial^2 q}{\partial s \partial t} + \frac{1}{M}\frac{\partial^2 M}{\partial s \partial t} + \frac{1}{E}\frac{\partial^2 E}{\partial s \partial t} \right) H \qquad (1)$$

where M and E are the total mass an energy within the system, respectively, and q is the fraction of that total mass and energy available to a given species, ecosystem, or biosphere [12]. In practice, the equation is solved for a finite set of environmental factors of interest with functional forms proportional to q, M and E. It is also simpler to normalize H with respect to some standard of comparison (e.g. Earth's surface).

The hardest problem of the habitability equation (1) is to calculate q because it is highly dependent on the life form under consideration. However, for the global biosphere we can define an upper limit q, assuming the biosphere can use up to all mass and energy available in a thin layer over the surface of a planet. Thus, this approach can be used to estimate the upper limit

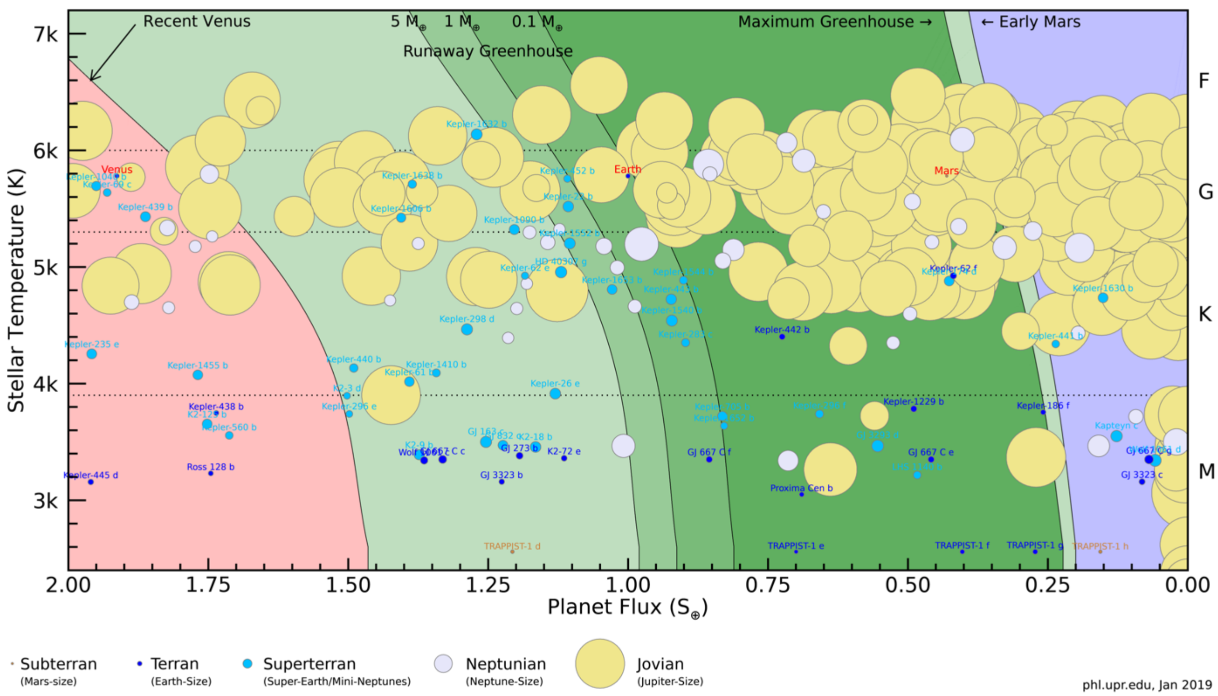

Figure 1. The figure above shows all planets near the habitable zone (green shades). Only those planets less than 10 Earth masses or 2.5 Earth radii are labeled. Size of the circles corresponds to the radius of the planets (estimated from a mass-radius relationship when not available).

habitability of any planetary body. Solving equation (1) for the steady state within a near-surface thin layer of a planetary body we get

$$H_b = \frac{S(1-A)}{S_\oplus(1-A_\oplus)}\left(\frac{R}{R_\oplus}\right)^4\left[\frac{\rho_a\rho_h\rho_l f(1-f)}{\rho_{a\oplus}\rho_{h\oplus}\rho_{l\oplus}f_\oplus(1-f_\oplus)}\right]^{\frac{1}{3}} \qquad (2)$$

where H_b is the upper habitability limit of a potential biosphere as compared to Earth (*i.e.* H_b = 1), S is the stellar flux, A the bond albedo, R the radius of the planet, f the area fraction of the hydrosphere, and ρ_a, ρ_h, and ρ_l are the density of the atmosphere, hydrosphere, and lithosphere at the surface level, respectively. Not all of these parameters are independent between them, for example, the larger the planet the less likely is to have a rocky surface exposed to the atmosphere.

