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On the possibility of Earth-type habitable planets around 47 UMa

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Abstract

We investigate whether Earth-type habitable planets can in principle exist in the planetary system of 47 UMa. The system of 47 UMa consists of two Jupiter-size planets beyond the outer edge of the stellar habitable zone, and thus resembles our own Solar System most closely compared to all exosolar planetary systems discovered so far. Our study of habitability deliberately follows an Earth-based view according to the concept of Franck and colleagues, which assumes the long-term possibility of photosynthetic biomass production under geodynamic conditions. Consequently, a broad variety of climatological, biogeochemical, and geodynamical processes involved in the generation of photosynthesis-driven life conditions is taken into account. The stellar luminosity and the age of the star/planet system are of fundamental importance for planetary habitability. Our study considers different types of planetary continental growth models and takes into account a careful assessment of the stellar parameters. In the event of successful formation and orbital stability, two subjects of intense research, we find that Earth-type habitable planets around 47 UMa are in principle possible! The likelihood of those planets is increased if assumed that 47 UMa is relatively young ($\lesssim$6 Gyr) and has a relatively small stellar luminosity as permitted by the observational range of those parameters.

Keywords: Exobiology; Extrasolar planets; Geophysics; Orbits

1. Introduction

Planets have now been observed around nearly 100 solar-type stars. 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 and Butler, 1998, 2000; Marcy et al., 2000; Butler et al., 2002). In addition, the discovery of 10 exosolar planetary systems (i.e., υ And, HD 168443, GJ 876, HD 82943, HD 74156, 47 UMa, 55 Cnc, HD 37124, HD 12661, HD 38529) has now also been reported (in addition to one unconfirmed case). Clearly, the ultimate quest of extra-solar planet research is to identify Earth-type planets located in the habitable zones (HZs) of their host stars, which, however at the present time, is still beyond technical feasibility. Nevertheless, the presence of terrestrial planets around other stars is strongly implied by various observational findings, which include (1) the steep rise of the mass distribution of planets with decreasing mass, which implies that more small planets form than giant ones (albeit different formation mechanisms for gas giant and terrestrial planets); (2) the detection of protoplanetary disks (with masses between 10 and 100 times that of Jupiter) around many solar-type stars younger than ~3 Myr; (3) evidence of rapid growth (within 0.1 Myr) of dust particles based on IR and millimeter-wave observations; and (4) the discovery of "debris disks" around middle-aged stars, the presumed analogs of the Kuiper belt and zodiacal dust (Marcy and Butler, 2000, and references therein).

The study of hypothetical terrestrial planets around 47 UMa is particularly interesting because this system 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 and Marcy (1996) and Fischer et al. (2002), respec-

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tively, who also deduced values for the orbital eccentricities of the planets. Second, 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 in Earth-like distances around the star (e.g., Wetherill, 1996; Laughlin et al., 2002) or would trigger orbital instabilities for those planets (e.g., Jones et al., 2001; Noble et al., 2002) during inward migration (Boss, 1995). Third, it is found that the central star has properties very similar to 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 as pointed out by Gonzalez et al. (2001) and others. Gonzalez et al. even used this criterion for defining the Galactic Habitable Zone (GHZ) in our galaxy.

It is well known that the position of a Jupiter-type planet relative to the star critically determines whether terrestrial-type planets are able to form. A key study has been given by Wetherill (1996), who explored (among other topics) the number of habitable planets (as defined according to Kasting et al. (1993)) dependent on the orbital radius of "Jupiter," which was treated as a free parameter. He found that if the orbital radius of Jupiter was chosen too small, the number of Earth-type planets was drastically reduced largely because the planetary embryos perturb one another, preventing them from growing into larger objects. On the other hand, the number of habitable planets will also depend on the particulars of the protoplanetary disk, including the surface density structure. A more recent study that focuses on the dynamical evolution of the 47 UMa giant planet system and on the possibility of terrestrial planet formation around 47 UMa has been presented by Laughlin et al. (2002). They noted that the formation of Earth-type planets around 47 UMa is much less likely than in a solar-type system due to the close proximity of the two Jupiter-type gas giants. On the other hand, they argued that if sufficiently large planetary embryos did form during the runaway accretion phase, a large unaccreted embryo could exist in the HZ of 47 UMa, and this body may be large enough to support Earth-type plate tectonics, a likely prerequisite for Earth-type biological evolution.

A pivotal requirement for biological evolution of life, including intelligent life, is long-term orbital stability of Earth-like planets around their host stars. Orbital stability of terrestrial-type planets has been investigated by Gehman et al. (1996), who considered several early discovered systems with giant planets, and more recently by Jones et al. (2001), who studied ρ CrB, 47 UMa, GJ 876, and υ And. The main conclusion of the latter paper is that orbits of terrestrial planets around 47 UMa are likely to be stable over time spans of biological significance. For more recent work see also Fischer et al. (2002), Noble et al. (2002), Jones and Sleep (2002), and Goździewski (2002). Typically, stellar HZs are defined as regions near the central star, where the physical conditions are favorable for liquid water to be available at the planet's surface for a period of time long enough for biological evolution to occur (e.g., Franck et al., 2000b). A number of attempts has been made to determine the extent of HZs for different types of main-sequence stars (e.g., Hart, 1979; Kasting et al., 1993; Forget and Pierrehumbert, 1997; Kasting, 1997; Franck et al., 2000a,b). These studies show that the stellar luminosity is the decisive parameter for defining the position and extent of the HZs.

