THE NUMBER OF HABITABLE PLANETS IN THE MILKY WAY OVER COSMOLOGICAL TIME SCALES

Werner von Bloh, Siegfried Franck, Christine Bounama, Hans-Joachim Schellnhuber

Potsdam Institute for Climate Impact Research, P.O. Box 60 12 03, 14412 Potsdam, Germany,
Email: bloh@pik-potsdam.de

ABSTRACT

A general modelling scheme for assessing the suitability for life on any Earth-like extrasolar planet is presented. This approach is based on an integrated Earth system analysis in order to calculate the habitable zone in main-sequence-star planetary systems. A new attempt by Lineweaver [1] to estimate the formation rate of Earth-like planets over cosmological time scales is applied to calculate the average number of habitable planets in the Milky Way as a function of time. The combination of this results with our estimations of extrasolar habitable zones yields the average number of habitable planets over cosmological time scales. We find that there was a maximum number of habitable planets at the time of Earth's origin.

Key words: habitable zone, Earth-like planets, panspermia.

1. INTRODUCTION

One prominent and still open question is whether life exist on other planets. Recent progress in astronomical measurement techniques has confirmed the existence of a multitude of extrasolar planets. Up to now nearly 100 planets have been observed around solar-type stars, where most of them are giant planets. The ultimate quest of extrasolar planet research is to identify Earth-like planets located in the habitable zone of their host stars. The habitable zone (HZ) is defined as the region around a star within which a planet might enjoy moderate surface temperatures required for higher life forms. At present time, however, the detection of such Earth-like planets is still beyond technical feasibility. Therefore we are restricted to theoretical considerations in order to estimate the number of habitable Earth-like planets which could principally harbour life. The knowledge of two factors is crucial for this attempt. On the one hand it is necessary to know the planet formation rate (PFR) of Earth-like planets, on the other hand the probability that the planet formed is habitable has to be assessed. Recent results of Lineweaver [1] can be used to calculate PFR as a function of cosmological time. The extent of HZs for different types of main-sequence stars has been determined by different authors [2, 3, 4]. In the following we apply our definition of habitability [5, 6], that does not just depend on the parameters of the central star, but also on the properties of the planetary geodynamics. The calculation of the HZ for different central star masses allows us to determine the probability that an Earth-like planet is habitable. Finally it is possible to estimate the number of habitable planets in the Milky Way.

2. METHODOLOGY

To calculate the PFR it is necessary to estimate the star formation rate (SFR). Based on the most recent observational data, Lineweaver [1] fits the SFR for the universe to an exponentially increasing function for the first 2.6 Gyr after Big Bang followed by an exponential decline. He uses this fit to quantify star metallicity as an ingredient for the formation of Earth-like planets. The metallicity μ is built up during cosmological evolution through stars, i.e.,

$$\mu \sim \int_0^t \mathrm{SFR}(t')\mathrm{d}t'. \tag{1}$$

Then the PFR can be parameterised in the following way:

$$\mathrm{PFR} = 0.05 \cdot \mathrm{SFR} \cdot p_E(\mu) \cdot [1 - p_J(\mu)], \tag{2}$$

where p_E is the probability that Earth-like planets are formed and p_J the probability for hot Jupiter formation with orbits at which they would destroy Earth-like planets . The prefactor 0.05 reflects the assumption that 5% of the stars are in the range of $0.8 \ldots 1.2$ solar masses (M_s). The relation between metallicity and the probability $p_E(1 - p_J)$ is a so-called Goldilocks problem: if the metallicity is too low, there is not enough material to build Earth-like planets; if the metallicity is too high, there is a high probability of forming hot Jupiters. Taking all these effects into account, one can derive the time-dependent PFR. In Fig. 4a we show the PFR recalculated from Lineweaver [1] and rescaled to the present star formation rate in the Milky Way of about one solar mass per year.

