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Habitable zones and the number of Gaia's sisters

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Abstract. We present a general modeling scheme for assessing the suitability for life on any Earth-like extrasolar planet by calculating the habitable zone (HZ) in main-sequence-star planetary systems. Our approach is based on an integrated Earth system analysis that relates the boundaries of the HZ to the limits of C4-photosynthetic processes. Within this model, the evolution of the HZ for any main-sequence-star planetary system can be calculated straightforwardly, and a convenient filter can be constructed that picks the candidates for photosynthesis-based life from all the extrasolar planets discovered by novel observational methods. These results can be used to determine the average number of planets per planetary system that are within the HZ. With the help of a segment of the Drake equation, the number of "Gaias" (i.e., extrasolar terrestrial planets with a globally acting biosphere) can be estimated. Our calculation gives about half a million Gaias in the Milky Way.

1. Introduction

If we ask the question about the possible existence of the life outside the Earth, we first have to determine the habitable zone (HZ) for our solar system. The HZ of distances between a main sequence star and an Earth-like planet is roughly defined as the range of mean orbital radii, which imply moderate planetary surface temperatures suitable for the development and subsistence of carbon-based life. The latter precondition is usually taken as the requirement that liquid water is permanently available at the planet's surface. The HZ concept was introduced by Huang (1959, 1960) and extended by Dole (1964) and Shklovskii & Sagan (1966).

For our purposes an Earth-like planet is one similar in mass and composition to Earth. Its mass has to be sufficient to maintain plate tectonics in order for the global carbon cycle to operate and stabilize the surface temperature. It is generally accepted that the Earth's climate is mainly determined by the atmospheric CO_2 level. On geological time scales, i.e. over hundreds and thousands of million years, the Earth's climate is stabilized against increasing insolation by a negative feedback provided by the global carbon cycle: higher surface temperatures increase the precipitation and so increase the weathering rates resulting in decreasing atmospheric CO_2 content and decreasing greenhouse effect. In the case of lower surface temperatures, the negative feedback loop acts analogously.

We know that only our modern Earth has liquid water at its surface. In contrast, Venus is much too hot for the existence of liquid water. At the Venusian orbit the insolation is too strong that the above described negative feedback breaks down: on Venus the atmosphere became so full of water vapor that no infrared radiation from the surface was able to escape to space. The resulting higher surface temperatures forced the vaporization of water to the atmosphere. This positive feedback effect is called "runaway greenhouse". On the other hand, the negative feedback loop stabilizing Earth's climate may also fail if we would shift the planet too much away from the Sun. At such distances CO_2 condenses to form CO_2 clouds that increase the planetary albedo, i.e. the reflection of solar radiation, and cause lower surface temperatures. If the planet's surface would be covered with snow and ice, the albedo would increase further. This positive feedback loop is called "runaway glaciation".

Concerning Mars, we presently know of no life, but there is an ongoing discussion about the possibility that life might have been there in the past. The present Martian surface temperature is so low that CO_2 condenses and the polar ice caps contain a mixture of CO_2 ice and water ice. However, the climate on Mars may not always have been so inhabitable. Early in the Martian history, the climate is thought to have been more suitable for the existence of liquid water at or near the surface (Franck et al. 2000b). The evidence comes from the interpretation of images that show the geology of the surface features (see, e.g., Golombek 1999).

The same type of considerations described above for the solar system with the Sun as the central star can also be done for stars other than our Sun. Such investigations are of special importance because we now have novel techniques for the detection of extrasolar planetary systems. The expected basic results for the HZ around other central stars are relatively simple: to have a surface temperature in the range similar to the Earth's, a planet orbiting a less massive central star would have to be closer to the star than 1 AU (Astronomical Unit) whereas a planet orbiting a brighter star, that is more massive than our Sun, would have to be farther than 1 AU from the star. But the problem is a little bit more complicated: we also have to take into account the different times that stars spend on the main sequence.