In the following, we adopt a definition of HZ previously used by Franck et al. (2000a,b). Here habitability (i.e., 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 planetary climate model ("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. In principle, this leads to additional spatial and temporal limitations of 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 already been applied to planet Earth (Franck et al., 1999, 2000a), and has also been used in habitability studies of different types of stars during main-sequence evolution (Franck et al., 2000b). Moreover, this type of concept has also been used for estimating the number of Earth-type planets ("Gaias") in our galaxy (Franck et al., 2001).

Our paper is structured as follows: In Section 2, we discuss our methods and the stellar parameters. Section 3 describes our studies of planetary habitability in the 47 UMa system. Section 4 gives our conclusions.

2. Methods and stellar parameters

2.1. Orbital stability analysis

Planetary habitability requires orbital stability of the Earth-type planet over a biologically significant length of times in the stellar HZ. Detailed studies regarding 47 UMa have been given by Gehman et al. (1996), Jones et al. (2001), Fischer et al. (2002), Noble et al. (2002), and Jones and Sleep (2002), which indicate that this condition is fulfilled in at least some parts of the 47 UMa HZ. *Note that in those papers a traditional definition of stellar HZ is adopted, i.e., the HZ is solely given by the stellar luminosity, and does not depend on the planetary models.*

Jones et al. (2001) explored the dynamical stability for terrestrial planets within HZs of four stars with detected gas giant planets. Without knowing about the second giant planet later discovered by Fischer et al. (2002), they concluded that 47 UMa is the best candidate to harbor terrestrial planets in orbits that could remain confined to the HZ. Jones et al. assumed a terrestrial planet of one Earth mass that was put at different initial positions of the stellar HZ. The orbital motion of that planet was followed to up to 1×10^9 years using a mixed variable symplectic integration method. Orbital instability was assumed if the terrestrial planet entered the so-called Hill radius of the innermost giant planet. They found that the outermost stable orbit is close to 1.32 AU. Jones et al. also considered nonzero inclinations between terrestrial and gas giant orbits up to $i = 10°$, which did, however, not seriously impact their results.

Previously, a less rigorous orbital stability limit was given by Gehman et al. (1996) using an analytical approach, and also assuming somewhat preliminary orbital data for the 47 UMa system. They argued that the outer boundary of the zone of orbital stability for the terrestrial planet is at 1.6 AU, which is not inconsistent with the results obtained by Jones et al. (2001). A study that also considered the existence of the second Jupiter-type has been given by Noble et al. (2002). The authors explored orbital stability for a one Earth-mass planet in the 47 UMa system initially placed at 1.13, 1.44, and 1.75 AU inside the stellar HZ. Noble et al. identified orbital stability for the initial position at 1.13 AU, but no orbital stability for 1.44 and 1.75 AU was obtained, consistent with the findings by Jones et al. In case of the initial position at 1.44 AU, the terrestrial planet was found to wander between 1.185 and 1.617 AU in the first 700 years of orbital integration thwarting any possibility of habitability. In the paper by Fischer et al. (2002), in which the discovery of the second giant planet has been announced, the authors also briefly discussed the effects of the secondary giant planet on the orbital stability of terrestrial planets. They argued that orbital stability of terrestrial planets is warranted as most test Earth-mass planets are found to survive within the HZ over 10^6-year timescales. On the other hand, this study is only of limited use as the authors did not communicate the extent of the stellar HZ used in those computations.

Subsequent work by Jones and Sleep (2002) also considered the presence of the two giant planets. They argued that the second giant planet noticeably reduces the range of orbital stability of Earth-mass planets in the HZ of 47 UMa. In those simulations, the outer radius of orbital stability was found to be as low as 1.2 AU. This value is, however, also affected by the possible mass and eccentricity ranges of the Jupiter-type planets taken into consideration. Nonetheless, the authors again concluded that Earth-type planets are still possible in the inner part of the present-day stellar HZ (note again the definition of HZ used here!), assuming that they stay away from mean-motion resonances invoked by the two giant planets and that certain extreme values for the masses and eccentricities of the giant planets are not realized.

A further paper that analyzes the orbital stability of Earth-mass planets has been given by Goździewski (2002), based on the so-called MEGNO integration technique. He found that the HZ of 47 UMa is characterized by an alternation of narrow stable and unstable zones with the latter related to the mean motion and secular resonances with the giant planets. Beyond 1.3 AU, no stable zones were found. The positions and widths of the various unstable zones sensitively depend on the masses and orbital parameters of the two giant planets, which are both uncertain. The author noted that his investigations did not include all possibilities of bounded orbital dynamics of hypothetical terrestrial planets, but rather provide a characteristic landscape filled with stable and unstable orbital evolutions.

