PLANETARY HABITABILITY: ESTIMATING THE NUMBER OF GAIAS IN THE MILKY WAY

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ABSTRACT

Recently, enormous progress in astronomical measurement techniques has confirmed the existence of extra-solar planets and stimulated the ongoing debate about other civilizations outside the solar system. The Drake equation identifying the relevant factors for a statistical estimation can provide further information about the magnitude of possible extraterrestrial civilizations. Although several factors are highly speculative, a subset of them describing the selection of contemporary biospheres interacting with their environment on a global scale (Gaias) can be stated more precisely. In this paper, the effect of geodynamics on the habitability of planetary systems is investigated. It is found that the number of contemporary sisters of Gaia is twofold higher than as calculated with respect to geostatic models. Our estimation for the number of Gaias gives 2.4 millions.

Key words: Habitable zone; Gaia; Drake equation.

1. INTRODUCTION

Within the last years, widely recognized breakthroughs in astronomical measurement techniques have provided high evidence for extra-solar planets. The success exploits both the gravitational influence exerted by every planet on its more massive central star and the fractional reduction in the light from the star as the planet's transit (e.g. Marcy et al. (2000)). Up to now, more than about 50 credible planets outside the solar system have been detected (Extra-solar Planets Catalog by J. Schneider: http://www.usr.obspm.fr/planets). Most of them seem to have a mass similar to giant planets and unexpected small orbits. But there are also speculations about the discovery of an Earth-sized planet in the middle of the Milky Way (Rhie et al., 1998).

The success of high sophisticated observation techniques has led astronomers to forecast the imminent dawning of a golden age of astronomy. Questions that scientists once considered beyond the reach of observation may soon find at least partial answers. Especially, is there life or are the planets found beyond the solar system at least habitable? And, mostly discussed within the SETI-Program, are there enough Gaias, i.e., habitable planets to get a realistic chance for detecting extraterrestrial technological civilizations capable of radiating enormous amounts of transmitter power?

How can we estimate the number of technological civilizations that might exist among the stars? In order to do such a cosmic biosphere prospecting, one can determine at least the order of magnitude by using the Drake equation, which was first presented by Drake in 1961 (see, e.g., Terzan & Bilson, 1997; Dick, 1998; Jakosky, 1998) and identifies specific factors considered to play a role in the development of such civilizations. Some of them are highly speculative.

2. GAIAN SELECTION

From the view of Earth-system analysis, we will focus our presentation on an estimation for the contemporary sisters of Gaia in the Milky Way selected from the Drake equation. These are habitable planets with a biosphere interacting with its environment on a global scale, denoted by $\mathcal{N}_{\mathrm{Gaia}}$. The number of civilizations, $\mathcal{N}_{\mathrm{CIV}}$, is given by:

$$\mathcal{N}_{\mathrm{CIV}} = \mathcal{N}_{\mathrm{Gaia}} \cdot f_{\mathrm{CIV}} \cdot \delta, \tag{1}$$

where $\mathcal{N}_{\mathrm{Gaia}}$ is

$$\mathcal{N}_{Gaia} := N_{\mathrm{MW}} \cdot f_P \cdot n_{\mathrm{CHZ}} \cdot f_L. \tag{2}$$

Let us discuss the specific factors in detail:

- N_{MW} denotes the total number of stars in the Milky Way.
- f_P is the fraction of stars with planets. Although the fraction of Sun-like stars with planets is currently unknown, recent findings indicate that planetary systems may be common for stars like the Sun.

- n_{CHZ} is the average number of planets per planetary system which are suitable for the development of life.

- f_L is the fraction of habitable planets where life emerges and a full biosphere develops, i.e., a biosphere interacting with its environment on a global scale (Gaias).

- f_{CIV} denotes the fraction of sisters of Gaias developing technical civilizations. Life on Earth began over 3.85 billion years ago Jakosky (1998). Intelligence took a long time to develop. On other life-bearing planets it may happen faster, it may take longer, or it may not develop at all.