At the present time, the determination of habitable zones in extrasolar planetary systems is of special interest because in the last few years up to ≈ 70 objects have been identified with the help of novel techniques (The Extrasolar Planets Encyclopaedia by J. Schneider at `http://www.obsm.fr/planets`). Unfortunately, most of the discovered planets are giants on orbits surprisingly close to the central star. Nevertheless, there is hope to find also Earth-like planets with the help of those astronomical observing programs, launched in the early 1990s, that rely on planet detection in the Milky Way via gravitational microlensing

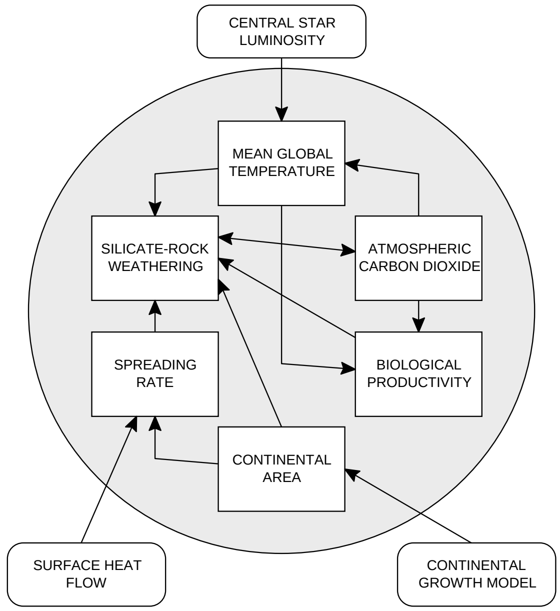

Figure 1. Box model. The arrows indicate the different forcing and feedback mechanisms.

observation and other techniques (Bennett & Rhie 1996). The most important programs are Massive Compact Halo Objects (MACHO), Probing Lensing Anomalies Network (PLANET), Experience pour la Recherche d'Objects Sombres (EROS), and Optical Gravitational Lensing Experiments (OGLE).

The next two sections describe model calculations for the Sun and for other single main sequence stars, respectively. In the final section we show how we can use these results for an estimation of the number of Earth-like planets with a globally acting biosphere ("Gaias") in the Milky Way.

2. Integrated systems approach for an Earth-like planet

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 stellar luminosity, L, the silicate-rock weathering rate, $F_{\rm wr}$, and the global energy balance to estimate the partial pressure of atmospheric and soil carbon dioxide, $P_{\rm atm}$ and, $P_{\rm soil}$, 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 dimensionless quantities:

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

where $f_{\rm wr} \equiv F_{\rm wr}/F_{\rm wr,0}$ 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 $f_{\rm sr} \equiv S/S_0$ is the spreading rate normalized by the present value. With the help of Equation 1 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 (see Figure 2). The connection between the stellar parameters and the planetary climate can be formulated by using the Williams equation (Williams 1998), i.e.,

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

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

3. Habitable zones

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^{-5} bar. 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:

$$HZ := \{R \mid \Pi(P_{\rm atm}(R,t), T(R,t)) > 0\} = [R_{\rm inner}(t), R_{\rm outer}(t)]. \tag{3}$$

