The Diversity and Distribution of Habitable Worlds

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Introduction: There are about four thousand known exoplanets but only a few of those might have the conditions necessary to support life (Habitable Exoplanets Catalog, 2019). Unfortunately, we do not have enough information about them to fully assess their potential for life. Our current criteria for habitability mostly consist on estimates on their potential to be rocky and support surface liquid water (Ramírez, 2018). Additional factors include the age of the system (Rushby *et. al.*, 2013; Safonova & Shchekinov, 2016), the activity of the star, which might work in favor or against habitable conditions (Lingam & Loeb, 2017; Rimmer *et al*., 2018), orbital dynamics (Méndez & Rivera-Valentín, 2017), and tidal effects (Valencia *et al.,* 2018). Therefore, we do not know yet the diversity of habitable worlds in the universe.

Global Habitability Model: Habitability is generally defined as the suitability of an environment for life, formally known as *habitat suitability* in biology (US Fish and Wildlife Service, 1980; Roloff & Kernohan, 1999; Hirzel & Le Lay, 2008). The habitability H of a system bounded by a space and time of interest can be calculated from a general mass and energy equation (Méndez *et al*., 2018). In practice, the equation is solved for a finite set of environmental factors of interest with functional forms proportional to the mass and energy of the bounded system. We can define an upper limit to the habitability of a surface biosphere assuming life can use all the mass and energy available. One steady-state solution of the habitability equation from bulk properties within a near-surface thin layer of a planetary body is

$$H_\oplus = \frac{qME}{q_\oplus M_\oplus E_\oplus} \approx \left[\left(\frac{P_s}{P_\oplus}\right)\left(\frac{f}{f_\oplus}\right)\left(\frac{1-f}{1-f_\oplus}\right)\right]^{\frac{1}{3}}\left(\frac{R}{R_\oplus}\right)^4\left(\frac{T_s}{T_{s\oplus}}\right)^{\frac{11}{3}} \quad (1)$$

where $H_\oplus$ is the upper habitability limit of a potential biosphere as compared to Earth (*i.e. Earth* = 1), T_s is the surface temperature, P_s surface pressure, R the radius of the planet, and f the area fraction of the hydrosphere. These parameters are not independent between them, for example, the larger the planet the less likely is to have a rocky surface exposed to the atmosphere.

The four parameters of equation (1) are a minimum set of planetary properties for a first-order global estimate of the potential habitability of a planet. Only the planet radius is known today for most exoplanets. The surface temperature, pressure and ocean fraction f might be estimated by far future space observatories via photometry with direct imaging (Fujii *et al.*, 2010). Nevertheless, these parameters can be used today to explore potential scenarios and degeneracies, or compare the habitability of simple energy balance models and GCM model outputs such as those generated from NASA's ROCKE-3D (Way *et al.,* 2017).

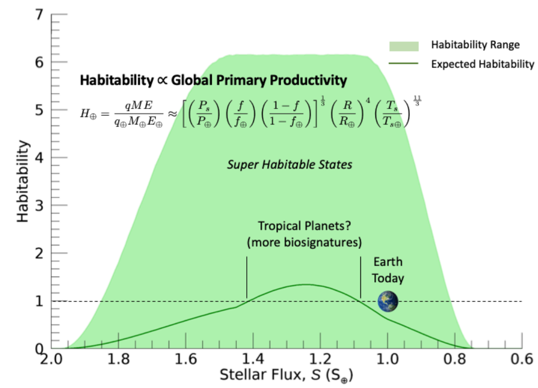

Figure 1. General relation between global surface habitability (green shade) and stellar flux.

Conclusion: A global surface habitability model applicable to solar and extrasolar planetary bodies was develop. The model is based on the upper limits of mass and energy available for life and thus independent of the lifeform under consideration. We statistically explored multiple scenarios and found that there are at least five major types of habitable worlds. Those more abundant are harder for biosignatures detections and those similar to Earth are much less common. The best ocean to land ratio is between 0.5 to 0.7, close to the terrestrial value. Any anticorrelation between measures of habitability and biosignatures can be interpreted as an abiotic process or as life as we don't know it. To some extent, planets larger than Earth and with denser atmospheres (Figure 1) can become much more habitable than Earth, up to 6 times (*i.e.* support a larger biomass per unit of space and time). The probability of planets with Earth-sized biospheres around Proxima Centauri and TRAPPIST-1 is very small.

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