- δ describes the average ratio of civilization lifetime to Gaia lifetime. It measures simply the fraction of planets with intelligent life that develop technological civilizations, i.e., technology that releases detectable signs of their existence into space.

f_{CIV} and δ are highly speculative: there is just no information about the *typical* evolutionary path of life or the characteristic "life span" of communicating civilizations. Regarding the fate of ancient advanced civilizations, the typical life-time was limited by increasing environmental degradation or over-exploitation of natural resources. One can also speculate that the development and utilization of certain techniques which facilitate the arise of advanced civilizations may be accompanied with new vulnerabilities or hazard potentials which endanger the continuance of civilizations. As a consequence, the lifetime of any advanced (communicating) civilization may be limited to the range of few hundreds of years, but this is really uncertain.

f_L seems to be potentially assessable by geophysiological theory and observation and the remaining factors are deducible from biogeophysical science. The key factor in Equation 2 is n_{CHZ}. For the assessment of n_{CHZ} it is necessary to investigate the habitability of an extra-solar planetary system. In general, the habitable zone (HZ) around a main sequence star has been defined as the region within which an Earth-like planet might enjoy moderate surface temperatures needed for advanced life forms (Huang, 1959; Dole, 1964; Terzan & Bilson, 1997).

Calculations of the HZ for the solar system and for other main sequence stars have been provided by Hart (1978), Hart (1979), Kasting (1992), Kasting et al. (1993), Kasting (1997), and Williams & Kasting (1997). In recent works (Franck et al., 1999, 2000a,b,c) it has been demonstrated that geodynamics has a significant effect on the carbonate-silicate cycle which governs the long-term stabilization of the environmental conditions on Earth. Therefore, we will focus our analysis on the question, how geodynamics affects n_{CHZ} and, as a consequence, $\mathcal{N}_{\mathrm{Gaia}}$.

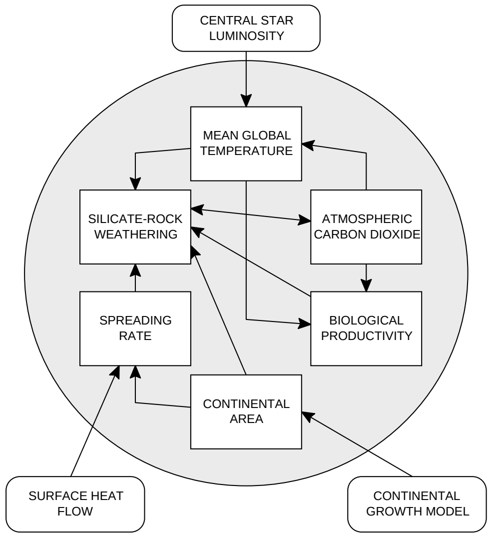

Figure 1. Box model. The arrows indicate the different forcing and feedback mechanisms.

3. HABITABLE ZONE UNDER GEODYNAMIC CONDITIONS

Let us start with a consideration of our own planetary system: the histories and fates of the three terrestrial planets Venus, Earth, and Mars suggest that a combination of distance from the Sun, planetary size, as well as geologic and biologic evolution controls the habitability of a planet. On Earth, the carbonate-silicate cycle is the crucial element for a long-term homeostasis under increasing solar luminosity. In most studies (see, e.g., Caldeira & Kasting, 1992), the cycling of carbon is related to the tectonic activities and the present continental area as a snapshot of the Earth's evolution. Such models are called geostatic models (GSM). On the other hand, in geological time scales the deeper parts of the Earth are considerable sinks and sources for carbon and the tectonic activity as well as the continental area have changed noticeable. 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 increasing solar luminosity, L, the silicate-rock weathering rate, F_{wr}, and the global energy balance to estimate the partial pressure of atmospheric and soil carbon dioxide, P_{atm} and, P_{soil}, the mean global surface temperature, T, and the biological productivity, Π, as a function of time, t, in the geological past and future (Figure 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:

$$f_{\mathrm{wr}} \cdot f_A = f_{\mathrm{sr}}, \qquad (3)$$

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

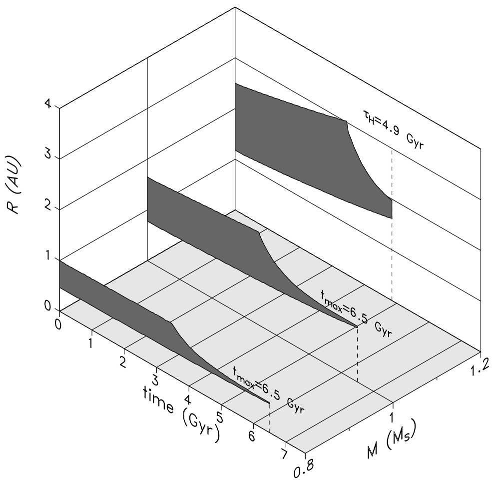

Figure 2. Width and position of the GDM HZ (grey shaded) as a function of time for three different central-star masses ($M = 0.8, 1.0, 1.2 M_s$) for an Earth-like planet. t_{max} is the maximum life span of the biosphere limited by geodynamic effects. τ_H indicates the hydrogen burning time on the main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

$f_{\rm sr} \equiv S/S_0$ is the spreading rate normalized by the present value. With the help of Equation 3 we can calculate the normalized weathering rate from geodynamics via continental growth model and time function of spreading rate (Franck et al., 2000a). For the investigation of an Earth-like planet under the external forcing of any main-sequence star we apply the linear growth model (Franck & Bounama, 1997).