The seven parameters of equation (2) are the minimum set of planetary properties for a first-order global estimate of the potential habitability of a planet. Unfortunately, only the stellar flux S and the planet radius R are known today for some exoplanets (Figure 1). The bond albedo A and ocean fraction f might be measured by future space observatories via photometry with direct imaging [13]. The surface atmospheric density ρ_a can be estimated from atmospheric temperature, pressure and composition derived from spectroscopy. The densities of the ocean water and rocky surfaces, ρ_h and ρ_l, are not expected to be much different from terrestrial values. Nevertheless, these parameters can be used today to explore potential scenarios and degeneracies, or compare planetary model outputs such as those generated from NASA's ROCKE-3D [14].

Equation (2) can also be used to explore the evolution of habitability of Solar System objects such as Earth, Mars, and even Titan, assuming its lakes provide the liquid substrate for life (Table 1). Potential subsurface habitats, such as those of Europa and Enceladus, require a new derivation from equation (1) where more details about the environment are included (e.g. the particular concentration of molecular species). Since habitability will be very low in such cases compared to our surface biosphere, then the standard of comparison could be the terrestrial deep oceans or hydrothermal systems. Furthermore, upper limits of Net Primary Productivity (NPP) can be estimated from equation (1) [12].

Table 1. Comparison of the current biosphere habitability of Earth with that of upper limits for potential biospheres of early Mars and current Titan.

Planetary Body	Surface Habitability
Earth	1.0
Early Mars	≤ 0.034
Titan	≤ 0.000139

Diversity of Habitable Worlds: We statistically explored multiple scenarios for habitable worlds based on their global surface habitability using equation (2). Five major types were identified with very distinct habitability. We also found that the best ocean to land ratio for habitable worlds is 0.72, close to the terrestrial value. To some extent, planets larger than Earth and with thicker atmospheres (e.g. Super-Earths) can become much more habitable than Earth (i.e. support a larger biomass per unit of space and time).

Distribution of Habitable Worlds: We also explored the potential spatial distribution of habitable worlds in the current distribution of stars in the Solar Neighborhood. We estimated the occurrence and mean separation between these worlds. The probability of planets with Earth-sized biospheres around Proxima Centauri and TRAPPIST-1 is very small.

Conclusion: We developed a global surface habitability model applicable to solar and extrasolar planetary bodies. The model is based on the upper limits of mass and energy available for life and thus independent of the lifeform under consideration. Early Mars was no more than 3.4% as habitable as Earth today. The surface habitability of Titan today is less than 0.01%. These values constrain the potential maximum biomass present on any of these bodies. We also found that there are at least five major types of habitable worlds. Those more abundant are harder to detect and those similar to Earth are less common. An anticorrelation between measures of habitability and biosignatures can be interpreted as an abiotic process or as life as we don't know it.

References: [1] The Habitable Exoplanets Catalog (2018). [2] Ramirez, R. M. (2018) *Geosciences,* **8**(8), 280. [3] Rushby, A. J., *et al.* (2013) *Astrobiology*, **13**, 9. [4] Safonova, M. J. and Shchekinov, Y. A. (2016) *Int. J. Astrobiol.*, **15**(2) 93–105. [5] Lingam, M. & Loeb, A. (2017) *ApJ,* **848**(1), 41. [6] Rimmer, P. B., *et al.* (2018) *Sci Adv.*, **4**(8). [7] Méndez, A. and Rivera-Valentín, E. G. (2017) *ApJL,* **837**(1), L1. [8] Valencia, D., *et al.* (2018) *ApJ,* **857**(2), 106. [9] US Fish and Wildlife Service (1980). [10] Roloff, G. J. and Kernohan, B. J. (1999) *Wildlife Society Bulletin (1973-2006)*, **27**, 973. [11] Hirzel, A. H. and Le Lay, G. (2008) *J. of Appl. Ecol.*, **45**, 1372. [12] Méndez, A., *et al.* (2018) *LPS XLIX*, Abstract #2511. [13] Fujii, Y., *et al.* (2010) *ApJ*, **715**(2), 866. [13] Way, M. J., *et al.* (2017) *ApJ,* **231**(1) 12.

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