THE HABITABLE ZONE OF EARTH-LIKE PLANETS AROUND 47 UMA

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ABSTRACT

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 rather closely. The habitability of this system for Earth-like planets is investigated following a concept, which assumes the long-term possibility of photosynthetic biomass production under geodynamic conditions. In particular, 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. In the event of successful formation, we find that Earth-like habitable planets around 47 UMa are in principle possible.

1. INTRODUCTION

Planets have now been observed around almost 100 solar-type stars. Based on the available observational techniques, most detected objects are giant (Jupiter-like) planets or brown dwarfs, although a few planets with sub-Saturn masses have also been identified (e.g. [1]. In addition, the discovery of seven extrasolar planetary systems (i.e., υ And, HD 168443, HD 83443, Gl 876, HD 82943, HD 74156, 47 UMa) has now also been reported. Clearly, the ultimate quest of extra-solar planet research is to identify Earth-like planets located in the habitable zones (HZs) of their host stars, which however at the present time is still beyond technical feasibility.

The study of hypothetical terrestrial planets around 47 UMa is particularly interesting because this system is rather similar to our own Solar System. 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) [2, 3]. 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., 4, 5] or would initiate orbital instabilities for those planets [e.g., 6, 7]. Third, it is found that the central star has properties very similar to the Sun, including effective temperature, spectral type, and metallicity [8, 9].

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 [e.g., 10]. In the following, we adopt a definition of HZ previously used by [10, 11]. 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.

A further constraint for habitability of an Earth-like

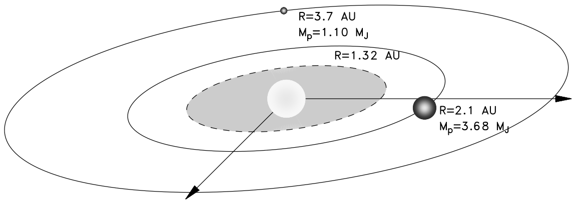

Fig.1. The extrasolar planetary system around 47 UMa. The dashed line denotes the outermost stable orbit of an Earth-like planet.

planet is orbital stability. Jones *et al.* [6] 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, 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 1×10^9 yrs using a mixed variable symplectic integration method. Orbital instability was assumed if the terrestrial planet entered the so-called Hill radius. They found that the outermost stable orbit is close to 1.32 AU (Fig. 1).

2. ESTIMATING HABITABILITY OF AN EARTH-LIKE PLANET

An Earth system model is applied to assess the habitability of Earth-like planet around 47 UMa. On Earth, the carbonate-silicate cycle is the crucial element for a long-term homoeostasis under increasing solar luminosity. 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.

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. 2). 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

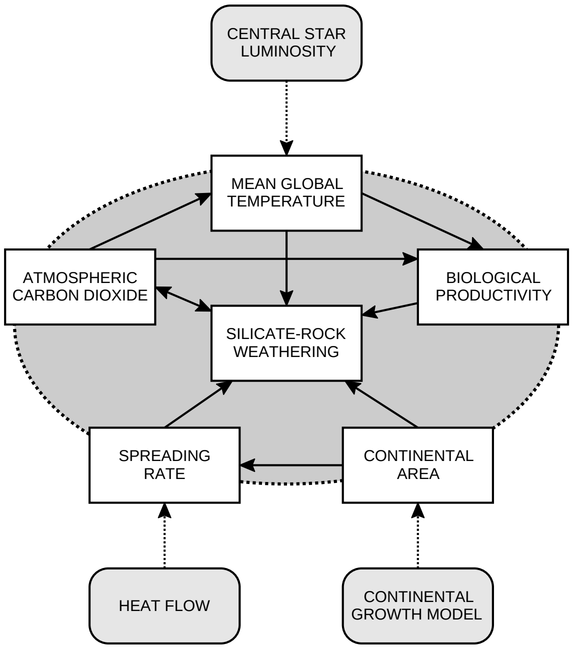

Fig.2. Box model of the integrated system approach. The arrows indicate the different forcings (dotted lines) and feedback mechanisms (solid lines).

help of dimensionless quantities

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

where $f_{\rm wr} \equiv F_{\rm wr}/F_{\rm wr,0}$ is the weathering rate normalised by the present value, $f_A \equiv A_c/A_{c,0}$ is the continental area normalised by the present value, and $f_{\rm sr} \equiv S/S_0$ is the spreading rate normalised by the present value. With the help of Eq. (1) we can calculate the normalised weathering rate from geodynamics based on the continental growth model and spreading rate [11]. For the investigation of an Earth-like planet under the external forcing of 47 UMa, a G1V star [8], we utilise three different continental growth models: delayed growth, linear growth, and constant area [12] (Fig. 2).