The number of habitable planets in the Milky Way, $P(t)$, can be calculated with the help of a convolution integral:

$$P(t) = \int_0^t \mathrm{PFR}(t') \times p_{\mathrm{hab}}(t-t')\mathrm{d}t'. \quad (3)$$

The probability, p_{hab}, that an Earth-like planet at time Δt after its formation is within the habitable zone (HZ) can be expressed as follows [7]:

$$p_{\mathrm{hab}}(\Delta t) = \frac{1}{C}\int_{0.8M_s}^{1.2M_s} M^{-2.5}\int_{R_{\mathrm{inner}}(M,\Delta t)}^{R_{\mathrm{outer}}(M,\Delta t)} R^{-1}\mathrm{d}R\mathrm{d}M, \quad (4)$$

where $C = 1.57 M_s^{-1.5}$ is a normalisation factor resulting from solving Eq. 4 between the central-star-mass-dependent minimum and maximum HZ boundaries $0.1 \cdot M/M_s$ AU and $4 \cdot M/M_s$ AU, respectively. In order to estimate p_{hab}, the following assumptions are made:

1. The stellar masses M are distributed according to a power law [8] $\propto M^{-2.5}$;
2. the distribution of planets can be parameterised by $p(R) \propto R^{-1}$, i.e. their distribution is uniform on a logarithmic scale in the distance R from the central star [7, 9];
3. following Lineweaver [1] we restrict our attention to the set of Sun-like stars in the mass range from 0.8 to 1.2 solar masses (M_s); and
4. R_{inner} and R_{outer} are the inner and outer boundaries of the HZ, respectively. They are explicit functions of the central star mass and the age of the corresponding planetary system [5].

In previous studies climatic constraints, e.g. the presence of liquid water at the planetary surface, have been used to assess the habitability of terrestrial planets around different types of stars [3]. Our method [6] defines additional constraints: first, habitability is linked to photosynthetic activity and second, habitability is strongly influenced by the “geodynamics” of the Earth-like planet. To estimate these constraints for the determination of the inner and outer boundaries of the HZ we use our Earth system model [5]. It couples the increasing central star luminosity, the silicate-rock weathering rate, and the global energy balance to estimate the partial pressure of atmospheric carbon dioxide, the mean global surface temperature, and the biological productivity as functions of time Δt (see Fig. 1). The main point is the long-scale balance between the CO_2 sink in the atmosphere-ocean system and the metamorphic (plate-tectonic) sources. This is expressed with the help of dimension-less quantities:

$$f_{\mathrm{wr}} \cdot f_A = f_{\mathrm{sr}}, \quad (5)$$

where $f_{\mathrm{wr}} \equiv F_{\mathrm{wr}}/F_{\mathrm{wr},0}$ is the weathering rate normalised by the present value, $f_A \equiv A_c/A_{c,0}$ is the

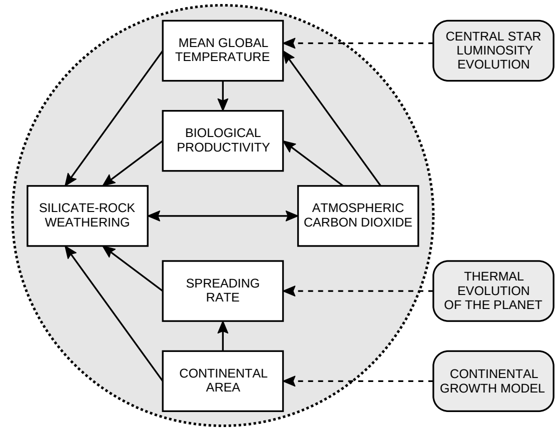

Figure 1. Integrated system box model. The arrows indicate different forcings and feedback mechanisms.

continental are a normalised by the present value, and $f_{\mathrm{sr}} \equiv S/S_0$ is the spreading rate normalised by the present value. Models with fixed continental area and fix ed tectonic activity ($f_A \equiv f_{\mathrm{sr}} \equiv 1$) are called geostatic models (GSM) . We favour so-called geodynamic models (GDM) that take into account both the growth in continental area and the decline in the spreading rate. With the help of Eq. 5 we can calculate the normalised weathering rate from geodynamics via continental growth model and time function of spreading rate. For the investigation of an Earth-like planet under the external forcing of any main-sequence star we apply the linear growth model [10].

