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Letter to the Editor

A Habitable Planet around HD 85512 ?

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ABSTRACT

Aims. In this study we assess the habitability of HD85512 b, a 3.6 M_{Earth} planet orbiting a K5V star. The radial velocity data and orbital parameters for HD 85512 b have just been published, based on data from the dedicated HARPS-upgrade GTO program.

Methods. This paper outlines a simple approach to evaluate habitability of rocky planets from radial velocity (RV) searches by using atmospheric models of rocky planets with $H_2O/CO_2/N_2$ atmospheres, like Earth. We focus our analysis on HD 85512 b. To first order the limits of the Habitable Zone depend on the effective stellar flux distribution in wavelength and time, the planet's Bond albedo, and greenhouse gas effects in this approach. We also discuss the dependence of habitability on the measurement accuracies.

Results. We provide a simple set of parameters which can be used for evaluating current and future planet candidates from RV searches for their potential habitability. We find that HD 85512 b could be potentially habitable if the planet exhibits more than 50% cloud coverage. HD 85512 b is, with Gl 581d, the best candidate for exploring habitability to date, a planet on the edge of habitability.

Key words. Astrobiology, Techniques: radial velocities, Earth, Planets and satellites: individual: HD 85512 b, atmospheres

1. Introduction

The dedicated HARPS-Upgrade GTO program recently published the RV data and the orbital parameters of a new low-mass planet of 3.6 ± 0.5 M_{Earth} min. mass around the star HD 85512 (Pepe et al. 2011). HD 85512 is a K5V star with 0.126 ± 0.008 L_{Sun}, 0.69 M_{Sun} and an effective temperature, T_{eff}, of 4715 ± 102. HD 85512 b orbits its star in 58.43 ± 0.13 days at 0.26 ± 0.005 AU with an eccentricity of 0.11 ± 0.1, which places it near the inner edge of the Habitable Zone (HZ) (table 1). Here we assume that the planet's actual mass is close to its min. mass, which is consistent with rocky planet models. The planet is one of the least massive planets detected to date. It is the least massive planet confirmed in the HZ.

Different aspects of what determines the boundaries of the HZ have been discussed broadly in the literature (see section 2). The width and distance of the HZ annulus - as well as T_{eff}, - for an Earth-like atmosphere depends to a first approximation on 4 main parameters: 1) incident stellar flux, which depends on stellar luminosity, spectral energy distribution and eccentricity of the system, 2) overall planetary Bond albedo, 3) greenhouse gas concentration, and 4) energy distribution in the planetary atmosphere. We compare these values to Earth, Venus as well as Gl 581c to assess the habitability of HD 85512 b.

We introduce the concept of the HZ in section 2, explore the influence of first order effects and how the measurement uncertainties for planetary candidates from RV searches, focussing on HD 85512 b, in section 3. Section 4 states our conclusions. Our approach can be applied to current and future candidates provided by RV searches.

2. The concept of the Habitable Zone

The HZ has been calculated by several groups (see e.g. [Kaltenegger & Sasselov, 2011], [Abe et al., 2011]). The main differences among these studies are the climatic constraints imposed. For this paper we focus on the circumstellar HZ ([Kasting et al., 1993], [Selsis et al., 2007]), defined as an annulus around a star where a planet with a $CO_2/H_2O/N_2$ atmosphere and a sufficiently large water content, like Earth, can host liquid water permanently on a solid surface. These atmosphere model only represents one possible nature of HD 85512 b in a wide parameter space (see results). Note that this definition of the HZ is adopted because it implies surface habitability and in turn allows remote detectability of life as we know it. Subsurface life that could exist on planets with very different surface temperatures is not considered here, because of the lack of remotely detectable atmospheric to assert habitability.

In this definition, the two edges of the HZ as well as the equilibrium temperature of the planet, T_{eq}, depend on the Bond albedo of the planet A, the luminosity of the star L_{star}, the planet's semi major axis D, as well as the eccentricity e, of the orbit, and in turn the average stellar irradiation at the planet's location. A more eccentric orbit increases the annually averaged irradiation proportional to $(1-e^2)^{-1/2}$ (see [Williams & Pollard, 2002]). In our atmospheric models the greenhouse effect is included in the overall albedo calculations. The inner edge of the HZ denotes