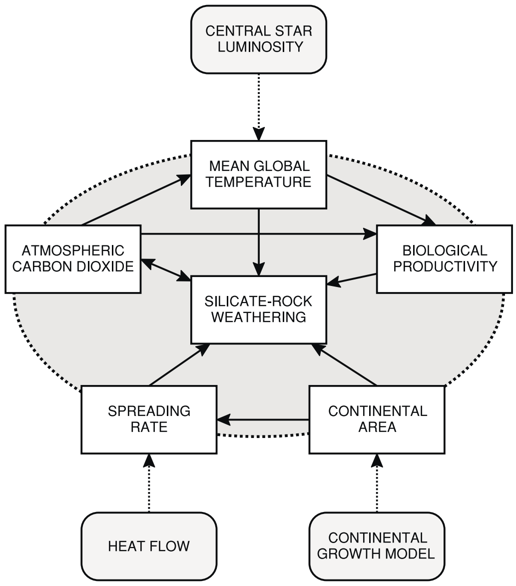

Fig. 1. Box model of the integrated system approach. The arrows indicate the different forcings (dotted lines) and feedback mechanisms (solid lines).

2.2. *Integrated system approach for estimating habitability of an Earth-type planet*

On Earth, the carbonate–silicate cycle is the crucial element for a long-term homeostasis under increasing solar luminosity. In most studies (e.g., Caldeira and 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. Such models are called geostatic models (GSM). On the other hand, on geological timescales 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 favor the so-called geodynamical models (GDM) that 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_{wr}, the global energy balance to allow estimates of the partial pressure of atmospheric and soil carbon dioxide, P_{atm} and P_{soil}, respectively, the mean global surface temperature, T_{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-

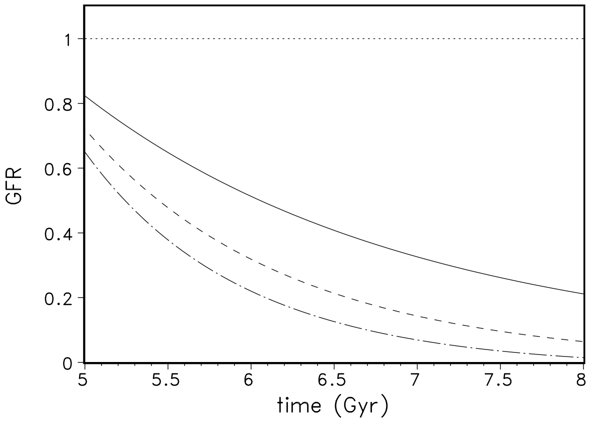

Fig. 2. The time-dependent geophysical forcing ratio (GFR) for the geostatic model (dotted line) and for the geodynamic model with three continental growth scenarios: constant area (solid line), linear growth (dashed line), and delayed growth (dashed–dotted line).

tectonic) sources. This is expressed with the help of dimensionless quantities

$$f_{\mathrm{wr}} \cdot f_A = f_{\mathrm{sr}}, \tag{1}$$

where $f_{\mathrm{wr}} \equiv F_{\mathrm{wr}}/F_{\mathrm{wr},0}$ is the weathering rate normalized by the present value, $f_A \equiv A_c/A_{c,0}$ is the continental area normalized by the present value, and $f_{\mathrm{sr}} \equiv S/S_0$ is the spreading rate normalized by the present value. With the help of Eq. (1) 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 utilize three different continental growth models: delayed growth, linear growth, and constant area (Franck and Bounama, 1997). In Fig. 2 we show the resulting geophysical forcing ratio GFR $:= f_{\mathrm{sr}}/f_A$ for the GSM and the three different continental growth scenarios of the GDM.

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

$$\frac{L}{4\pi R^2}\left[1 - \alpha(T_{\mathrm{surf}}, P_{\mathrm{atm}})\right] = 4 I_R(T_{\mathrm{surf}}, P_{\mathrm{atm}}). \tag{2}$$

Here α denotes the planetary albedo, I_R the outgoing infrared flux, and R 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:

$$\frac{\Pi}{\Pi_{\max}} = \left(1 - \left(\frac{T_{\mathrm{surf}} - 50^\circ\mathrm{C}}{50^\circ\mathrm{C}}\right)^2\right) \times \left(\frac{P_{\mathrm{atm}} - P_{\min}}{P_{1/2} + (P_{\mathrm{atm}} - P_{\min})}\right). \tag{3}$$

