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The habitable zone of Earth-mass planets around 47 UMa: results for land and water worlds

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Abstract: In a previous paper, we showed that Earth-type habitable planets around 47 UMa are in principle possible if a distinct set of conditions is warranted. These conditions include that the Earth-type planets have successfully formed and are orbitally stable and, in addition, that the 47 UMa star–planet system is relatively young ($\lesssim$6 Gyr). We now extend this study by considering Earth-like planets with different land/ocean coverages. This study is again based on the so-called integrated system approach, which describes the photosynthetic biomass production taking into account a variety of climatological, biogeochemical and geodynamical processes. This approach implies a special characterization of the habitable zone defined for a distinct type of planet. We show that the likelihood of finding a habitable Earth-like planet on a stable orbit around 47 UMa critically depends on the percentage of the planetary land/ocean coverage. The likelihood is significantly increased for planets with a very high percentage of ocean surface ('water worlds').

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Introduction

Over the last decade very significant progress has been made in the detection and assessment of planets around stars other than the Sun. Based on the available observational techniques, most detected objects are giant (Jupiter-like) planets (or brown dwarfs if $M > 13M_J$), although a few planets with sub-Saturn masses have also been identified (e.g. Marcy & Butler 1998, 2000; Marcy *et al.* 2000; Butler *et al.* 2002). On the other hand, no Earth-type planets have been found yet with the likely exception of Earth-mass planets around the pulsar PSR 1257+12 (Wolszczan & Frail 1992). The first planet found around an ordinary stars has been 51 Peg b, a close-in 'hot Jupiter' (Mayor & Queloz 1995). The existence of Earth-type planets around stars other than the Sun is strongly implied by various observational findings including: (1) the steep rise of the mass distribution of planets with decreasing mass, which implies that more small planets form than giant ones; (2) the detection of protoplanetary discs (with masses between 10 and 100 times that of Jupiter) around many solar-type stars younger than $\sim$3 Myr; and (3) the discovery of 'debris discs' around middle-aged stars, the presumed analogues of the Kuiper belt and zodiacal dust (Marcy & Butler 2000 and references therein).

The focus of present-day research on Earth-type planets includes studies of the orbital stability of those planets as well as highly preliminary studies of habitability. A system of particular interest is that of 47 UMa because it resembles our own solar system most closely. First, 47 UMa hosts two Jupiter-mass planets in nearly circular orbits at respectable distances from the host star (i.e. 2.09 and 3.73 AU). These two Jupiter-type planets were discovered by Butler & Marcy (1996) and Fischer *et al.* (2002), respectively, who also deduced values for the orbital eccentricities of the planets. Secondly, it is known that there are no Jupiter-mass planets in the inner region around the star, which would otherwise thwart the formation of terrestrial planets at Earth-like distances around the star (e.g. Wetherill 1996; Laughlin *et al.* 2002) or would trigger orbital instabilities for those planets (e.g. Noble *et al.* 2002) during inward migration (Boss 1995). Thirdly, it is found that the central star has properties very similar to those of the Sun, including effective temperature, spectral type and metallicity (Henry *et al.* 1997; Gonzalez 1998). Metallicities not too dissimilar to the Sun are probably required for building up Earth-type habitable planets, even though no information exists regarding the frequency of terrestrial planets as a function of stellar metallicity (e.g. Gonzalez *et al.* 2001).

The analysis of orbital stability of (hypothetical) terrestrial planets in extra-solar planetary systems has to take into account the effects of the giant planet(s) in those systems. In many cases the giant planets restrict the orbital stability of the terrestrial planet to a small or very small orbital domain or prevent orbital stability completely. For recent studies concerning Earth-mass planets in the 47 UMa system see Fischer *et al*. (2002), Noble *et al*. (2002), Jones & Sleep (2002) and Godźiewski (2002). Jones & Sleep (2002) provided extensive calculations considering the presence of both giant planets. They concluded that terrestrial planets are in principle orbitally stable within about 1.2 AU of the star, assuming that they stay away from mean-motion resonances, and some extreme values for the masses and eccentricities of the giant planets are not realized. A further study has been given by Godźiewski (2002), which is based on a different type of integration method. He found that the default habitable zone (HZ) of 47 UMa is characterized by an alternation of narrow stable and unstable zones with the latter being related to the mean motion and secular resonances with the giant planets. Beyond 1.3 AU, no stable zones were found.