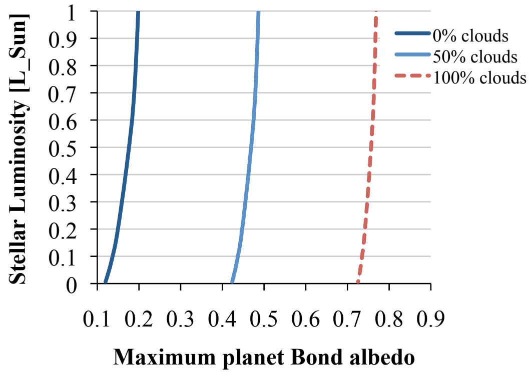

Fig. 1. Maximum planetary Bond albedo at the inner edge of the HZ derived for Earth-like atmosphere models for 0%, 50% and 100% clouds (from left to right).

the location where the entire water reservoir can be vaporized by runaway greenhouse conditions, followed by the photo-dissociation of water vapor and subsequent escape of free hydrogen into space. The outer boundary denotes the distance from the star where the max. greenhouse effect fails to keep CO_2 from condensing permanently, leading to runaway glaciation ([Kasting et al., 1993]). Note that at the limits of the HZ, the Bond albedo of a habitable planet is fully determined by its atmospheric composition and depends on the spectral distribution of the stellar irradiation (Fig. 1). For a planet with a dense atmosphere, like Earth, T_{eq} has to be below 270 K and above 175 K to be habitable (see e.g. [Kaltenegger & Sasselov, 2011]).

To simply estimate if a planet is potentially habitable ($175K \leq T_{eq} \leq 270K$), one can use eq.(1) to approximate T_{eq} for Earth-like planets around stars with T_{eff} from 7200 K to 3200 K using the max. albedo derived for different cloud coverage from Fig.1.

$$T_{eq} = ((1-A)L_{star}/(4\beta D^2(1-e^2)^{1/2}))^{1/4} \quad (1)$$

β represents the fraction of the planetary surface that reradiates the absorbed flux. β is 1 if the incident energy is uniformly reradiated by the entire surface of the planet, e.g. for a rapidly rotating planet with an atmosphere, like Earth (see results). Note that T_{eq} does not correspond to any physical temperature at the surface or in the atmosphere.

Fig.1 shows the max. albedo derived from these models for an Earth-like atmosphere. The specific effects of clouds on the albedo depends on their height as well as particle size distribution (see e.g. (Zsom et al in prep), [Goldblatt & Zahnle, 2011]). The 100% cloud value (dashed lines) is used here to show the extreme effect of clouds on the HZ in accordance with work by Selsis ([Selsis et al., 2007]). We model rocky planets with $H_2O/CO_2/N_2$ atmospheres to calculate the max. Bond albedo as a function of irradiation and atmosphere composition and the edges of the HZ for HD 85512 b. These models represent rocky geological active planets and produce a dense CO_2 atmosphere at the outer edge, an Earth-like atmosphere in the middle, and a dense H_2O atmospheres at the inner edge of the HZ. Between those limits, we assume that on a geological active planet, climate stability is provided by a feedback mechanism in which atmospheric CO_2 concentrations vary inversely with

Table 1. Parameters for HD 85512 b ([Pepe et al., 2011])

Parameters HD 85512	
Spectral Type	K5V
Distance [pc]	11.15
L [L_{Sun}]	0.126 ± 0.008
$T_{eff}[K]$	4715 ± 102
M [M_{Sun}]	0.69
Parameters HD 85512 b	
a [AU]	0.26 (±0.005)
e	0.11 (±0.10)
m sin i [M_{Earth}]	3.6 (±0.5)

planetary surface temperature. From the case studies by Kasting ([Kasting et al., 1993]) the inner l_{in}, and outer limit l_{out}, of the solar HZ can be extrapolated to stars with luminosity L, and T_{eff} between 3700 K and 7200 K using eq.(2).

$$l_x = (l_{xsun} - a_x T_{star} - b_x T_{star}^2)(L/L_{sun})^{1/2} \quad (2)$$

with $a_{in} = 2.761910^{-5}, b_{in} = 3.809510^{-9}, a_{out} = 1.378610^{-4}, b_{out} = 1.428610^{-9}$, and $T_{Star} = T_{eff} - 5700, l_x$ (l_{in} and l_{out}) in AU, and T_{eff} and T_{star} in K. Depending on the fractional cloud cover, the theoretical water loss limit ($T_{surf} = 373$K) of the HZ of our Solar System assuming 0%, 50% and 100% cloud coverage, give l_{in} as 0.95, 0.76 and 0.51 AU and l_{out} as 1.67, 1.95 and 2.4 AU, respectively (see e.g. [Selsis et al., 2007]). The inner limit for the 50% cloud case corresponds to the Venus water loss limit, a limit that was empirically derived from Venus position in our Solar System (0.72 AU). Note that a planet found in the HZ is not necessarily habitable, since many factors may prevent habitability like the lack of water.