The relationship between the stellar luminosity, L, and the radiation temperature, $T_{\rm rad}$, for the pertinent mass range is given by the Hertzsprung-Russell diagram. The connection between the stellar parameters and the planetary climate can be formulated by using the Williams equation (Williams, 1998), i.e.,

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

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

In our model photosynthesis-based life is possible if the surface temperature, T, is in the so-called temperature tolerance window $[0°\mathrm{C} \ldots 100°\mathrm{C}]$ and $P_{\rm atm}$ is higher than 10 ppm. We calculate the behavior of our virtual Earth system at various distances, R, from the central star. This determines the HZ as the region around a central star within which an Earth-like planet has a non-vanishing biological productivity $\Pi(P_{\rm atm}, T)$. In this way the HZ is the habitable R-corridor in time, t:

$$\begin{aligned} HZ &:= \{R \mid \Pi(P_{\rm atm}(R,t), T(R,t)) > 0\} \\ &:= [R_{\rm inner}(t), R_{\rm outer}(t)] \end{aligned} \qquad (5)$$

In Figure 2 we have plotted the width and position of the HZ for 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 biological productivity 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.

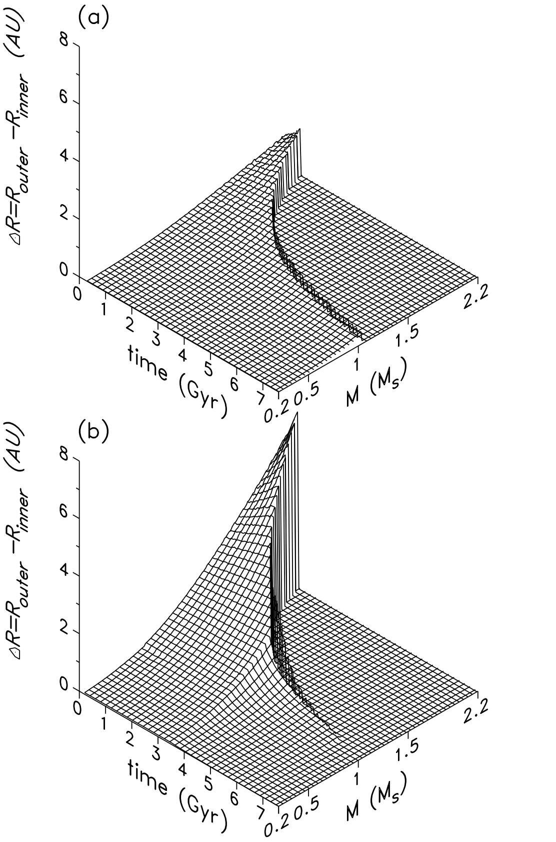

Figure 3. (a) The width, $\Delta R = R_{\rm outer} - R_{\rm inner}$, of the HZ as a function of time, t, and stellar mass, M, calculated by using the geostatic model. (b) The width, ΔR, of the HZ given by the geodynamic approach. ΔR is measured in astronomical units.

In Figures 3a,b the width $\Delta R = R_{\rm outer} - R_{\rm inner}$ of the HZs for GSM and GDM are plotted as a function of time and mass of the central star, M. Up to 4.5 Gyr the HZ for the GDM is significantly larger compared to GSM. In the GDM case, however, the HZ ends at 6.5 Gyr due to geodynamic effects, while for GSM the HZ is limited only by the lifetime of the central star on the main sequence, τ_H. τ_H depends exponentially on M, $\tau_H \propto M^{-2.88}$ at least for low mass central stars (Kippenhahn & Weigert, 1990; Franck et al., 2000c).