If orbital stability of terrestrial planets is warranted within a certain distance from the star, studies of habitability are motivated. Principle results on habitability for different types of stars have been given by Kasting *et al*. (1993). They studied the position and extent of stellar habitable zones around different types of stars and showed that the stellar luminosity is the most decisive parameter in that respect. For more recent results see, for example, Williams & Pollard (2002) and references therein. In this paper, we adopt a somewhat different definition of HZ (already used by Franck *et al*. 1999, 2000a, b). Here habitability (i.e. the presence of liquid water at all times) does not just depend on the parameters of the central star, but also on the properties of the planet itself (an 'integrated system approach'). In particular, habitability is linked to the photosynthetic activity of the planet, which in turn depends on the planetary atmospheric CO_2 concentration, and is thus strongly influenced by the planetary geodynamics. This leads to additional spatial and temporal limitations on habitability, as the stellar HZ (defined for a specific type of planet) becomes narrower with time due to the persistent decrease of the planetary CO_2 concentration.

This concept has also been used by Cuntz *et al*. (2003) in our previous study of habitability for 47 UMa. In this paper, we studied three different continental growth models, which were: delayed growth, linear growth and constant area. We found that Earth-type habitable planets around 47 UMa are possible in principle, but are much less likely than in a system with solar system-like properties, defined by the luminosity of the central star and the orbital distances of two Jupiter-type planets. In the event of successful formation, the likelihood of Earth-type planets was found to be increased if it is assumed that 47 UMa has a relatively low luminosity and that the 47 UMa star–planet system is relatively young ($\lesssim$6 Gyr). A relatively low stellar luminosity of 47 UMa is required to establish the HZ relatively close to the star. Otherwise, terrestrial planets are subjected to orbital instabilities initiated by the two Jupiter-size planets. A relatively small age is relevant in the view of the adopted planetary growth models. The reason is that if the age of the star–planet system is 6 Gyr or less, the existence of life is consistent with all three continental growth models taken into consideration.

Note that Cuntz *et al*. (2003) considered an Earth-like land/ocean distribution for their planetary surface models. In this paper, we will relax this assumption by allowing the continental area to vary between 10% and 90%. This will definitely affect the planetary habitability, and will furthermore result in different habitable zones around 47 UMa in response to the different planetary models. Our paper is structured as follows. In the following section, we discuss the integrated system approach used in our models, allowing one to define habitability. Thereafter, we discuss our models and present our conclusions.

The integrated system approach

On Earth, the carbonate–silicate cycle is the crucial element for long-term homeostasis under increasing solar luminosity. In most studies (e.g. Caldeira & Kasting 1992), the cycling of carbon is related to the tectonic activities and to the present continental area as a snapshot of the Earth's evolution. On the other hand, on geological time-scales the deeper parts of the Earth are considerable sinks and sources for carbon. In addition, the tectonic activity and the continental area change noticeably. Therefore, we favour the so-called geodynamical models, which take into account both the growth of continental area and the decline in the spreading rate (Franck *et al*. 2000a).

