Origins: From the Protosun to the First Steps of Life
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Bio-habitability and life on planets of M-G-type stars

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Abstract. The recent detection of Earth-sized planets in the habitable zone of Proxima Centauri, Trappist-1, and many other nearby M-type stars (which consist some 75% of the stars) has led to speculations, whether liquid water and life actually exist on these planets. Defining the bio-habitable zone, where liquid water and complex organic molecules can survive on at least part of the planetary surface, we suggest that planets orbiting M-type stars may have life-supporting conditions for a wide range of atmospheric properties (Wandel 2018). We extend this analysis to synchronously orbiting planets of K- and G-type stars and discuss the implications for the evolution and sustaining of life on planets of M- to G-type stars, in analogy to Earth.

Keywords. Habitable Zone, exoplanets, M-type stars, climate model

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1. Introduction

Most of the recently discovered exo-planets orbit Red Dwarf stars (RDs), which constitute about 75% of the stars in the Milky Way galaxy. They are characterized by a luminosity much lower than that of our sun. Consequently, habitable planets (in the Habitable Zone, HZ, defined as enabling surface liquid water in the presence of an adequate atmosphere) orbit closely and hence are likely to be gravitationally locked. The findings of the Kepler telescope have shown that 10–75% of the RDs have habitable Earth to Super-Earth sized planets (the range depends on the precise definition of the HZ, 10% is the percentage for very conservative borders, 75% for wider HZ-borders (see e.g. Batalha *et al.* 2013; Dressing and Charbonneau, 2015), which implies that such planets could be found within less than 10 light years from Earth (Wandel, 2015; 2017). In addition to RDs, K-type stars may also have habitable tidally locked or synchronously orbiting planets (Wandel & Gale, 2019). While some authors point out some disadvantages for the evolution of life on planets orbiting M-type stars, such as high levels of XUV radiation and stellar winds, which may cause atmosphere erosion (Heller, Leconte & Barnes 2011; Leconte *et al.* 2015; Lingam & Loeb, 2017), other works argue that such planets may nevertheless host life as we know it (e.g. Tarter *et al.* 2007; Gale & Wandel, 2017; Wandel & Tal-Or, 2019). They point out that the impact of the high XUV flux received by planets orbiting in the habitable zone of young M-type hosts, may be less important for aquatic life.

Model Predictions of the Climates of RD-planets

A major requirement for life is a surface temperature range which supports liquid water and complex organic molecules. This depends on the irradiation from the host star, but to a large extent also on the planet's atmosphere. Global Circulation Models (GCMs) using radiative transfer, turbulence, convection and volatile phase changes can be used to calculate the conditions on planets, given the properties of their atmospheres. Such 3D climate models of M-dwarf planets suggest the presence of liquid water for a variety of atmospheric conditions (e.g. Pierrehumbert 2011, Wordsworth 2015). Climate modeling studies have shown that an atmosphere only 10% of the mass of Earth's atmosphere can transport heat from the day side to the night side of tidally locked planets, enough to prevent atmospheric collapse by condensation (Joshi *et al.* 1997; Tarter *et al.* 2007; Scalo *et al.* 2007; Heng & Kopparla 2012). On locked planets the water may be trapped on the night side (e.g. Leconte 2013), but on planets with enough water or geothermal heat, part of the water remains liquid (Yang *et al.* 2014). 3D GCM simulations of planets in the habitable zone of M-dwarfs support scenarios with surface water and moderate temperatures (Yang *et al.* 2014; Leconte *et al.* 2015; Owen & Mohanty 2016; Turbet *et al.* 2016; Kopparapu *et al.* 2016; Wolf 2017 to name a few).

While rocky planets with no or little atmosphere, like Mercury, have an extremely high day-night contrast and planets with a thick, Venus-like atmosphere tend to be nearly isothermal, intermediate cases, with up to 10 bar atmospheres, conserve significant surface temperature gradients (e.g. Selsis *et al.* 2011).

We argue here that life clement environments may be supported on many tidally locked planets. Recent calculations (Wandel 2018) suggest that planets orbiting M-type stars may have life supporting temperatures, at least on part of their surface, for a wide range of atmospheric properties. It is possible to extend this treatment to other stellar types (K an G) and show that tidally locked planets may well have conditions allowing photosynthesis (Gale & Wandel 2017). Given the very large number of potential planets, and the possibility of liquid water on at least some of the tidally locked planets, we discuss here characteristics of complex life which may evolve on the tidally locked planets and how they may differ from life on Earth.

Wandel (2018) supplements the usual treatment of the habitable zone (the region around a star where planets can support liquid water, e.g. Kasting, Whitmire & Reynolds, 1993), with the definition of a bio-habitable zone, where surface temperatures can support complex organic molecules, in addition to liquid water. The atmospheric properties that affect the surface temperature distribution are reduced to two factors: circulative heat redistribution and heating (due to atmospheric greenhouse effect and irradiation by the host star). The presence of surface liquid water and life supporting temperatures are analyzed within this two-dimensional parameter space.

