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Host Star Evolution for Planet Habitability

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Abstract With about 2000 exoplanets discovered within a large range of different configurations of distance from the star, size, mass, and atmospheric conditions, the concept of habitability cannot rely only on the stellar effective temperature anymore. In addition to the natural evolution of habitability with the intrinsic stellar parameters, tidal, magnetic, and atmospheric interactions are believed to have strong impact on the relative position of the planets inside the so-called habitable zone. Moreover, the notion of habitability itself strongly depends on the definition we give to the term "habitable". The aim of this contribution is to provide a global and up-to-date overview of the work done during the last few years about the description and the modelling of the habitability, and to present the physical processes currently includes in this description.

Keywords Star · Evolution · Planet · Habitability · Habitable zone

Introduction

To study habitability, a definition of the notion of life is required. While this definition is unclear yet, it is widely admitted that one of the first conditions for a planet to be habitable is to be inside the so-called habitable zone (Hart 1976; Leconte et al. 2015) that is the region where long term liquid water can be found at the surface of a planet. The presence of liquid water is though to be, as on Earth, the main element required by organisms to metabolize and reproduce (Kasting 2010; Güdel et al. 2014).

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Liquid water is also one of the elements that is required for the origin of life. While the habitable zone is usually only seen as a snapshot to assess habitability (Kasting et al. 1993; Leconte et al. 2013), the past and future evolution of its limits intimately follow the intrinsic evolution of the stellar parameters. Because of this intrinsic evolution, a planet in the habitable zone is not necessarily habitable, however, the habitable zone is the first condition to check to assess the habitability of a given newly detected planet. We thus clearly need to fully understand its evolution as a function of the stellar parameters. The aim of this work is to highlight the impact of stellar parameter such as metallicity, mass, and rotation on the habitable zone limits.

Thanks to the increase of the accuracy and precision of modern techniques of observation, the size and mass of detected exoplanets have continuously decreased since the first detection of 51 Peg b ($\approx 150\ M_\oplus$) (Mayor and Queloz 1995). While the first detected exoplanets were gaseous so called hot Jupiter, the detection of telluric planet starts to be quite common. Among these newly detected planets, there is one interesting example, Kepler 186 f (Quintana et al. 2014) orbiting around an M-type star, that possesses a radius very close to the Earth's one ($1.11\ R_\oplus$) but unfortunately without precise mass estimation (0.32–$3.77\ M_\oplus$). Tidal interactions between the two bodies are very active (because the planet is quite close to its star, i.e., 0.35–0.4 AU) and act at strongly modifying the orbital motion of the planet. Constraining habitability of such planet is thus quite challenging and motivating since all the physical mechanisms that act in stellar vicinity have to be taken into account.

The structure of the paper is as follows: in Section 2 we describe the habitable zone and how its limits are numerically estimated, we then applied these limits in the case of a solar type star and looked at their evolution as a function of time, metallicity and rotation. We finally analyse the impact of the stellar mass and conclude in Section 3.

Habitable zone

The habitable zone (hereafter HZ) is classically defined as the region where a rocky planet can maintain, given its atmosphere, liquid water on its surface (see Kopparapu et al. 2013, 2014; Linsenmeier et al. 2015; Torres et al. 2015). Kasting et al. (1993) provide a simple analytic expression to get the HZ limits (hereafter HZL)

$$d = \left(\frac{L/L_\odot}{S_{eff}}\right)^{0.5} AU,$$

where d is the inner or outer edge of the HZ, and S_{eff} is the effective stellar flux (Kasting et al. 1993; Kopparapu et al. 2013, 2014) define as the ratio between the outgoing IR flux from the planet and the net incident flux from the star

$$S_{eff} = \frac{F_{IR}}{F_{inc}},$$

which is an indicator of the relative "strength" of the greenhouse effect. Using the 1-D radiative-convective climate cloud-free model developed by the Kasting's group, Kopparapu et al. (2013, 2014) provide a self-consistent parametric equation to calculate the HZL. By exploring the stellar effective temperature range, they expressed S_{eff} as a function of T_{eff} for different cases of HZL definition (and thus planetary atmosphere) as

$$S_{eff} = S_{eff\odot} + aT_* + bT_*^2 + cT_*^3 + \ldots,$$

where $T_* = T_{eff} - 5780\,K$, $S_{eff\odot}$ is estimated by assuming that the total incident flux at the top of the atmosphere is the present solar constant at Earth's orbit, and the constants a, b and c are model parameters that depend on the considered planetary atmosphere and are given in Kopparapu et al. (2014).