Our numerical model couples the stellar luminosity, L, the silicate-rock weathering rate, $F_{\rm wr}$, and the global energy balance to allow estimates of the partial pressure of atmospheric and soil carbon dioxide, $P_{\rm atm}$ and $P_{\rm soil}$, respectively, the mean global surface temperature, $T_{\rm surf}$, and the biological productivity, Π, as a function of time, t (Fig. 1). The main point is the persistent balance between the CO_2 sink in the atmosphere–ocean system and the metamorphic (plate-tectonic) sources. This is expressed with the help of dimensionless quantities

$$f_{\rm wr} f_{\rm A} = f_{\rm sr}, \tag{1}$$

where $f_{\rm wr} \equiv F_{\rm wr}/F_{\rm wr,0}$ is the weathering rate normalized by the present value, $f_{\rm A} \equiv A_{\rm c}/A_{\rm c,0}$ is the continental area normalized by the present value, and $f_{\rm sr} \equiv S/S_0$ is the spreading rate normalized by the present value. Equation (1) can be rearranged by introducing the geophysical forcing ratio (GFR):

$$f_{\rm wr} = \frac{f_{\rm sr}}{f_{\rm A}} =: \mathrm{GFR}. \tag{2}$$

With the help of equation (2), we can calculate the normalized weathering rate from geodynamics based on the continental growth model and spreading rate (Franck *et al*. 2000a). For the investigation of an Earth-like planet under the external forcing of 47 UMa, a G1V star (Henry *et al*. 1997), we adopt a model planet with a prescribed continental area.

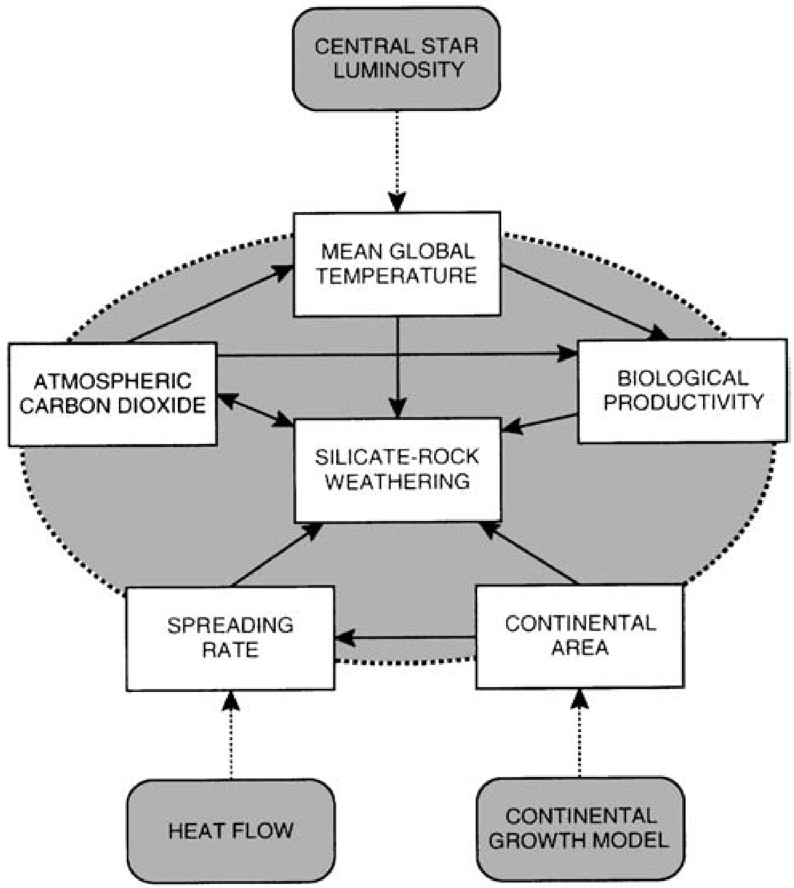

Fig. 1. Box model of the integrated system approach (Franck *et al.* 2000a; Cuntz *et al.* 2003). The arrows indicate the different forcings (dotted lines) and feedback mechanisms (solid lines).

The fraction of continental area to the total planetary surface is varied between 0.1 and 0.9. The resulting geophysical forcing ratios are shown in Fig. 2.

The connection between the stellar parameters and the planetary climate can be formulated using a radiation balance equation (Williams 1998)

$$\frac{L}{4\pi R^2}[1-\alpha(T_{\rm surf}, P_{\rm atm})]=4I_{\rm R}(T_{\rm surf}, P_{\rm atm}), \tag{3}$$

where α denotes the planetary albedo, $I_{\rm R}$ is the outgoing infrared flux and R is the distance from the central star.