Surface Temperature distribution on locked and synchronous planets

We extend the surface temperature model for tidally locked planets to synchronous (like Mercury, which has a spin-to-orbit period ratio of 3:2) and nearly synchronous (e.g. Venus) orbiting planets. In the latter, the spin (day/night) period is relatively long, comparable to the orbital period. We find that the circulative heat transport is enhanced and can be represented by an effective heat redistribution factor (Wandel & Gale 2019)

The planet is defined as being within the bio-Habitable Zone, if its lowest surface temperature is above freezing, that is, $T_{\rm min} > 273$K, and its highest surface temperature is below the highest temperature which allows complex organics, that is $T_{\rm max} < 400$K. This is depicted in Fig. 2, below. The lower temperature limit is naturally chosen as the freezing point of water, which is only weakly dependent on pressure, and is widely accepted as a lower limit for organic processes. The surface temperature of a locked planet is fiven by

$$\sigma T^4(\theta) = (1-A)SF(\theta) \tag{1}$$

where σ is the Stefan Boltzman constant, A is the Bond albedo and F *is a function of the latitude angle, the substellar point defined as* $\theta = 0$. The irradiation or insolation is given by $S = L_*/4\pi a^2$, where a is the distance of the planet from its host star and L_* is host star's luminosity. If the planet is locked and has no horizontal circulation or energy

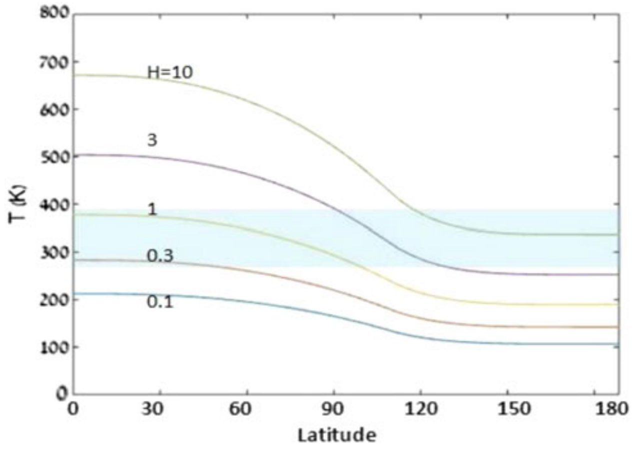

Figure 1. Temperature profiles for several values of the heating factor H. A global heat redistribution of $f = 0.2$ is assumed. The liquid water temperature range at 1 bar is indicated by the shaded light blue area.

redistribution, then $F = \cos(\theta)$ for $0 < \theta < 90$ and $F = 0$ for $90 < \theta < 180$. In the opposite case, planets with an efficient horizontal heat spread or those rotating rapidly, are nearly isothermal, $F = 1/4$ and the equilibrium surface temperature is $T_{eq} = [(1 - A)S/4\sigma]^{1/4}$. In the intermediate case we assume that a fixed fraction, f, of the stellar irradiation at each point is redistributed evenly over the whole planetary surface due to circulation in the planet's atmosphere. In this case we have $0 < f < 1$. While in the day hemisphere the heating is modulated by the angle from the substellar point, on the night hemisphere it is homogenous:

$$F(\theta) = \begin{cases} \frac{f}{4} + (1 - f)cos(\theta) & 0 \leq \theta \leq 90^\circ \\ \frac{f}{4} & 90^\circ < \theta \leq 180^\circ \end{cases} \tag{2}$$

It is convenient to combine the albedo, the atmospheric screening a and greenhouse factor H_g with the insolation or irradiation S, into a single dimensionless parameter, which we call the heating factor

$$H = (1 - A)H_g\alpha\, S/S_\oplus. \tag{3}$$

where $S/S_\oplus$ is the insolation relative to Earth and H_g is the greenhouse factor, i.e. the amount of heat capture of the atmosphere. The lowest and highest temperatures can be written as

$$T_{min} = 278\ (Hf)^{1/4}\,\mathrm{K} \tag{4}$$

$$T_{max} = T_0 = 394\ H^{1/4}(1\text{-}{}^3\!/\!_4 f)^{1/4}\ K \tag{5}$$

Surface temperature profiles for various values of the combined heating factor H are shown in Fig 1. A moderate local heat transport is assumed (Wandel 2018).

Fig 2 shows the temperature range on a tidally locked planet (eqs 4,5) as a function of the heating factor H. From the intersection of the curves with the boundaries of the bio-habitable temperature zone it is possible to derive the habitability range of the heating factor. As shown in the figure by the arrows at the bottom, for $0 < T < 100C$ the bio-habitable range of the greenhouse heating factor turns out to be $0.2 < H_g < 30$. Letters show the four values of the terrestrial planets of the Solar System. Note that Venus, Earth and Mars have average temperatures consistent with the equilibrium solid green curve (isothermal surface, effective f=1), while Mercury's temperature range is shown by the vertical arrow.