Here $\Pi_{\max}$ denotes the maximum biological productivity, which is assumed to amount to twice the present value Π_0 (Volk, 1987). $P_{1/2} + P_{\min}$ is the value at which the pressure-dependent factor is equal to 1/2, and $P_{\min}$ is fixed at 10^{-5} bar, the presumed minimum value for C_4-photosynthesis (Pearcy and 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_{atm}, Eq. (3) yields maximum productivity at $T_{\mathrm{surf}} = 50^\circ\mathrm{C}$ and zero productivity for $T_{\mathrm{surf}} \leq 0^\circ\mathrm{C}$ and $T_{\mathrm{surf}} \geq 100^\circ\mathrm{C}$. At this point we should again emphasize that all calculations are done 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 nonvanishing biological productivity, $\Pi > 0$, i.e.,

$$\mathrm{HZ} := \{R \,|\, \Pi(P_{\mathrm{atm}}(R,t), T_{\mathrm{surf}}(R,t)) > 0\}\,. \tag{4}$$

In previous studies the habitability around different types of stars has been assessed based on the results of Kasting et al. (1993). In the recent work by Noble et al. (2002), the inner boundary of the HZ is taken as the maximum distance from the star where a runaway greenhouse effect occurs leading to the evaporation of all surface water ($R_{\mathrm{inner}} = 1.05$ AU), while for the outer boundary the most optimistic so-called early Mars limit is assumed ($R_{\mathrm{outer}} = 1.83$ AU). Consequently, the HZ is limited only by climatic constraints invoked by the luminosity of the central star. Our method described above relies on additional constraints, however. First, habitability is linked to the photosynthetic activity of the planet (Eq. (4)) and second, habitability is strongly influenced by the planetary geodynamics. In principle, this leads to additional spatial and temporal limitations of habitability.

Let us emphasize that we assume an Earth-like planet with plate tectonics, a crucial ingredient for our models. The importance of plate tectonics for habitability for planet Earth has been discussed by Gonzalez et al. (2001) and Goldsmith and Owen (2002). On the other hand, our present understanding of plate tectonics is highly incomplete. The first theoretical steps to tackle this problem were taken by Solomatov and Moresi (1997). Nonetheless, some principle questions remain (Tackley, 2000): the most basic of those is why Earth has developed plate tectonics at all. This motivates us to restrict our investigation to an Earth-mass planet with Earth-like geodynamics.

2.3. Luminosity and age of 47 UMa

Following the integrated system approach for estimating habitability described above, the HZ around 47 UMa is impacted by the stellar luminosity and the age of the star–planet system. The stellar luminosity essentially defines the

Table 1
Stellar parameters of 47 UMa

Parameter	Value	Uncertainty	Note
Spectral type	G1V	—	(1)
$T_{\rm eff}$ [K]	5800	±75	(2)
[Fe/H]	0.01	±0.06	(2), (3)
M_V	4.29	—	(2)
BC	−0.03	±0.01	(4)
V	5.05	±0.05	(5)
d [pc]	14.08	±0.13	(6)

Note. (1) Henry et al. (1997); (2) Gonzalez (1998); (3) based on the standard spectroscopic notation, $[X/Y] \equiv \log_{10}[N_X/N_Y] - \log_{10}[N_X/N_Y]_\odot$, where N_X and N_Y represent the number density abundances of element X and Y, respectively; (4) interpolated assuming $B - V = 0.61$ (Henry et al., 1997) following Gray (1992); (5) Hoffleit and Jaschek (1982), *The Bright Star Catalogue;* (6) Perryman et al. (1996), *Hipparcos* data.

planetary climate, whereas the age constrains the parameters of the GDM.

First we focus on the determination of the stellar luminosity, including its uncertainty bars. Perryman et al. (1996) summarized the *Hipparcos* distances for (suspected) planet stars, including 47 UMa. These measurements are believed to be most accurate. The 47 UMa parallax was found as $\pi_{\rm HIP} = 71.04 \pm 0.66$ mas based on 58 accepted and 0 rejected measurements. This value can be used to calculate the stellar distance and to obtain an essentially model-independent value for the stellar luminosity. The distance is given as $d = 1/\pi_{\rm HIP}$. The stellar luminosity, L, expressed in units of the solar luminosity, $L_\odot$, is obtained from the following well-known set of equations

$$\log \frac{L}{L_\odot} = 0.4(M_{\rm bol,\odot} - M_{\rm bol}) \tag{5}$$

$$M_{\rm bol} = M_V - BC \tag{6}$$

$$V - M_V = 5 \log d - 5 \tag{7}$$

with $M_{\rm bol}$ as bolometric magnitude, M_V as absolute visual magnitude, V as apparent visual magnitude, d as distance (in pc), and BC as bolometric correction. For the Sun, we assume $M_{\rm bol,\odot} = 4.79$. The stellar parameters of 47 UMa are given in Table 1. Note that 47 UMa is of solar-like spectral type and furthermore has solar metallicity, which seems to be important for the formation of terrestrial-type habitable planets, even though no information regarding the frequency of terrestrial planets as a function of stellar metallicity exists (e.g., Gonzalez et al., 2001). Based on Eqs. (5) to (7), the luminosity of 47 UMa is given as $L = 1.54$ $L_\odot$. For the lower and upper limit of L, we find 1.41 $L_\odot$ and 1.67 $L_\odot$, respectively. These values were calculated assuming linear propagation of the uncertainties of the respective variables.