In our model, biological productivity is considered to be solely a function of the surface temperature and the CO_2 partial pressure in the atmosphere,

$$\frac{\Pi}{\Pi_{\rm max}}=\left[1-\left(\frac{T_{\rm surf}-50\,^{\circ}{\rm C}}{50\,^{\circ}{\rm C}}\right)^2\right]\left[\frac{P_{\rm atm}-P_{\rm min}}{P_{1/2}+(P_{\rm atm}-P_{\rm min})}\right], \tag{4}$$

where $\Pi_{\rm max}$ denotes the maximum biological productivity, which is assumed to amount to twice the present value Π_0 (Volk 1987). $P_{1/2}+P_{\rm min}$ is the value at which the pressure-dependent factor is equal to 1/2, and $P_{\rm min}$ is fixed at 10^{-5} bar, the presumed minimum value for C_4 photosynthesis (Pearcy & Ehleringer 1984; Larcher 1995). The evolution of the biosphere and its adaption to even lower CO_2 partial pressures are not taken into account in our model. For a given $P_{\rm atm}$, equation (4) yields maximum productivity at $T_{\rm surf}=50\,^{\circ}$C and zero productivity for $T_{\rm surf}\leqslant 0\,^{\circ}$C and $T_{\rm surf}\geqslant 100\,^{\circ}$C. At this point we should emphasize that all calculations are performed for a planet with Earth mass and size, and an Earth-like radioactive heating rate in its interior.

The HZ around 47 UMa is defined as the spatial domain where the planetary surface temperature stays between 0 and 100 °C and where the atmospheric CO_2 partial pressure is higher than 10^{-5} bar to allow photosynthesis. This is equivalent to a non-vanishing biological productivity, $\Pi>0$, i.e.

$$\text{HZ}:=\{R|\Pi(P_{\rm atm}(R,t), T_{\rm surf}(R,t))>0\}. \tag{5}$$

In previous studies the habitability around different types of stars has been assessed based on the results of Kasting *et al.* (1993). In this approach, the HZ is limited only by climatic constraints invoked by the luminosity of the central star. Our method described, which has already been adopted in previous studies (Cuntz *et al.* 2003), relies on additional constraints, however. First, habitability is linked to the photosynthetic activity of the planet (equation 5) and secondly, habitability is strongly affected by the planetary geodynamics. In principle, this leads to additional spatial and temporal limitations of habitability.

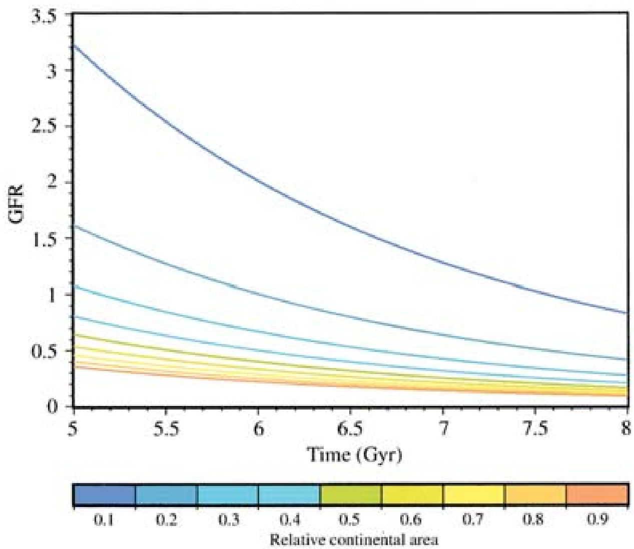

Fig. 2. The time-dependent geophysical forcing ratio for different relative continental areas.