The relationship between the stellar luminosity, L, and the radiation temperature, T_{rad}, for the pertinent central star mass range is given by the Hertzsprung-Russell diagram. The connection between the stellar parameters and the planetary climate can be formulated by using a radiation balance equation [11], i.e.,

$$\frac{L(t)}{4\pi R^2}[1-\alpha(T, P_{\mathrm{atm}}, T_{\mathrm{rad}})] = 4 I_R(T, P_{\mathrm{atm}}). \quad (6)$$

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

We define the HZ as the region around a central star within which an Earth-like planet has a non-vanishing biological productivity Π. Π is defined as a function of surface temperature, T, and CO_2 atmospheric partial pressure, P_{atm}:

$$\frac{\Pi}{\Pi_{\max}} = \left(1 - \left(\frac{T - 50°\mathrm{C}}{50°\mathrm{C}}\right)^2\right) \times \times \left(\frac{P_{\mathrm{atm}} - P_{\min}}{P_{1/2} + (P_{\mathrm{atm}} - P_{\min})}\right). \quad (7)$$

$\Pi_{\max}$ is the maximum productivity and is assumed to be twice the present value of Π_0 [12]. $P_{1/2} + P_{\min}$ is the value at which pressure-dependent factor is equal to $1/2$ and $P_{\min} = 10^{-5}$ bar (10 ppm) is the minimum value for C_4-photosynthesis [13, 14]. There is no photosynthesis-based life possible if T is outside the temperature-tolerance window [$0°$C $\ldots 100°$C] and $P_{\rm atm}$ is lower than 10^{-5} bar. We assume a maximum value of $P_{\rm atm} = 10$ bar. In this way the HZ is the habitable R-corridor in time, Δt:

$$\begin{aligned} \mathrm{HZ} &:= \{R \mid \Pi(P_{\rm atm}(R,\Delta t), T(R,\Delta t)) > 0\} \\ &= [R_{\rm inner}(\Delta t), R_{\rm outer}(\Delta t)] \end{aligned} \quad (8)$$

3. RESULTS AND DISCUSSION

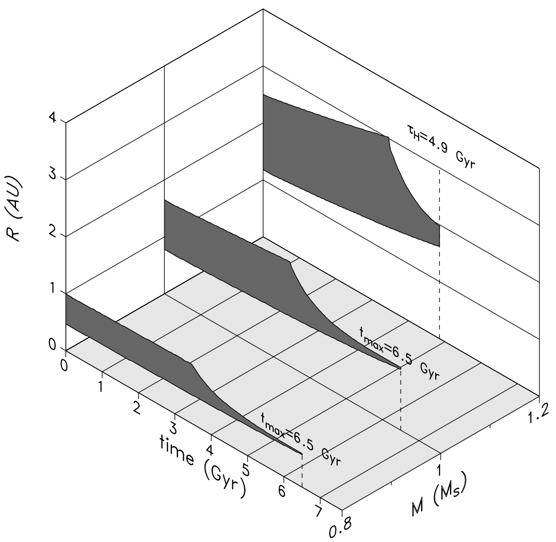

Figure 2. Width and position of the HZ (grey shaded) as a function of time for three different central-star masses ($M = 0.8, 1.0, 1.2 M_s$) for an Earth-like planet. t_{max} is the maximum life span of the biosphere limited by geodynamic effects. τ_H indicates the hydrogen burning time on the main sequence limiting the life span of more massive stars.

We calculate the behaviour of this virtual Earth system at various distances R from the central star. In Fig. 2 we have plotted the width and position of the HZ for

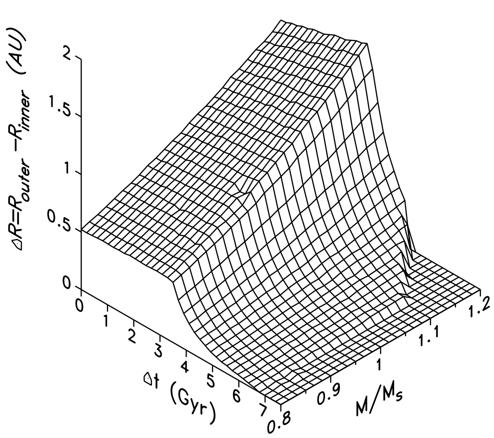

Figure 3. The width, $\Delta R = R_{\rm outer} - R_{\rm inner}$, of the HZ for an extrasolar planetary system as a function of time from its origin, Δt, and stellar mass, M.

