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HOST'S STARS AND 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 talk 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.

1 Introduction

Thanks to the increase of the accuracy and precision of modern techniques of observation, the size and mass of detected exoplanet have continuously decreased since the first detection of 51 Peg b ($\approx 150 M_\oplus$, Mayor & Queloz 1995). While the first exoplanets detected 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 from 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 at act in stellar vicinity have to be taken into account. To fully understand the habitability of an exoplanet we first need to 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.

2 Habitability

2.1 *Definition*

The habitability of an exoplanet is defined by two characteristics: the fact that the planet is inside the habitable zone and that the physical ingredients, that are required to host and sustain life, are present. 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)

$$d = \left(\frac{L/L_\odot}{S_{eff}}\right)^{0.5} \text{AU}, \tag{2.1}$$

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

$$S_{eff} = \frac{F_{IR}}{F_{inc}}. \tag{2.2}$$

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Using the 1-D radiative-convective climate cloud-free model developed by the Kasting's group, Kopparapu et al. (2013, 2014) provide a parametric equation to calculate the HZL

$$S_{eff} = S_{eff\odot} + aT_* + bT_*^2 + cT_*^3 + dT_*^4 \tag{2.3}$$

where $T_* = T_{eff} - 5780$ and $S_{eff\odot}$ is estimated by assuming that the total incident flux at the top of the atmosphere is the present solar constant at Earth's orbit. The inner limit of the HZ is usually described as the runaway greenhouse limit where the green house effect starts to have a positive feedback, i.e. the limit where the surface temperature $T_{surf} > 647$ K at which oceans are entirely evaporated. The outer edge of the HZ is defined by the maximum greenhouse limit where the greenhouse effect starts to be reduced by the Rayleigh scattering by the CO_2. This limit corresponds to a surface temperature of about 273 K.

2.2 The 1 $M_\odot$ star

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 of models will be published in a forthcoming paper of Amard et al. (in prep.). For the 1 $M_\odot$ star, we use the 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.

2.2.1 Evolution of the limits of the habitable zone

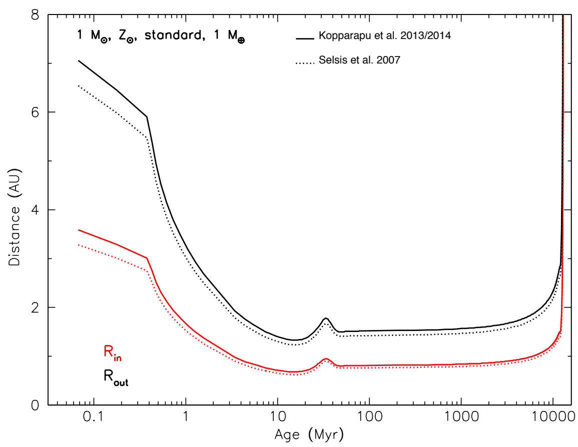

Fig. 1. Evolution of the HZL as a function of age for a 1 $M_\odot$ with solar metallicity. Red and black lines represent the inner and outer edge of the HZ, respectively. The solid, and dotted lines are associated to HZ's prescription from Kopparapu et al. (2014) and Selsis et al. (2007), respectively.

Here we focus on solar-type star with solar metallicity and use the non-rotating model from Lagarde et al. (2012). Figure 1 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 phase along the Hayashi track (Hayashi 1961) is associated to a rapid and sharp decrease of the HZL. After the Hayashi track (between $2\ 10^2$ and $1.5\ 10^7$ years) the HZL of the star reach a minimum value of about 0.68 AU for the inner edge of the HZ (HZ_{in}) and 0.70 AU for the outer edge of the HZ (HZ_{out}). The HZL then increases following the increase of stellar luminosity towards the zero age main-sequence (ZAMS, that is located in Figure 5 at the "bump"). At the end of the PMS (about 30 Myr), the star reaches the ZAMS where the stellar structure temporally stops to evolve followed by the stop of the evolution of the HZL. 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 5-6 Gyr) and towards the red giant branch (RGB) the HZL sharply increases following the increase of stellar luminosity.