The HZ around 47 UMa is defined as the spatial domain where the planetary surface temperature stays between 0°C 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.,

$$HZ := \{R \mid \Pi(P_{\rm atm}(R,t), T_{\rm surf}(R,t)) > 0\}. \tag{2}$$

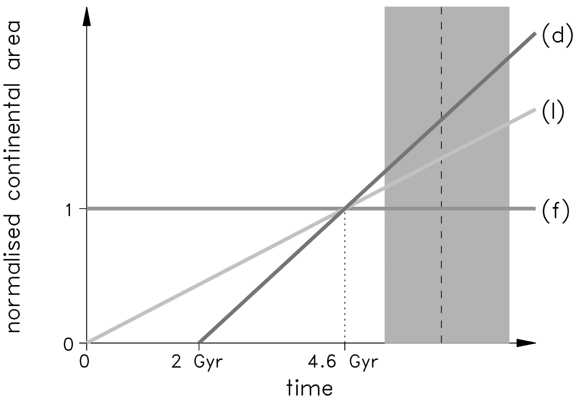

Fig.3. Three different continental growth models applied to our Earth system model: (d) delayed growth, (l) linear growth, (f) fixed area. The grey shaded area indicates the relevant time frame for the age of 47 UMa.

3. RESULTS AND DISCUSSION

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. As permitted time frame for the stellar age of 47 UMa, we assumed 6.32 (+1.2,-1.0) [13].

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 case of the linear growth model, and after 5.97 Gyr in the delayed growth model (see Fig. 2). These results are found to be independent of the assumed stellar luminosity, even though the HZs for the different growth models are positioned at different distances from the star. Clearly, in 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.

The position of the various HZs is particularly relevant if the orbital stability of the terrestrial planets is taken into account. The orbital stability of those planets is in principle jeopardised by the gravitational influence of the two Jupiter-type gas giants. Jones *et al.* [6] have shown that due to the influence of the innermost gas giants, no stable orbits for an Earth-mass is possible outside of 1.32 AU, a result also consistent with the findings by [7]. This means that the orbital distance domain for Earth-mass planets is heavily restricted if the 47 UMa luminosity is assumed to be near the higher end of the permitted observationally deduced range. This is surely not the case for lumi-

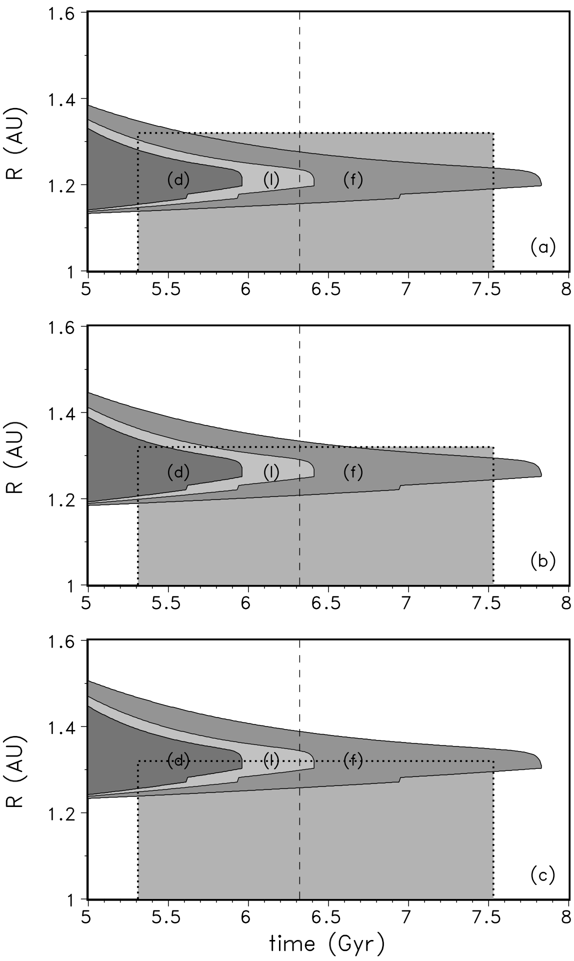

Fig.4. The HZ around 47 UMa for three different luminosities: (a) 1.41, (b) 1.54, and (c) 1.67 $L_\odot$. The differently labelled areas indicate the extent of the HZ assuming different types of continental growth models, which are: fixed area (f), linear growth (l), and delayed growth (d). The dotted lines indicate the permissible parameter space (also shown as dark grey areas) as constraint by the stellar age and the orbital stability limit at 1.32 AU (see text).

nosities near the lower end of the permitted range.

This can also be expressed as follows: In case of $L = 1.41 L_\odot$, the innermost planet does not significantly restrict the extent of the HZ for a Earth-mass planet, as this only occurs through the most appropriate continental growth model. On the other hand, for $L = 1.54 L_\odot$ and $L = 1.67 L_\odot$, both the gravitational effect of the innermost gas giant and the planetary continental growth model contribute seriously to the extent of the effective HZ around 47 UMa.

In spite of 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 seems to be among the most promising system out of the seven extrasolar planetary systems discovered to date. Clearly, 47 UMa should be worth serious attention in future terrestrial planet search missions.

4. ACKNOWLEDGEMENTS

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