Next we focus on the determination of the stellar age, which can also be used as a proxy for the age of the planet. In case of 47 UMa, several different methods have been utilized. Long-term Ca II monitoring of 47 UMa at Mount Wilson made it possible to deduce an activity index, which implies an age of 7 Gyr from the age–activity relation of Donahue (1993), in agreement with the estimate of 6.9 Gyr by Edvardsson et al. (1993) from isochrone fitting (see discussion by Henry et al., 1997). Updated estimates based on the Ca II method by Henry et al. (2000) yielded a somewhat smaller age of 6 Gyr.

In the more recent work by Ng and Bertelli (1998), revised ages for a sample of stars were calculated using the Edvardsson et al. data sets. They assumed different distance determinations, including the Lutz–Kelker correction for the absolute visual magnitude and *Hipparcos* parallaxes. Using the 47 UMa *Hipparcos* parallax, which manifests the most accurate distance determination so far (see above), a smaller age of 6.32 (+1.2, −1.0) Gyr was obtained. Lachaume et al. (1999) revisited the age values given by Ng and Bertelli. They confirmed the 47 UMa mean age obtained by Ng and Bertelli, but argued in favor of much larger and more asymmetric uncertainty bars, with the age of 47 UMa now given as 6.3 (+2.0, −2.4) Gyr. Moreover, earlier work by Fuhrmann et al. (1997) based on stellar evolution computations yielded an age of 7.3 (−1.9, +1.9) Gyr consistent with both estimates. Considering that the Ca II observations allow separate age estimates of 6 and 7 Gyr in stiff disagreement with the lower and upper age limits by Lachaume et al., we conclude that the age uncertainties by Ng and Bertelli (1998) are more realistic. These values are therefore assumed in the following.

3. Studies of planetary habitability

We now discuss our results. We computed models for three different stellar luminosities, i.e., 1.41, 1.54, and 1.67 $L_\odot$, which reflect the lower limit, likely value, and upper limit of the 47 UMa luminosity at the present time (see Fig. 3). Clearly, these values should not imply an evolutionary time series for the central star. Concerning the Earth-type planet, we assumed three different types of continental growth models in the context of the geodynamic model, which are no growth, linear growth, and delayed growth (see Section 2.2). For comparison, we also considered the geostatic model (GSM), in which no change of habitability as function of time is implied. As a permitted time frame, we assumed 6.32 (+1.2, −1.0) (Ng and Bertelli, 1998) (see Section 2.3).

Due to the action of geodynamic activity, resulting in the temporal decrease of the planetary atmospheric CO_2 concentration, the different types of geodynamic models are only able to sustain life up to a certain planetary evolutionary time. Life becomes impossible after 7.82 Gyr if the constant area (no growth) model is assumed, after 6.40 Gyr in the case of the linear growth model, and after 5.97 Gyr in the delayed growth model (see Fig. 3). These results are found to be independent of the assumed stellar luminosity, even though the HZs for the different growth models are