3. Results

Using the specifics of HD 85512 b we demonstrate the influence of the main parameters on its position in the HZ as well as the potential habitability of the planet. Fig. 2 relates the uncertainties in the measurements for RV planets, e, D as well as L_{star} on its position in the HZ (right) and on the flux on top of the planetary atmosphere. S_0 is the solar flux received at the top of Earth's atmosphere at 1 AU, ($S_0 = 1360Wm^{-2}$). The error on the y-axis shows the uncertainty in L_{star} and the error on the x-axis shows the uncertainty in the planet's position (left) as well as its irradiation (right). The limits of the HZ are shown here for 0%, 50% and 100% cloud coverage for comparison. Note that the x-axis in Fig. 2 (right) is increasing toward the left because the irradiation of the planet increases with decreasing distance from its host star. The two panels in Fig. 2 relate the distance of the planet and the limits of the HZ to the flux received at the planet's position. The uncertainty of the derived e of 0.11 ± 0.1 is small and therefore does not changes the flux received at the planet's position significantly, only by +1.6% and -0.6%. The uncertainty of the planet's semi major axis of 0.26 ± 0.005 AU change the incident flux on top of the planet's atmosphere by +4% and 3.7%. The biggest factor in the measurement uncertainties in L_{star} of 0.126 ± 0.008 that changes the flux at the planet's location by 6.3%.

The min. flux on top of the planet's atmosphere is given for min. L_{star}, min. e, and max. D. The max. irradiation

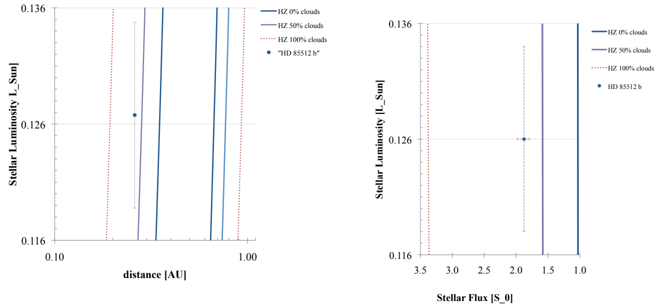

Fig. 2. Effect of the total measurement errors in semi-major axis and eccentricity and the resulting uncertainty (left) on the position in the HZ and (right) irradiation at the position of HD 85512 b in units of solar flux received at the top of Earth's atmosphere at 1 AU, $S_0 = 1360 W m^{-2}$. The error on the y-and x-axis shows the uncertainty in L_{star} and the planet's position (left) as well as its irradiation (right). The limits of the HZ are shown for 0%, 50% and 100% cloud coverage as comparison.

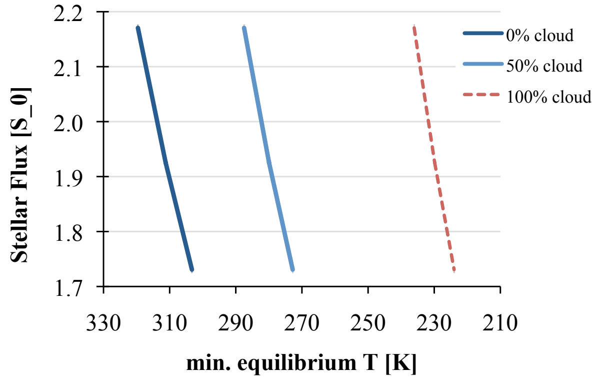

Fig. 4. Minimum T_{eq} of HD 85512 b for 0%, 50% and 100% cloud coverage (left to right). The y axis corresponds to the total uncertainty of the stellar flux received at the planet's location +12%, -10.7% in S_0, due to measurement uncertainties

