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Habitability and Stability of Orbits for Earth-Like Planets in the Extrasolar System 47 UMa

Siegfried Franck, Werner von Bloh, Christine Bounama

Potsdam Institute for Climate Impact Research, P.O. Box 601203,
14412 Potsdam, Germany

Manfred Cuntz

Department of Physics, University of Texas at Arlington, Box 19059,
Arlington, TX 76019, USA

Abstract. We investigate wether Earth-type habitable planets can in principle exist in the planetary system of 47 UMa. The system 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. We estimate if Earth-type habitable planets planets around 47 UMa are in principle possible by investigating if a distinct set of conditions is warrented. 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 (younger than approximately 6 Gyr) and has a relatively small stellar luminosity as permitted by the observational range of those parameters. We show that the likelihood to find 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").

1. Introduction

Up to now, more than 100 planets have been detected around stars other than the Sun. Most of these planets are Jupiter-like planets or brown dwarfs, but no Earth-type planets have been found yet. The extrasolar system of 47 UMa (see Fig.1) consists of two Jupiter-size planets at respectable distances from the host star and thus resembles our own solar system most closely compared to all extrasolar systems discovered so far (Fischer et al. 2002).

Furthermore, 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 star (Laughlin et al. 2002) or would trigger orbital instabilities for those planets during inward migration. The central star has properties very similar to those of the Sun, including effective temperature, spectral type and metallicity (Henry et al. 1997). Metallicities not too

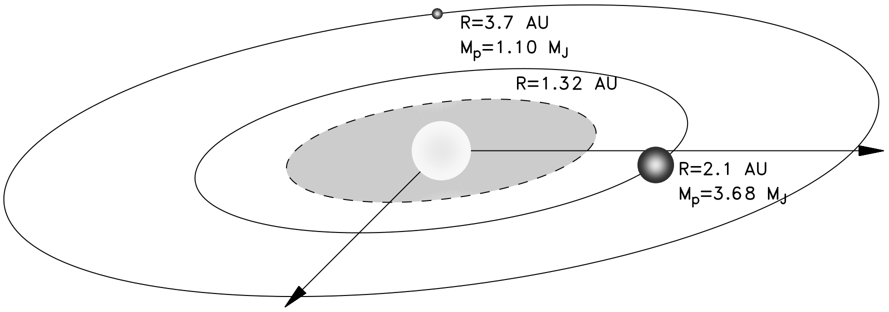

Figure 1. The extrasolar planetary system 47UMa. The dashed line denotes the outermost stable orbit of an Earth-like planet found by Jones & Sleep (2002).

dissimilar to our Sun are probably required for building up Earth-type habitable planets. The main question is, whether Earth-like planets harbouring life can exist around 47 UMa, i.e. planets within the habitable zone (HZ). Typically, stellar HZs are defined as regions near the central star, where the physical conditions are favourable for liquid water to be available at the planet's surface for a period of time long enough for biological evolution to occur. In the following, we adopt a definition of HZ previously used by (Franck et al. 2000). 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. 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.

2. Model Description

To estimate the habitability of an Earth-like planet, a so-called integrated Earth system approach is applied. Our model couples the stellar luminosity, the silicate rock weathering rate and the global energy balance to calculate the partial pressure of atmospheric and soil carbon dioxide, the mean global surface temperature, and the biological productivity as a function of time (Fig.2).

Planetary habitability requires orbital stability of the Earth-type planet over a biologically significant length of time in the HZ. There exist a variety of papers (Fischer et al. 2002; Noble et al. 2002; Jones & Sleep 2002; Gehman et al. 1996; Jones et al. 2001) 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. Jones et al. (2001) explored the dynamical stability for terres-

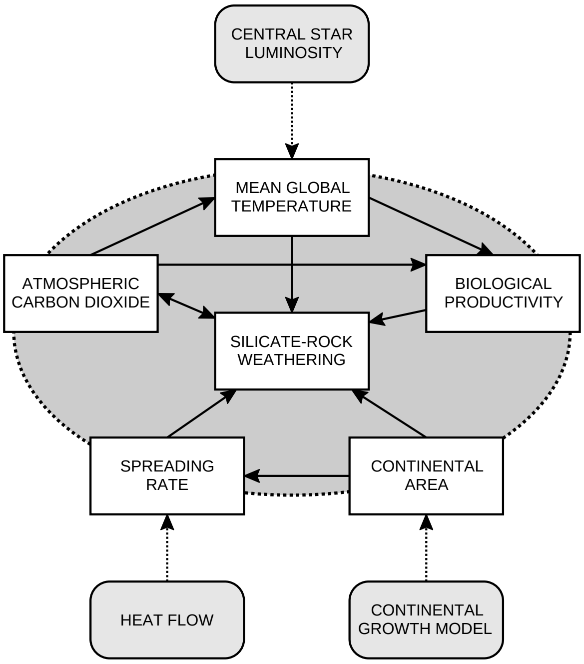

Figure 2. Box model of the integrated system approach. The arrows indicate the different forcings and feedback mechanisms.(Cuntz et al. 2003)