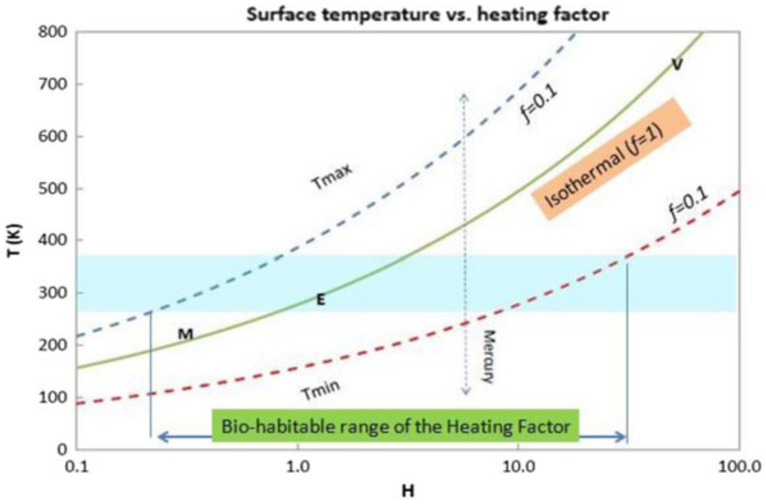

Figure 2. Minimum and maximum surface temperatures of tidally locked planets as a function of the heating factor *H*. The green solid curve shows the equilibrium temperature for an isothermal planet, while the dashed curves show the highest and lowest surface temperatures of a tidally locked planet with 10% global redistribution ($f = 0.1$). Also shown are the locations of the four terrestrial planets of our Solar System.

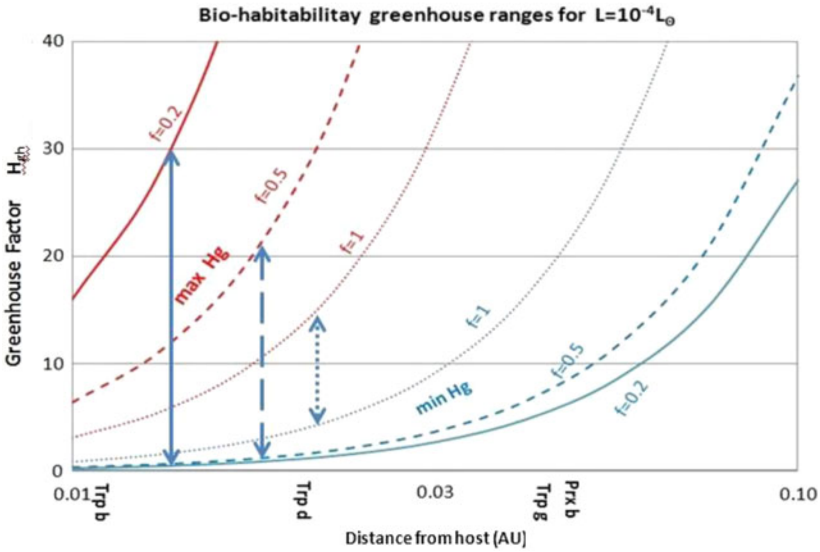

Figure 3. Maximal (red, upper) and minimal (blue, lower) bio-habitable zone boundaries of the greenhouse factor vs. the distance from the host star, for three values of the heat circulative redistribution parameter: $f = 0.2$ (solid), 0.5 (dashed) and 1 (dotted). The host luminosity is assumed to be $L = 10^{-4} L_{\odot}$. The locations of Proxima b and 3 of the Trappist-1 planets are marked on the x-axis

Fig 3 shows the greenhouse part (H_g) of the heating factor, as a function of the distance from a host star with a luminosity of $10^{-4} L_{\odot}$ (similar to that of Trappist-1), for 3 values of *f*. The locations of several of the Trappist-1 planets are marked on the x-axis. The y-axis shows the optical depth to infrared radiation, roughly indicating the atmosphere's opacity in the "lower wavelength" (near IR), which is related to the greenhouse heating factor by $t_{lw} = H_g - 1$.

Conclusion

We have show that tidally locked planets of M-type stars may have temperatures suitable for liquid water and complex organic molecules on at least part of their surface for a wide range of atmospheric properties. Extending this analysis to synchronously orbiting planets, makes these conclusions applicable also to K and perhaps even G-type stars, where the habitable zone extends much further from the host star, and hence habitable planets would less likely be tidally locked, but may still be in nearly synchronous orbits. In analogy to extended daylight latitudes on Earth extreme environments.

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Discussion

MANKO VOLODYMYR: Tidally locked planets almost definitely must undergo the libration (caused by orbital eccentricity or gravitational influence of other planets in the system). Do you know about models exploring these effects?

WANDEL: My model and previous works concentrate on the basic model of a single gravitationally locked planet, with a steady state surface temperature distribution. The effect of eccentricity on other planets may be explored at a future stage of the project.