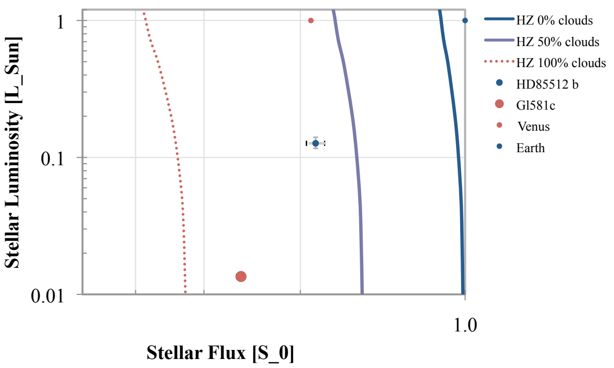

Fig. 3. L_{star} in L_{Sun}, versus stellar flux on top of the planetary atmosphere in S_0. The extent of the inner edge of the HZ for the water loss limit for 0%, 50% and 100% (dashed line) cloud coverage (from right to left) and Earth, Venus and Gl 581c are added for comparison.

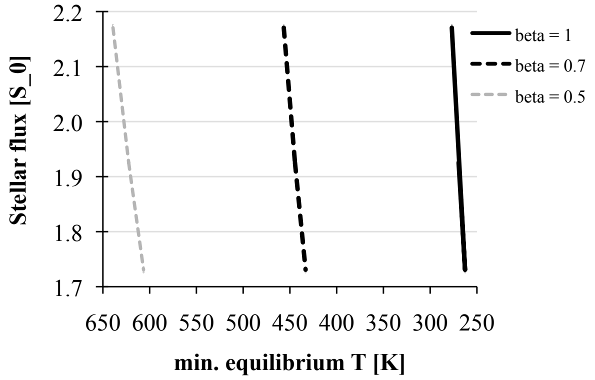

Fig. 5. Effect of the heat transfer parameter β on the T_{eq}. The range of the stellar flux on the y-axis corresponds to the maximum and minimum irradiation received by the planet due to stellar and planetary parameter uncertainties for HD 85512 b.

is given for max. L_{star}, max. e and min. D and change the planet's irradiation by about +12% and -10.7%. Even the max. increase in luminosity from uncertainties in the RV measurements does not put HD 85512 b outside the HZ.

Fig. 3 shows the L_{star} versus the stellar flux received on top of the planet's atmosphere in S_0. The error on the x-axis represents uncertainties in e and D, on the y-axis uncertainty in L_{star}. Earth, Venus as well as Gl 581c ([Mayor et al., 2009]) are added for comparison. The limits of the HZ are also shown for 0%, 50% and 100% cloud coverage. Gl 581 c receives about 30% more flux than Venus (1.91 S_0), while HD 85512 b receives 2% to 3% less flux than Venus on a circular (1.86 S_0) or eccentric (1.875 S_0) orbit, respectively. The total measurement uncertainties of +12% and -10.7% on the planet's irradiation change the overall flux received at HD 85512 b's position from 88% to 110% of the flux received by Venus. Fig. 4 and Fig. 5 show the influence of the planetary atmosphere model parameters on T_{eq} and habitability, the max. Bond albedo and β resectively. The curves represent models of 0%, 50% to 100% cloud cover respectively. We find that HD 85512 b could be potentially habitable if the planet exhibits more than 50% cloud coverage, assuming $\beta = 1$.

There is no indication of a second planet in the system as of now and e is expected to be zero. A planetary albedo of 0.48 for a circular orbit and 0.52 ± 0.05 for $e = 0.11 \pm 0.1$ is needed to keep T_{eq} below 270 K and the planet potentially habitable. As comparison Venus has a Bond albedo of about 0.75, while Earth and Mars have a Bond albedo of about 0.3, and 0.2 respectively. We let the reradiation parameter β (characterizing heat transfer around the planet) vary from 0.5 to 1 since we cannot rule out tidal locking. Fig.5 shows T_{eq} for HD 85512 b as a function of β factor for a Bond albedo of 0.52, which corresponds to the min. albedo needed to keep T_{eq} below 270K for e=0.11 and $\beta = 1$. Parameterizing the heat transfer is only a rough approximation to show the resulting effect and detailed 3D models are needed to verify these results. To keep T_{eq} below 270 K for $\beta = 0.7$, the planet would need a min. Bond Albedo of 0.9. For lower values of β $T_{eq} > 270$K. For atmospheres like Earth's, it is unlikely that β is much lower than 1. Detailed models have shown that even for planets in synchronous rotation direct illumination of only one hemisphere does not prevent habitability for planets with even modestly dense atmospheres like Earth (see e.g. [Edson et al., 2011]), provided atmospheric cycles transport heat from the dayside to the nightside.