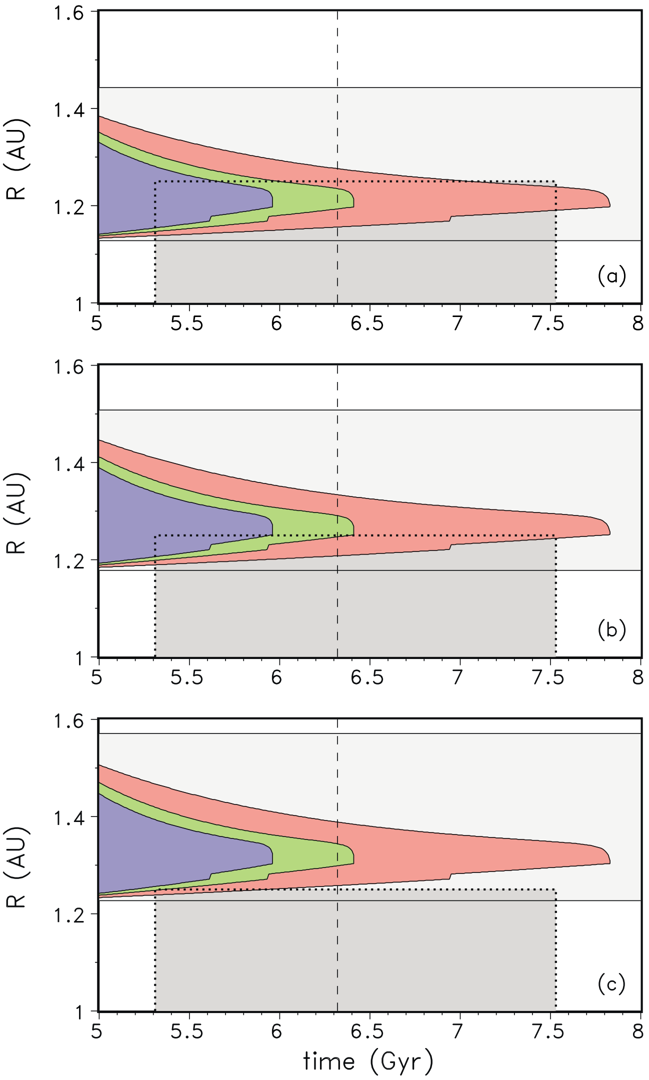

Fig. 3. The stellar HZ around 47 UMa for three different luminosities: (a) 1.41, (b) 1.54, and (c) 1.67 $L_\odot$. The red, green, and blue areas indicate the extent of the HZ assuming different types of continental growth models in the context of geodynamic models (GDM), which are no growth (red), linear growth (green), and delayed growth (blue). The light gray areas indicate the results for the geostatic model (GSM). The dotted lines indicate the permissible parameter space (also shown as dark gray areas) as constrained by the stellar age and the orbital stability limit at 1.25 AU.

positioned at different distances from the star. Clearly, in the case of the smallest luminosity, i.e., $L = 1.41 L_\odot$, the HZs for the various models are found closest to the star, whereas for the highest assumed luminosity, i.e., $L = 1.67 L_\odot$, the HZs are farthest away from the star, as expected. In the model of Kasting et al. (1993) the inner edge of the HZ is defined by the loss of water via a moist greenhouse effect starting at about 60°C. The influence of the upper temperature limit on the HZ has been discussed by Franck et al. (2000c). It has been shown that even a 50°C upper limit has a significant influence only on the inner HZ boundary and only within the first 1.7 Gyr of planetary evolution. In the case of 47 UMa a decrease of the upper temperature limit from 100 to 50°C will not change the results for the HZ in the investigated age interval.

The position of the various HZs is particularly relevant if the orbital stability of terrestrial planets is taken into account. Clearly, the orbital stability of those planets is in principle jeopardized by the gravitational influence of the two Jupiter-type gas giants, which are at orbital distances of 2.09 and 3.73 AU, respectively (Butler and Marcy, 1996; Fischer et al., 2002). Jones et al. (2001) have shown that due to the influence of the innermost gas giants, no stable orbits for a Earth-mass is possible outside of 1.32 AU, a result also consistent with the findings by Noble et al. (2002). If the second giant planet is considered, the domain of stable orbits is reduced, with the exact outer stability limit depending on the planetary and orbital parameters. In addition, the deduced stability limit also seems to be dependent on the choice of the integration method as revealed by the somewhat contradictionary results in the literature (see Section 2.1). Therefore, we use a representative stability limit of 1.25 AU in our models, which should be subject to further investigations.

In fact, the orbital distance domain for Earth-mass planets is seriously restricted if the 47 UMa luminosity is assumed to be near the high end of the permitted observationally deduced range. This is surely not the case for luminosities near the low end of the permitted range. This can be summarized as follows: In the case of $L = 1.41 L_\odot$, the two giant planets do not heavily restrict the extent of the HZ for an Earth-type planet, which is essentially determined by the choice of the most appropriate continental growth model. On the other hand, for $L = 1.54 L_\odot$ both the gravitational effects of the gas giants and the planetary continental growth model seriously limit the extent of the HZ around 47 UMa. In the case of $L = 1.67 L_\odot$, the effective HZ around 47 UMa is virtually nonexistent. For example, Jones and Sleep (2002) found that in some of their simulations, the outer radius of orbital stability is as low as 1.2 AU (or even lower), thwarting the possibility of habitable Earth-mass planets around 47 UMa except in the case of a relatively low stellar luminosity.

Finally, we should comment on an interesting aspect of the star–planet evolutionary age, which was assumed as 6.32 (+1.2, −1.0) (Ng and Bertelli, 1998). Lineweaver (2001) estimated the likely age distribution of terrestrial planets in the Universe using metallicity as a selection effect. He found that the average age of Earth-like planets around a Sun-like star should be 6.4 ± 0.9 Gyr, implying that 74 ± 9% are older than Earth while 26 ± 9% are younger. This estimated mean age is surprisingly close to the age found for 47 UMa. The study of Lineweaver (2001) has been based on a careful analysis of the universal star formation rate, the gradual buildup of metals in the Universe, and the ability of producing and destroying Earth-like planets as a function of metallicity (which also takes into account the influence of "Jupiters," if present).

4. Conclusions

We studied whether Earth-type habitable planets could in principle exist around 47 UMa. We deliberately chose a Earth-centered approach by investigating the long-term possibility of photosynthetic biomass production under geodynamic conditions for a Earth-mass planet. Consequently, a broad variety of climatological, biogeochemical, and geodynamical processes involved in the generation of photosynthesis-driven life conditions was taken into account. We found that Earth-type habitable planets around 47 UMa are in principle possible, 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.