Franck et al. (2000c) presented the HZ for an Earth-like extra-solar planet at a given (but arbitrary) distance, R, in the stellar mass-time plane (Figure 4). Here the HZ is limited by the following effects:

- (I): The stellar life time on the main sequence decreases strongly with mass. Using simple scaling laws (Kippenhahn & Weigert, 1990), the central hydrogen burning period is estimated to be $\tau_H < 0.8$ Gyr for stellar masses $M > 2.2 M_s$. Therefore, there is no point in considering central stars with masses larger than $2.2 M_s$ because an Earth-like planet may need ≈ 0.8 Gyr of habitable conditions for the development of life (Hart, 1978, 1979). Smaller numbers for the time span required for the emergence of life have been discussed, for instance 0.5 Gyr (Jakosky, 1998). Performing calculations with $\tau_H < 0.5$ Gyr, one obtains qualitatively similar results, but the upper bound of central star masses is shifted to $2.6 M_s$.
- (II): When a star leaves the main sequence to turn into a red giant, there clearly remains no HZ for an Earth-like planet. This limitation is relevant for stellar masses in the range between 1.1 and $2.2 M_s$.
- (III): In the stellar mass range between 0.6 and $1.1 M_s$, the maximum life span of the biosphere is determined exclusively by planetary geodynamics, which is independent (in a first approximation, but see the limiting effect IV) of R. So one obtains the limitation $t < t_{max}$, where $t_{max} = 6.5$ Gyr.
- (IV): There have been discussions about the habitability of tidally locked planets. This complication is taken into account by indicating the domain where an Earth-like planet on a circular orbit experiences tidal locking. That domain consists of the set of (M, t)-couples which generate an outer HZ boundary below the tidal-locking radius. This limitation is relevant for $M < 0.6 M_s$.

Based on Equation 5 we introduce the continously habitable zone (CHZ) (Kasting et al., 1993) as a band of orbital distances where a planet is within the HZ for a certain time interval, τ.

4. PROBABILISTIC ESTIMATION FOR GALACTIC GAIA ABUNDANCE

The effect of the extension of the CHZ on the magnitude of galactic Gaia abundance can be estimated by considering the main-sequence (hydrogen burning) stars. The integration over the stellar distributions for distances, R, masses, M, and ages, t, (see

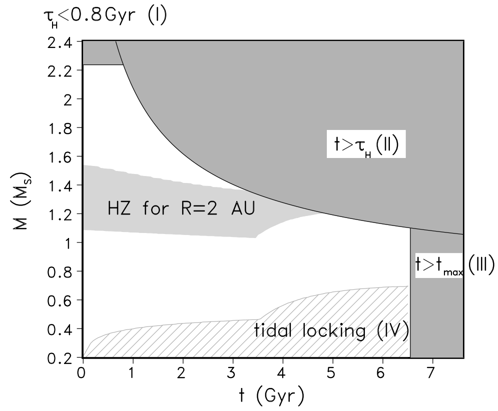

Figure 4. Shape of the GDM HZ (light grey shading) in the mass-time plane for an Earth-like planet at distance $R = 2$ AU from the central star. The potential overall domain for accommodating the HZ for planets at some arbitrary distance is limited by a number of factors that are independent of R: (I) minimum time for biosphere development, (II) central star life time on the main sequence, (III) geodynamics of the Earth-like planet, and (IV) tidal locking of the planet (nontrivial sub-domain excluded). The excluded realms are marked by dark grey shading in the case of the first three factors and by grey hatching for the tidal-locking effect. (Figure slightly modified from Franck et al. (2000c))

Figure 5) provides the geodynamic/geostatic abundance ratio as a function of the time-of-continuous-residence in the HZ. This is done by defining the probability that the position of a planet is in the interval $[R, R+dR]$ according to $p(R)dR$ whereby R is the distance to the central star. The probable number of planets within the CHZ $[\tilde{R}_{\text{inner}}(\tau), \tilde{R}_{\text{outer}}(\tau)]$ of an extra-solar planetary system can be formulated as follows Whitmire & Reynolds (1996):

$$P_{\text{hab}}(M,t) = C \int_{\tilde{R}_{\text{inner}}(M,\tau,t)}^{\tilde{R}_{\text{outer}}(M,\tau,t)} p(R')dR' \qquad (6)$$

In order to estimate n_{CHZ}, the following assumptions are taken to be valid:

1. the distribution of planets can be parameterized by $p(R) \propto \frac{1}{R}$, i.e., their distribution is uniform on a logarithmic scale Kasting (1996), which is not in contradiction to our knowledge of already discovered planetary systems,
2. the stellar masses, $M \in [0.4 M_s \ldots 2.2 M_s]$, are distributed according to a power law $M^{-2.5}$ Scheffler & Elsässer (1988),
3. the stellar ages, t, are equally distributed in $[0, \tau_H(M)]$,
4. the factor C is defined as $N_p / \int_{R_{\min}}^{R_{\max}} p(R')dR'$, where $N_p = 10$ is the average number of planets per stellar system, and $R_{\min} = 0.1$ AU and $R_{\max} = 20$ AU define the boundaries of the planetary system.