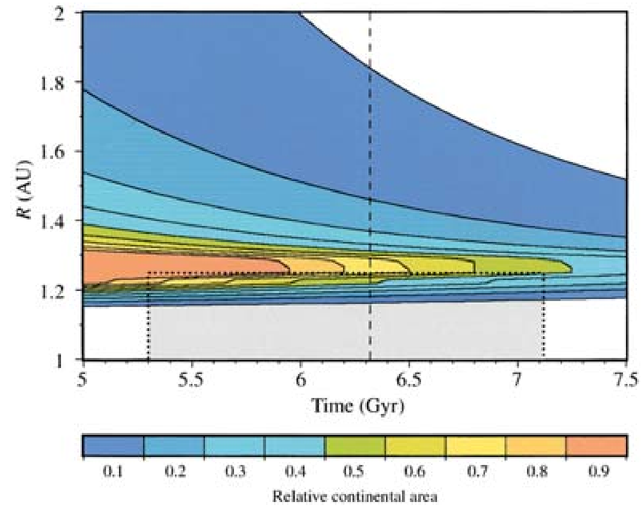

Fig. 3. The habitable zone around 47 UMa for the likely value of luminosity of $L = 1.54\ L_{\odot}$. The coloured areas indicate the extent of the HZ for different relative continental areas. The grey shaded area indicates the permissible parameter space as constrained by the stellar age and the orbital stability limit at 1.25 AU.

Results and discussion

Planetary habitability requires orbital stability of the Earth-type planet over a biologically significant length of time in the HZ. As mentioned above, there exists a variety of papers discussing the orbital stability of (hypothetical) terrestrial planets in the 47 UMa system, which is strongly influenced by the masses, orbital positions and eccentricities of the two Jupiter-size planets in that system. Therefore, we assume a representative value for the outer boundary of the orbital stability that is $R_{max} = 1.25$ AU (Cuntz *et al.* 2003). In order to calculate the HZ within the framework of our model it is necessary to estimate the age and the luminosity of the central star 47 UMa. Following the discussion of Cuntz *et al.* (2003) the mean luminosity L of 47 UMa is given as $1.54\ L_{\odot}$ based on Hipparcos data. For the lower and upper limit of L, we assume $1.41\ L_{\odot}$ and $1.67\ L_{\odot}$, respectively. As the stellar age, we assume 6.32 (+1.2, −1.0) Gyr based on stellar evolution computations (Ng & Bertelli 1998) and the Ca II age–activity relation (Henry *et al.* 2000).

In Fig. 3 we show the results of our calculations of the HZ for the likely value $L = 1.54\ L_{\odot}$ of the central star luminosity (colour shaded) and the grey-shaded range of orbital stability, $R \leqslant R_{max}$. The intersection of the two areas describes the interesting parameter range where an Earth-like planet on a stable orbit can exist within the HZ. It is evident that an almost completely ocean-covered planet ('water world') has the highest likelihood of being both habitable and orbitally stable. If the planet is covered with more than 50% continental area, then habitability and orbital stability cannot be found for the entire assumed range of stellar age. For a continental area of more than 90% of the total surface, no habitable solutions also meeting the requirement of orbital stability exist.

The likelihood that an Earth-like planet is both on a stable orbit and also within the stellar HZ can be quantitatively estimated from the ratio of the intersection of the HZ and the range of stable orbits. The likelihood is shown in Fig. 4 for three different luminosities, i.e. $1.41\ L_{\odot}$, $1.54\ L_{\odot}$, $1.67\ L_{\odot}$ and $t = 6.32$ Gyr as a function of the relative continental area. The likelihood decreases with increasing luminosity and increasing continental area. For $L \geqslant 1.54\ L_{\odot}$ no habitable and stable orbits can be found for a relative continental area greater than about 0.8. This limit is further reduced to about 0.4 in the case of $L = 1.67\ L_{\odot}$. Furthermore, we can reassess the relevance of the outer orbital stability limit invoked by the two Jupiter-size gas planets. Jones & Sleep (2002) have argued that the outer stability limit is at 1.2 AU and even closer to the star if relatively large masses and/or relatively high eccentricities are assumed for the two gas