The existence of Earth-type habitable planets depends on the following conditions: First, these planets must have formed out of the planetary disk and must be orbitally stable, despite the proximity of the two Jupiter-mass gas giants, which in principle favor the creation of an asteroid belt. Following Laughlin et al. (2002) and Thébault et al. (2002), the formation of Earth-type planets implies that relatively massive planetary embryos accreted close to the host star prior to the formation of the Jupiter-type planets. Second, 47 UMa must have a relatively low luminosity (within the observed range). Third, it would be advantageous if the 47 UMa star–planet system would be 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 as recently shown by Jones and Sleep (2002) and others. In that case, the extent of the stellar HZ would be relatively narrow or nonexistent as it would be "sliced off" by the gravitational influence of the two gas giants. A relatively small age would be relevant in the view of the planetary growth models studied here. In the case that the age of the star–planet system is 6 Gyr or less, the existence of life would be consistent with all three different types of continental growth models considered. This would not be true for larger age values, but nevertheless life-bearing solutions would still be possible. In the case of the geostatic continent model, no age-related restrictions apply. On the other hand, it would be highly intriguing to also consider Earth-type planets of larger and smaller masses as well as planets with geodynamic features radically different from those discussed in the Franck et al. (2000a) model, which would result in altered stellar HZs (defined for a specific type of planet).

Despite the various caveats stated above, indicating that the 47 UMa system is "a much less than ideal candidate" for extraterrestrial life, it should be noted that 47 UMa is by far the most promising system out of the exosolar planetary systems discovered to date. Clearly, 47 UMa should be worth serious attention in future terrestrial planet search missions.

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References

Boss, A.P., 1995. Proximity of Jupiter-like planets to low-mass stars. Science 267, 360–362.

Butler, R.P., Marcy, G.W., 1996. A planet orbiting 47 Ursae Majoris. Astrophys. J. 464, L153–156.

Butler, R.P., Marcy, G.W., Fischer, D.A., Vogt, S.S., Tinney, C.G., Jones, H.R.A., Penny, A.J., Apps, K., 2002. Statistical properties of extrasolar planets, in: Penny, A., Artymowicz, P., Lagrange, A.-M., Russell, S. (Eds.), Planetary Systems in the Universe: Observation, Formation and Evolution, IAU Symp. 202, in press.

Caldeira, K., Kasting, J.F., 1992. The life span of the biosphere revisited. Nature 360, 721–723.

Donahue, R.A., 1993. Surface Differential Rotation in a Sample of Cool Dwarf Stars. Thesis, New Mexico State University, Las Cruces.

Edvardsson, B., Andersen, J., Gustafsson, B., Lambert, D.L., Nissen, P.E., Tomkin, J., 1993. The chemical evolution of the galactic disk. I. Analysis and results. Astron. Astrophys. 275, 101–152.

Fischer, D.A., Marcy, G.W., Butler, R.P., Laughlin, G., Vogt, S.S., 2002. A second planet orbiting 47 UMa. Astrophys. J. 564, 1028–1034.

Forget, F., Pierrehumbert, R.T., 1997. Warming early Mars with carbon dioxide clouds that scatter infrared radiation. Science 278, 1273–1276.

Franck, S., Bounama, C., 1997. Continental growth and volatile exchange during Earth's evolution. Phys. Earth Planet. Inter. 100, 189–196.

Franck, S., Kossacki, K., Bounama, C., 1999. Modelling the global carbon cycle for the past and future evolution of the earth system. Chem. Geol. 159, 305–317.

Franck, S., Block, A., von Bloh, W., Bounama, C., Schellnhuber, H.-J., Svirezhev, Y., 2000a. Reduction of biosphere life span as a consequence of geodynamics. Tellus 52B, 94–107.

Franck, S., von Bloh, W., Bounama, C., Steffen, M., Schönberner, D., Schellnhuber, H.-J., 2000b. Determination of habitable zones in extrasolar planetary systems: where are Gaia's sisters? J. Geophys. Res. 105 (E1), 1651–1658.

Franck, S., Block, A., von Bloh, W., Bounama, C., Schellnhuber, H.-J., Svirezhev, Y., 2000c. Habitable zone for Earth-like planets in the solar system. Planet. Space Sci. 48, 1099–1105.

Franck, S., Block, A., von Bloh, W., Bounama, C., Garrido, I., Schellnhuber, H.-J., 2001. Planetary habitability: is Earth commonplace in the Milky Way? Naturwissenschaften 88, 416–426.

Fuhrmann, K., Pfeiffer, M.J., Bernkopf, J., 1997. Solar-type stars with planetary companions: 51 Pegasi and 47 Ursae Majoris. Astron. Astrophys. 326, 1081–1089.

Gehman, C.S., Adams, F.C., Laughlin, G., 1996. The prospects for Earth-like planets within known extrasolar planetary systems. Publ. Astron. Soc. Pac. 108, 1018–1023.

Goldsmith, D., Owen, T., 2002. The Search for Life in the Universe, 3rd ed. University Science Books, Sausalito, CA.