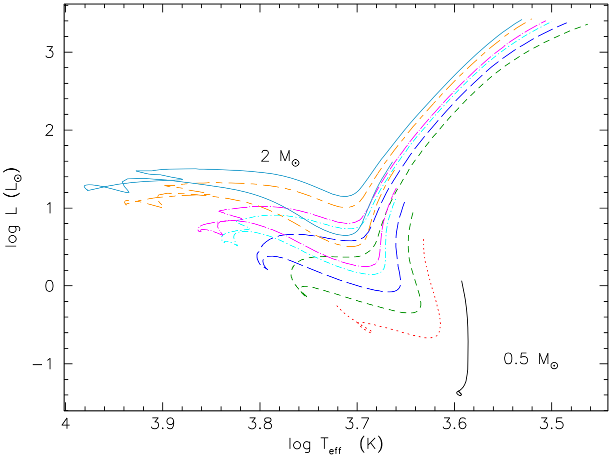
The inner limit of the HZ is usually described as the runaway greenhouse limit that is reached when there is a net positive feedback of the greenhouse effect on itself i.e. when the atmosphere starts to radiate in visible and in near IR thus increasing F_{IR} while F_{inc}, through the absorption of the H_2O compound, being saturated. This limit corresponds to surface temperature for the planet $T_{surf} > 647$ K (the critical point of water) at which oceans are entirely evaporated. The validity of this limit is currently under debate since at this point the surface temperature T_{surf} of a potentially habitable planet is clearly too high to sustain Earth-like life. Another inner edge limit is often used: the moist greenhouse limit that corresponds to the moment, when increasing the surface temperature of the planet, when the absorption of the H_2O compound is maximal. At that phase, the stratosphere of the planet is saturated with vapour and the surface temperature of the planet is about 373 K (i.e. the boiling point of water). The maximum greenhouse, where the Rayleigh scattering due to the CO_2 compound act at reducing the greenhouse effect, defines the outer edge of the habitable zone. At that point the surface temperature of the planet is assumed to be 273 K (i.e. the freezing point of water, Kasting et al. 1993; Selsis et al. 2007; Kopparapu et al. 2013; Kopparapu et al. 2014). Kopparapu et al. 2014 provides several estimation of the HZ for three planetary masses: 0.1, 1, and 5 Earth mass. However in this paper we focus ourselves on the Earth mass planet.

The Solar Case: Habitable Zone Evolution

This study is based on a grid of standard stellar models computed with the code STAREVOL for a range of initial masses between 0.5 and 2 $M_\odot$ and for four values of metallicity [Fe/H] = 0.26, 0, −0.56, and −2.16. The grid will be published in a forthcoming paper (Amard et al. in prep.).

For the 1 $M_\odot$ star (track in cyan in Fig. 1), we use standard and rotating stellar models from Lagarde et al. (2012) and refer to this paper for a detailed description of the model and of the evolution code STAREVOL.

Fig. 1 Stellar evolution tracks in the Hertzsprung-Russell diagram for models of 0.5, 0.6, 0.7,0.9,1.0, 1.2, 1.8, and 2 $M_\odot$ at solar metallicity



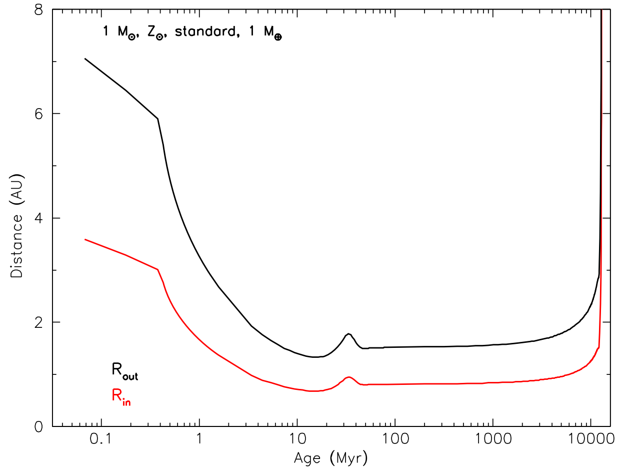


Fig. 2 Evolution of the HZL as a function of age for a 1M with solar metallicity. *Red* and *black lines* represent the inner and outer edge of the HZ respectively

Evolution of the Limits of the Habitable Zone

We first focus on a solar-type star with solar metallicity and use the standard (i.e. non-rotating) model from Lagarde et al. (2012). Figure 2 shows the temporal evolution of inner (red) and outer (black) edge of the HZ from the early pre-main-sequence (PMS) to the end of the main-sequence (MS) phase. The PMS is associated to a rapid and sharp decrease of the HZL and end up at about 10 Myr to minimal value of about 0.68 AU for the inner edge of the HZ (HZ_{in}) and 1.30 AU for the outer edge of the HZ (HZ_{out}). The HZL (both inner and outer edge) then increase again following the increase of stellar luminosity towards the zero age main-sequence (ZAMS, that is located in Figure 2 at the "bump"). Finally, during the MS phase (from 30 Myr up to about 5 Gyr) the HZL remains more or less constant at about 1.5 AU for the outer edge and 0.8 AU for the inner edge. At the end of the MS (from 5 to 6 Gyr) and towards the red giant branch (RGB), the HZL sharply increase following the increase of stellar luminosity.