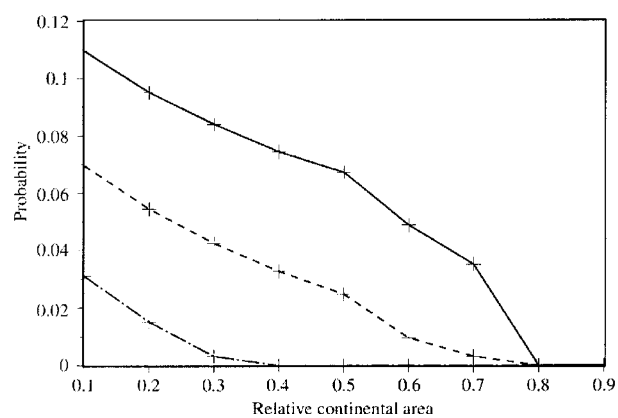

Fig. 4. Quantitative estimate of the relative likelihood of an Earth-like planet around 47 UMa with an assumed age of 6.32 Gyr, taking into account orbital stability and habitability. We assume the following luminosities: $1.41\ L_{\odot}$ (solid line), $1.54\ L_{\odot}$ (dashed line) and $1.67\ L_{\odot}$ (dashed-dotted line).

giants. In fact, assuming a continental area of only 10 %, we find that even in this case habitable solutions are at least mathematically possible. For an age of 6.32 Gyr and stellar luminosities of 1.41 $L_{\odot}$, 1.54 $L_{\odot}$ and 1.67 $L_{\odot}$, we find that habitability is still possible at an orbital distance of 1.11, 1.16 and 1.21 AU, respectively.

In general, we can state that finding an Earth-like habitable extrasolar planet is more promising the younger the system is and the lower its land coverage on its surface. Younger systems tend to be more geodynamically active and therefore contain more carbon dioxide in the planetary atmosphere. This leads to a stronger greenhouse effect and a broader HZ. Consequently, habitability is maintained at larger distances from the stars, i.e. regions of lower stellar flux densities, as also pointed out by Forget & Pierrehumbert (1997), Mischna *et al*. (2000) and others in their studies on the early Martian climate. In the case of Earth-like planets around 47 UMa, the relevance of this effect is seriously reduced, however, due to the lack of orbital stability of planets beyond about 1.25 AU. Planets with a relatively high percentage of land coverage show stronger weathering and therefore enhanced removal of carbon dioxide from the atmosphere. This leads to a weaker greenhouse effect and habitability ceases at smaller ages.

Conclusions

We studied in principle the possibility of Earth-like habitable planets around 47 UMa, assuming that these planets have successfully formed and are orbitally stable. In particular, we considered Earth-like planets with different land/ocean coverages. This study is again based on the integrated system approach, which describes photosynthetic biomass production under geodynamic conditions. We show that the likelihood of finding a habitable Earth-like planet on a stable orbit around 47 UMa depends critically on the percentage of the planetary land/ocean coverage. We find that an almost completely ocean-covered planet (a 'water world') has the highest likelihood of being both habitable and orbitally stable. On the other hand, for a stellar luminosity of $L = 1.54\ L_{\odot}$, the favoured value, habitability and orbital stability cannot be attained for the entire uncertainty range of stellar age if the planet is covered with more than 50 % continental area. For a continental area of more than 90 %, no habitable solutions meeting the requirement of orbital stability exist. The reason for this is that planets with increased land coverage show stronger weathering and therefore increased removal of carbon dioxide from the atmosphere, thus limiting habitability. In the case of 47 UMa the additional constraint of orbital stability also demands a relatively small stellar luminosity (within the observed range). We want to emphasize that our planet Earth can be classified as a 'water world' with a low relative continental area of about 1/3. Therefore, our Earth would have a slight chance of being habitable on a stable orbit in the 47 UMa system.

Acknowledgments

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