Gonzalez, G., 1998. Spectroscopic analyses of the parent stars of extrasolar planetary system candidates. Astron. Astrophys. 334, 221–238.

Gonzalez, G., Brownlee, D., Ward, P., 2001. The galactic habitable zone: galactic chemical evolution. Icarus 152, 185–200.

Goździewski, K., 2002. Stability of the 47 UMa planetary system. Astron. Astrophys. 393, 997–1013.

Gray, D.F., 1992. The Observation and Analysis of Stellar Photospheres. Cambridge Astrophys. Ser. 20. Cambridge Univ. Press, Cambridge.
Hart, M.H., 1979. Habitable zones about main sequence stars. Icarus 37, 351–357.
Henry, G.W., Baliunas, S.L., Donahue, R.A., Soon, W.H., Saar, S.H., 1997. Properties of sun-like stars with planets: 51 Pegasi, 47 Ursae Majoris, 70 Virginis, and HD 114762. Astrophys. J. 474, 503–510.
Henry, G.W., Baliunas, S.L., Donahue, R.A., Fekel, F.C., Soon, W., 2000. Photometric and Ca II H and K spectroscopic variations in nearby Sun-like stars with planets. III. Astrophys. J. 531, 415–437.
Hoffleit, D., Jaschek, C., 1982. The Bright Star Catalogue. Yale University Observatory, New Haven, CT.
Jones, B.W., Sleep, P.N., 2002. The stability of the orbits of Earth-mass planets in the habitable zone of 47 Ursae Majoris. Astron. Astrophys. 393, 1015–1026.
Jones, B.W., Sleep, P.N., Chambers, J.E., 2001. The stability of the orbits of terrestrial planets in the habitable zones of known exoplanetary systems. Astron. Astrophys. 366, 254–262.
Kasting, J.F., 1997. Habitable zones around low mass stars and the search for extraterrestrial life. Origins of Life 2nd Evolution of the Biosphere 27, 291–307.
Kasting, J.F., Whitmire, D.P., Reynolds, R.T., 1993. Habitable zones around main sequence stars. Icarus 101, 108–128.
Lachaume, R., Dominik, C., Lanz, T., Habing, H.J., 1999. Age determinations of main-sequence stars: combining different methods. Astron. Astrophys. 348, 897–909.
Larcher, W., 1995. Physiological Plant Ecology: Ecophysiology of Functional Groups. Springer-Verlag, New York.
Laughlin, G., Chambers, J., Fischer, D., 2002. A dynamical analysis of the 47 Ursae Majoris planetary system. Astrophys. J. 579, 455–467.
Lineweaver, C.H., 2001. An estimate of the age distribution of terrestrial planets in the Universe: quantifying metallicity as a selection effect. Icarus 151, 307–313.
Marcy, G.W., Butler, R.P., 1998. Detection of extrasolar giant planets. Ann. Rev. Astron. Astrophys. 36, 57–97.
Marcy, G.W., Butler, R.P., 2000. Planets orbiting other suns. Publ. Astron. Soc. Pac. 112, 137–140.
Marcy, G.W., Cochran, W.D., Mayor, M., 2000. Extrasolar planets around main sequence stars, in: Mannings, V., Boss, A.P., Russell, S.S. (Eds.), Protostars and Planets IV. Univ. of Arizona Press, Tucson, pp. 1285–1311.
Ng, Y.K., Bertelli, G., 1998. Revised ages for stars in the solar neighbourhood. Astron. Astrophys. 329, 943–950.
Noble, M., Musielak, Z.E., Cuntz, M., 2002. Orbital stability of terrestrial planets inside the habitable zones of extra-solar planetary systems. Astrophys. J. 572, 1024–1030.
Pearcy, R.W., Ehleringer, J., 1984. Comparative ecophysiology of C_3 and C_4 plants. Plant Cell Environ. 7, 1–13.
Perryman, M.A.C., and 21 colleagues, 1996. Hipparcos distances and mass limits for the planetary candidates: 47 Ursae Majoris, 70 Virginis, and 51 Pegasi. Astron. Astrophys. 310, L21–24.
Solomatov, V.S., Moresi, L.-N., 1997. Three regimes of mantle convection with non-Newtonian viscosity and stagnant lid convection on the terrestrial planets. Geophys. Res. Lett. 24, 1907–1910.
Tackley, P.J., 2000. Mantle convection and plate tectonics: toward an integrated physical and chemical theory. Science 288, 2002–2007.
Thébault, P., Marzari, F., Scholl, H., 2002. Terrestrial planet formation in exoplanetary systems with a giant planet on an external orbit. Astron. Astrophys. 384, 594–602.
Volk, T., 1987. Feedbacks between weathering and atmospheric CO_2 over the last 100 million years. Am. J. Sci. 287, 763–779.
Wetherill, G.W., 1996. The formation and habitability of extra-solar planets. Icarus 119, 219–238.
Williams, D.M., 1998. The Stability of Habitable Planetary Environments. Thesis, Pennsylvania State University, University Park.