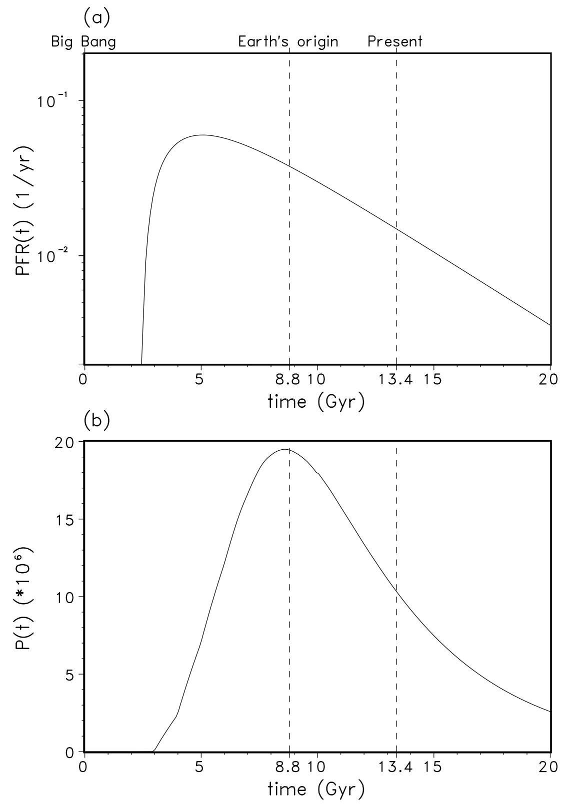

Figure 4. (a) Earth-like planet formation rate (PFR)[1], and (b) number of habitable planets $P(t)$ as a function of cosmological time for the Milky Way. The vertical dashed lines denote the time of Earth's origin and the present time, respectively.

the GDM for three different central star masses, $M = 0.8, 1.0, 1.2 M_s$ over time. First we can find that the width and the position of the HZ depend strongly on the mass of the central star. Furthermore, up to about 3.5 Gyr of cogenetic stellar and planetary evolution the outer boundary of the HZ is steadily increasing as a result of increasing central-star luminosity. After this point, the continental area has grown to such a size that weathering is very effective in bringing CO_2 out of the atmosphere and decreasing the outer boundary of the HZ which finally joins the inner one. For $1.2 M_s$ central stars life would be limited to 4.9 Gyr after starting cogenetic evolution because the central star leaves the main sequence and becomes a red giant. For 0.8 and $1.0 M_s$ central stars this limitation appears up to 6.5 Gyr after starting cogenetic evolution because continental growth and decline in spreading rate force atmospheric CO_2 content below 10^{-5} bar. In Fig. 3 the width $\Delta R = R_{\rm outer} - R_{\rm inner}$ of the HZ as a function of time and central star mass is plotted to emphasize the above mentioned qualitative characteristics.

Now we can come back to the calculation of the number of habitable planets within the Milky Way, $P(t)$ by evaluating Eqs. 3 and 4. The results for the calculation of $P(t)$ are presented in Fig. 4b. The value $P(t = 13.4\,\mathrm{Gyr})$ of about 10^7 is of the same order of magnitude as produced by recent calculations [15]. Evidently, the $P(t)$ has a distinct maximum at 8.5 Gyr. This just before the time of Earth's origin ($t = 8.8$ Gyr). This supports the idea that interstellar panspermia (see, e.g., [16, 17]) might have caused a kick start to the processes by which life originated on Earth: there is palaeogeochemical evidence of a very early appearance of life on Earth leaving not more than approximately 0.4 Gyr for the evolution of life from the simple precursor molecules to the level of the prokaryotic photoautotrophic cells [18, 19].

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