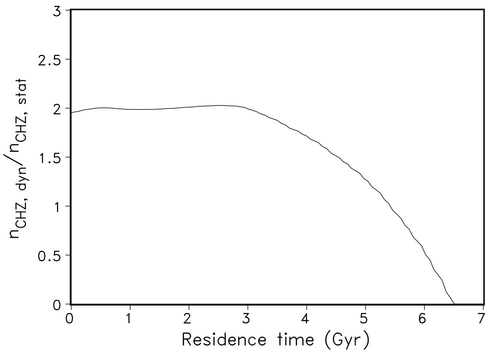

Figure 5. Geodynamic/geostatic abundance ratio as a function of time-of-continuous-residence, τ, in the habitable zone.

Then by integrating over masses, M, and their corresponding lifetime on the main sequence, $\tau_H(M)$, one gets:

$$n_{\text{CHZ}} = C' \int_{0.4M_s}^{2.2M_s} \frac{M^{-2.5}}{\tau_H(M)} \int_0^{\tau_H(M)} P_{\text{hab}}(M,t)dtdM, \tag{7}$$

where C' is defined as: $C' = 1/\int_{0.4M_s}^{2.2M_s} M^{-2.5}dM$. We get for the time interval $\tau = 500$ Myr necessary for the development of life (Jakosky, 1998) and our favored geodynamic model $n_{\text{CHZ}} = 0.012$. Figure 5 shows the geodynamic/geostatic abundance ratio of n_{CHZ}. It demonstrates a geodynamic correction of approximately 2 for a residence time up to 3 Gyr. Now we can start to calculate the number of Gaias with the help of Equation 2. Assuming $N_{\text{NW}} \approx 4 \times 10^{11}$ (Dick, 1998), $f_P \approx 0.05$ (Marcy et al., 2000), $n_{\text{CHZ}} = 0.012$, and $f_L \approx 10^{-2}$ (guesswork) we get

$$\mathcal{N}_{\text{Gaia}} = 2.4 \times 10^6. \tag{8}$$

According to Thi et al. (2001) the number of stars with extra-solar planets may be even much larger than previously thought ($f_P \approx 0.5$) increasing $\mathcal{N}_{Gaia}$ by one order of magnitude. In any way, this is a big and viable population.

5. CONCLUSION AND DISCUSSION

As we have seen in the last chapter (Equation 8) $\mathcal{N}_{\text{Gaia}}$ can have a very large value. But this estimation holds only for young extra-solar planetary systems (residence time ≤ 3 Gyr) where the abundance ratio for a planet with geodynamics is twice as large as for the geostatic case. After approximately 5.3 Gyr of residence time the geodynamic and the geostatic model coincide and the geodynamic/geostatic abundance ratio decreases with increasing residence time. Finally, after about 6.5 Gyr of residence time $\mathcal{N}_{\text{Gaia}}$ is zero for the geodynamic case, because $t_{\max} = 6.5$ Gyr is the maximum lifespan of the biosphere of the geodynamic model (Franck et al., 2000c). This is also indicated by the different behavior of GSM and GDM for Figures 3a and b, respectively. Our estimation does not include the occurrence of destructive cosmic events which may significantly reduce the number of other Gaias. Examples are X-ray-bursts, supernova explosions (Kiraly & Wolfendale, 2000), and “superflares” (Schaefer et al., 2000). There are new results implying that three-quarters of all Earth-like planets are on average 6.4 Gyr old (New Scientist, 2001). This would reduce our estimation for $\mathcal{N}_{\text{Gaia}}$ dramatically.

At this point we want to emphasize, that our model planet is Earth-like in the sense of possessing plate tectonics, because this is a crucial ingredient for our parameterization of the weathering rate. The present understanding of plate tectonics is not sufficient, however, to enable us to predict whether a given planet would exhibit such a phenomenon. Returning to the question in the headline we can give the following answer: for young extra-solar planetary systems there should be much more Gaias than estimated up to now. For planetary systems with the age ≈ 5 Gyr there is no effect of geodynamics on the Drake estimation. And for systems older than 6.5 Gyr we do not expect any other sister of Gaia.

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