trial 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 harbour terrestrial planets in orbits that could remain confined to the HZ for biologically significant time spans. 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 $1 \cdot 10^9$ yrs 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 non-zero 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, which 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 AU, 1.44 AU, and 1.75 AU inside the stellar HZ. They identified orbital stability for the initial position at 1.13 AU, but no orbital stability for 1.44 AU and 1.75 AU was obtained, consistent with the findings by Jones et al. (2001). 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 is 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 & 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 some of their 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!), assumed 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, which analyses 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 are sensitively depending 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. Therefore, we assume a representative value for the outer boundary of the orbital stability which 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. As 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).

3. Results and Discussion

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, $R < R_{\max}$. 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,

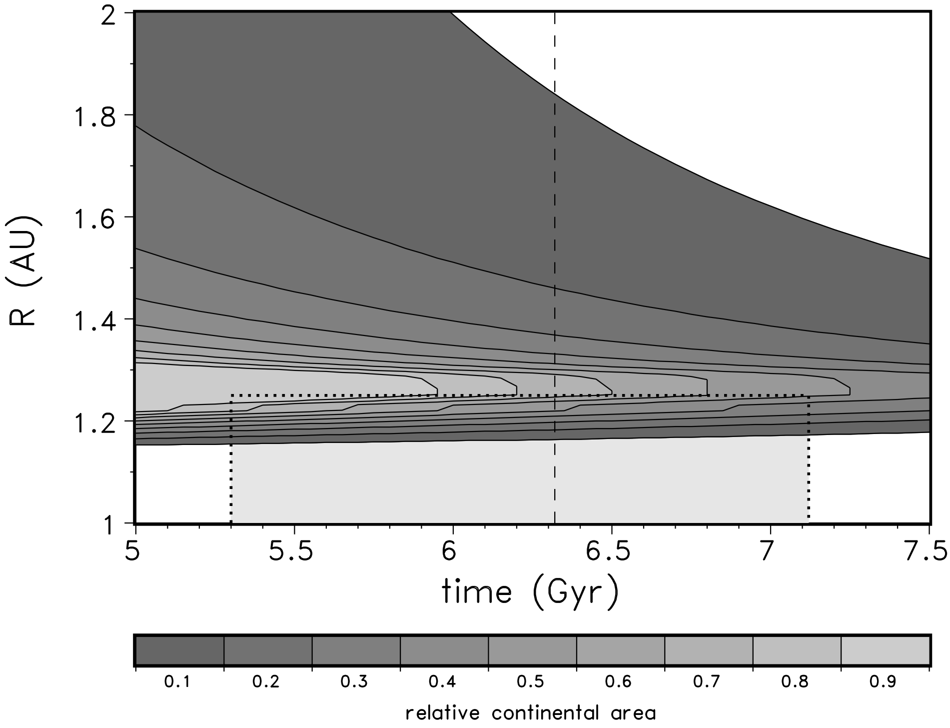

Figure 3. The habitable zone around 47 UMa for the likely value of luminosity $L = 1.54\ \mathrm{L}_\odot$. The gray shaded areas indicate the extent of the HZ for different relative continental areas. The gray shaded box indicates the permissible parameter space as constraint by the stellar age and the orbital stability limit at 1.25 AU. (Franck et al. 2003)

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.

In general, we can state that finding an Earth-like habitable extrasolar planet is the more promising the younger the system 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. As a consequence, habitability is maintained at larger distances from the stars, i.e., regions of lower stellar flux densities. In case of Earth-like planets around 47 UMa, the relevance of this effect is however seriously reduced due to the lack of orbital stability of planets beyond about 1.25 AU. Planets with a relative high percentage of land coverage show a stronger weathering and therefore an enhanced removal of carbon dioxide from the atmosphere. This leads to a weaker greenhouse effect and habitability ceases at smaller ages.

Finally, 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.

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