The first planets below 10 M_{Earth}, with both mass estimates and radius measurements, have provided a wide range of observed radii and densities. Especially in the mass range below $5M_{Earth}$, two planets in the multiple planet system, Kepler 11b and Kepler 11f ([Lissauer et al., 2011]), with 4.3 and $2.3M_{Earth}$ have radii of 1.97, 2.61 Earth radii and mean densities of 3.1, 0.7 g/cm^3, respectively. These derived densities also allow substantial envelopes of light gases for this mass range. We do not discuss observed planets with a mean density comparable to Earth, e.g. Corot 7b ([Léger et al., 2009]) and Kepler 10b ([Batalha et al., 2011]), here, because of their close distance to their host star and resulting temperature range that is much higher than for HD 85512 b. Such temperature differences would most likely influence the atmospheric composition. New Kepler results are expected to increase our sample of such planet's in the HZ. A larger sample will improve our understanding of this field and promises to explore a very interesting parameter space that indicates the potential coexistence of extended H/He and H_2O dominated atmospheres as well as rocky planet atmospheres in the same mass and temperature range. In this paper we only explore the potential habitability of HD 85512 b, assuming atmospheric models of rocky planets with $H_2O/CO_2/N_2$ atmospheres, like Earth, leaving the interesting question open whether a planet with an extended $H/He/H_2O$ could also be potentially habitable.

4. Discussion

Recent investigations of high precision radial velocity data samples have shown that between 20% and 50% of all sample stars exhibit RV variations indicating the presence of super-Earths or ice giants ([Lovis et al., 2009], [Howard et al., 2011]). Among them are two other possibly rocky planets around Gl 581 with masses of 5 and 8 M_{Earth}, respectively, lying at the edge of the HZ of their parent star ([Udry et al., 2007], [Mayor et al., 2009]). We do not include the unfortunately unconfirmed planet Gl581g in our analysis ([Forveille et al. in prep]).

The habitability of the most interesting planet until now, Gl 581 d, was discussed in detail by several groups (see e.g. [Kaltenegger et al., 2011]). On the outer edge of the HZ, Gl 581d requires several bar of CO_2 to remain habitable. Its min. mass is about two times that of HD 85512 b, increasing the probability of a substantial H/He envelope compared to HD 85512 b. As no radius is available for Gl 581d or HD 85512 b, the mean density of the planets can not be derived. A spectrum of its atmosphere is needed to distinguish a habitable world versus a Mini-Neptune (see e.g. [Kaltenegger et al., 2010]).

Our atmosphere models for HD 85512 b only include the greenhouse effects of H_2O, CO_2 and N_2. Any additional greenhouse gas that could be present on such hot planets could in additional increase the temperature of the planets surfaces. The effect of other greenhouse gasses on the inner edge of the HZ has not been explored yet and has therefore not been addressed here.

We assume that the planet's mass is similar to its min. mass here, what leads to a surface gravity of about 1.4 g for HD 85512 b, scaling its gravity with the mass and volume of a rocky planet. Atmosphere model calculations for a planet with surface gravity of 2.5 g found that the effects of increased gravity roughly compensate and the inner edge of the HZ is only 3% closer to the host star [Kasting et al., 1993]. For the expected gravity of HD 85512 b, this effect can be neglected.

5. Conclusions

This paper outlines a simple approach to evaluate habitability of rocky planetary candidates from radial velocity searches by assuming models for rocky planets with $H_2O/CO_2/N_2$ atmospheres, like Earth. We focus our analysis on HD 85512 b. We show the influence of the measurement uncertainties on its location in the Habitable Zone as well as its potential habitability. We find that HD 85512 b could be potentially habitable if the planet exhibits more than 50% cloud coverage. A planetary albedo of 0.48 $\pm$ 0.05 for a circular orbit, and an albedo of 0.52 for e=0.11 is needed to keep the equilibrium temperature below 270K and the planet potentially habitable.

With its low mass and its incident irradiation slightly lower than Venus, HD 85512 b is, with Gl 581 d, the best candidate for habitability known to date. If clouds were increasing the albedo of HD 85512 b, its surface could remain cool enough to allow for liquid water if present. HD 85512 b is a planet on the edge of habitability.

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