2.2.2 Metallicity effect

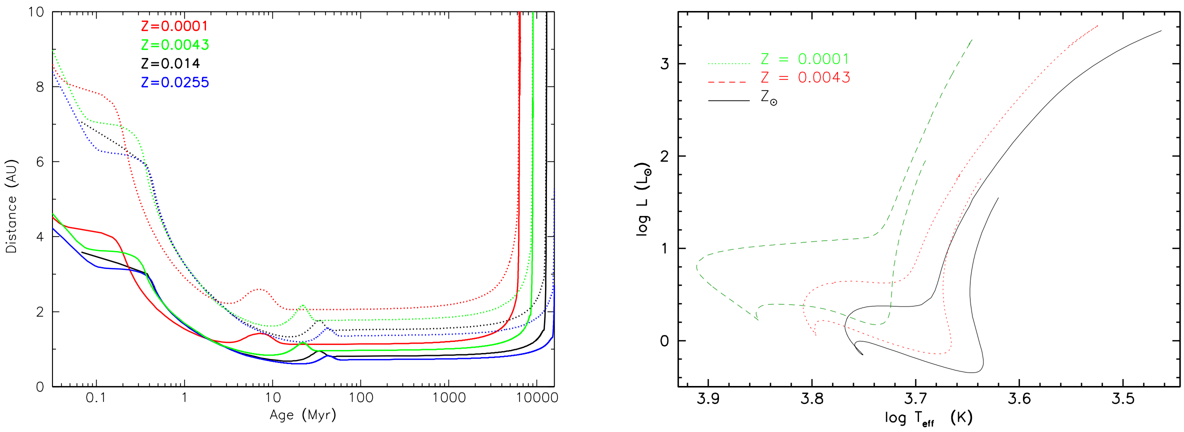

Fig. 2. Left: HZL as a function of the effective temperature for a 1 M$_{\odot}$ star and for four values of the metalliciy metallicity. The solid and dashed lines represent the inner and outer edge of the HZ, respectively. **Right:** Tracks in the HRD.

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, due to opacity effect, a shift in both effective temperature and luminosity that increase, at a given evolution phase, for decreasing metallicity. Figure 2 (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_{in} increases from 0.72 AU (Z= 0.0255) to 1.14 AU (Z= 0.0001) corresponding to an increase of 58%. For HZ_{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.

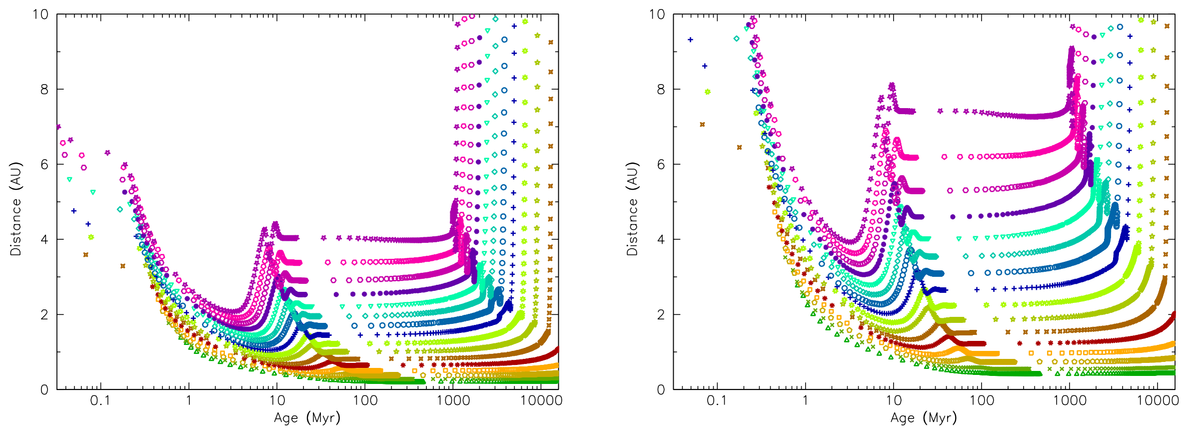

Fig. 3. Evolution of the inner (**Left**) and outer (**Right**) edge of the HZ as a function of time for stars between 0.5 (green triangle) and 2 (purple inclined star) M$_{\odot}$.

2.3 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 as well as to increase the size of the HZL. At ZAMS, the HZL increase from ≈ 0.5 AU for the 0.5 $M_\odot$ star to more than 8 AU for the 2 $M_\odot$. 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 low mass star is, on average, wider than higher 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).

3 Conclusions 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 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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References

Hayashi, C. 1961, PASJ, 13, 450

Kasting, J. F., Whitmire, D. P., & Reynolds, R. T. 1993, Icarus, 101, 108

Kopparapu, R. K., Ramirez, R., Kasting, J. F., et al. 2013, ApJ, 765, 131

Kopparapu, R. K., Ramirez, R. M., SchottelKotte, J., et al. 2014, ApJ, 787, L29

Lagarde, N., Decressin, T., Charbonnel, C., et al. 2012, A&A, 543, A108

Linsenmeier, M., Pascale, S., & Lucarini, V. 2015, Planet. Space Sci., 105, 43

Mayor, M. & Queloz, D. 1995, Nature, 378, 355

Quintana, E. V., Barclay, T., Raymond, S. N., et al. 2014, Science, 344, 277

Selsis, F., Kasting, J. F., Levrard, B., et al. 2007, A&A, 476, 1373

Torres, G., Kipping, D. M., Fressin, F., et al. 2015, ApJ, 800, 99