It is worth noting that because of the atmospheric composition used by Kopparapu et al. (2014), their HZ's prescriptions are only valid for a « recent » planet. Indeed, it is believed that the Earth's atmosphere have reach its present composition only 400 to 600 Myr ago which corresponds to the main sequence phase of the Sun. In this contribution we show the complete evolution of the HZ anyway in order to highlight the fact that stellar models should be used even during the earliest phase of stellar evolution since during such phases the stellar parameters strongly and sharply evolves.

Metallicity Effect

Metallicity is one of the main parameters that modify significantly the stellar structure and evolution. Here we study the impact of metallicity from [Fe/H] = 0.26 to [Fe/H] = −2.16 corresponding to Z = 0.0255 to Z = 0.0001 ([Fe/H] = 0 is the solar metallicity).

The main effect of metallicity is to induce a shift in both effective temperature and luminosity that increase, at a given evolution phase, for decreasing metallicity. When the metallicity decreases, the amount of bound-free absorption throughout the star, which comes from metals, is reduced. The direct effect of this is to reduce the stellar opacity, which allows the energy to escape more easily and thus increases the luminosity and temperature.

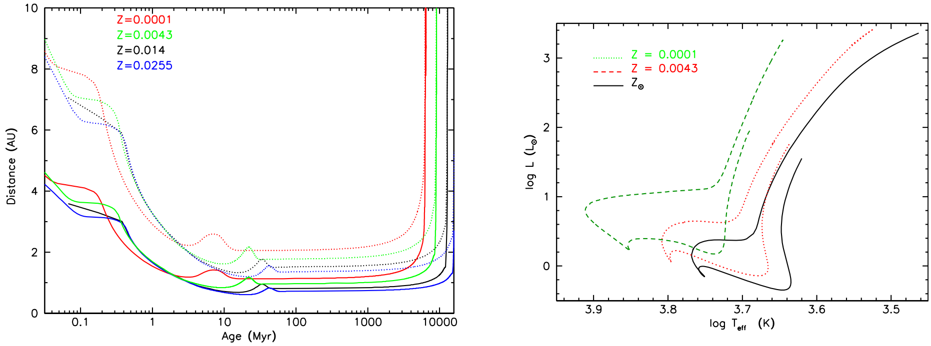


Fig. 3 (*Left*) HZL as a function of age for a 1 M$_\odot$ star and for four values of the metallicity. The solid and dashed lines represent the inner and outer edge of the HZ, respectively. (*Right*) Tracks in the HRD

Figure 3 (*left*) shows the impact of metallicity on the evolution of the inner and outer edge of the HZ for the case of the 1 M$_\odot$ star. For low metallicities the HZL reaches higher values when the star arrives on the ZAMS, and during the whole MS phase. At 100 Myr, HZ$_{\rm in}$ increases from 0.72 AU (Z = 0.0255) to 1.14 AU (Z = 0.0001) corresponding to an increase of 58 %. For HZ$_{\rm out}$, the increase rate is about the same (52 %) with an increase from 1.36 (Z = 0.0255) to 2.08 (Z = 0.0001) AU.

Impact of Rotation

A given star will see its effective surface temperature decreased with increasing rotation rate (see Fig. 4 (*right*)). This effect mainly comes from the centrifugal effect: as the rotation increases the equatorial radius of the star increases as well which produces the decrease of the effective temperature. Figure 4 (*left*) shows the evolution of the corresponding HZL for a standard model (solid line) and a rotating model (dashed line). Figure 4 (*left*) shows that the HZL are not affected by a change of rotation rate (the solid and dashed lines are superimposed). In STAREVOL the rotation is set from the first model (i.e. before the birthline).

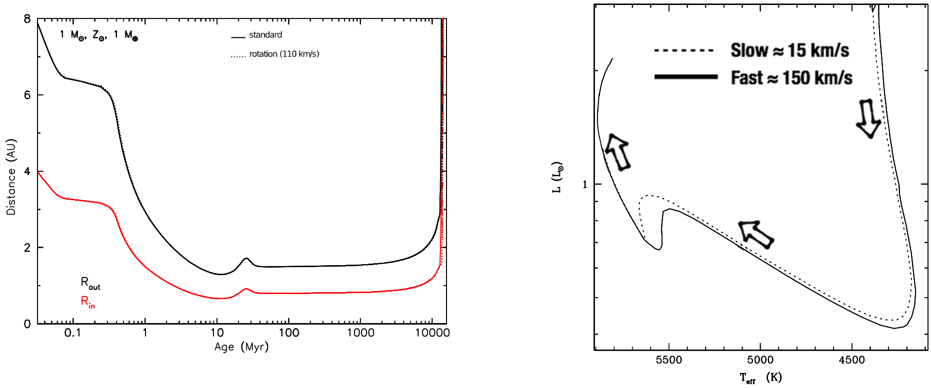


Fig. 4 (*Left*) Impact of rotation of the HZ limits in the case of a solar-type star with solar metallicity. Red and black lines represent the inner and outer edge of the HZ, respectively. Standard and model with rotation (110 km/s at ZAMS) are shown in solid and dotted lines, respectively. (*Right*) impact of the rotation on the HRD of a 1 M$_\odot$ star

Table 1 Size of the HZ as a function of the stellar mass

	0.5 M$_\odot$	1 M$_\odot$	1.5 M$_\odot$	2 M$_\odot$
ΔHZ (AU)	0.27	0.86	2.05	3.25

The rotation is here only taken into account for the solar type star. All others stars are standard non-rotating model. The impact of rotation and stellar activity on the evolution of the HZL will be explored in a forthcoming paper.

Mass Dependence

The stellar mass is also one of the major quantities that significantly modify the internal structure and intrinsic parameters (such as effective temperature, luminosity, lifetime) as well as their evolution for a given star. The shape of the HZL evolution strongly depends on the stellar mass considered. At a given time, luminosity and effective temperature increase for increasing mass. The direct effects on the HZ are to increase both inner and outer edge of the HZ. The width of the HZ also increases for increasing stellar mass. On average, for a non-rotating star with solar metallicity, the width of the HZ is about 0.27 AU for a 0.5 M$_\odot$ and 3.25 AU for a 2 M$_\odot$. The fact that the width of the HZ of high mass star is, on average, wider than low mass star could suggests that these stars are more willing to host habitable planet (i.e., the probability for a planet to be found inside the HZ is higher, see Table 1). However, others factors should also be considered, such as the fact that higher mass stars will evolve way more faster than low mass stars (Fig. 5).

Conclusion and Perspectives

To assess the habitability of an exoplanet we need to precisely define the location of the HZL. In most of the studies from the literature, these limits are only discussed for a given age and regardless of the temporal progress of stellar evolution. However, and as briefly shown here, the HZ strongly varies along the life of planet host stars, and depends on their mass and metallicity. In this work we looked at the effect of stellar parameters on the HZL along the

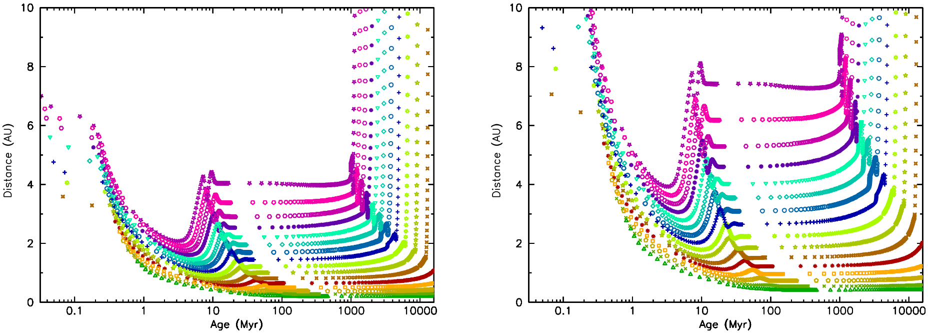


Fig. 5 Evolution of the inner (*left*) and outer (*right*) edge of the HZ as a function of time for stars between 0.5 (*green triangle*) and 2 (purple inclined star) M$_\odot$ with solar metallicity and with a 0.1 M$_\odot$ step between consecutive masses

stellar evolution from the early PMS to the tip of the RGB, as well as the effects of mass and metallicity. We show that the HZL is very sensitive to the metallicity and stellar mass that almost entirely control the HZL. These parameters are then crucial to be determined observationally when one looking for planetary habitability. In a forthcoming paper we will also studied the impact of rotation and stellar activity on the evolution of the HZL.

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