In Figure 3 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

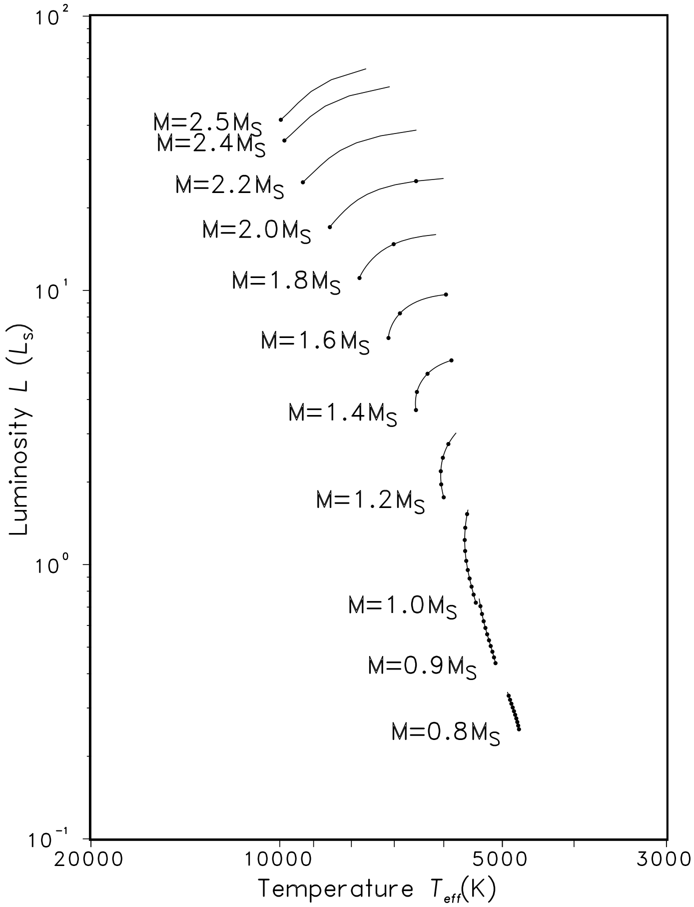

Figure 2. Hertzsprung-Russell diagram for central stars in the mass range between 0.8 and $2.5M_s$. Only the main sequence evolution is considered. Successive dots on the mass-specific branches are separated in time by 1 Gyr (Franck et al. 2000c).

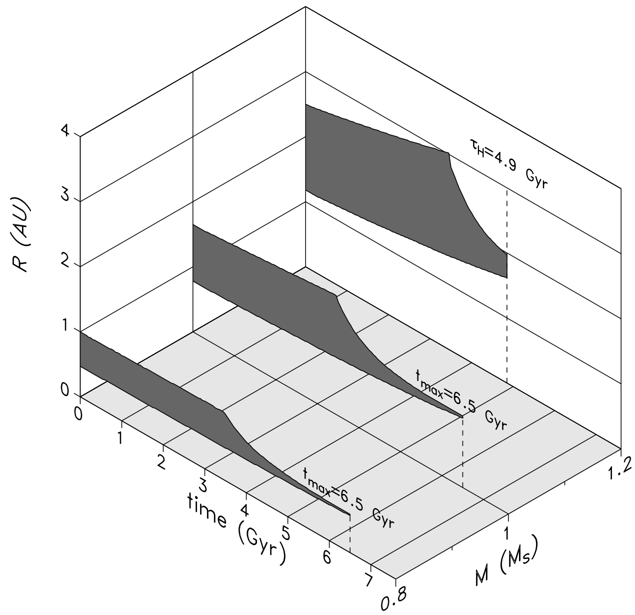

Figure 3. Width and position of the GDM HZ (grey shaded) as a function of time for three different central-star masses ($M = 0.8, 1.0, 1.2 M_s$) for an Earth-like planet. $t_{\max}$ is the maximum life span of the biosphere limited by geodynamic effects. τ_H indicates the hydrogen burning time on the main sequence limiting the life span of more massive stars.

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 (Franck et al. 2000c).

In Figures 4a,b the width $\Delta R = R_{\text{outer}} - R_{\text{inner}}$ 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 5). 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 calcula-

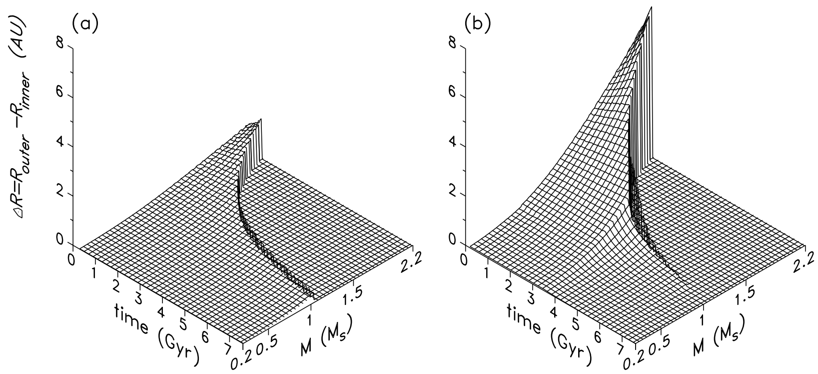

Figure 4. (a) The width, $\Delta R = R_{\text{outer}} - R_{\text{inner}}$, of the HZ as a function of time, t, and stellar mass, M, calculated by using the geostatic model. (b) The width, ΔR, of the HZ given by the geodynamic approach. ΔR is measured in astronomical units.

tions 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 $M < 0.6 M_s$.

4. Gaian selection

From the view of Earth-system analysis, we will focus our presentation on an estimation of the contemporary sisters of Gaia in the Milky Way selected from the Drake equation (see, e.g., Terzan & Bilson 1997, Dick 1998, Jakosky 1998). These are habitable planets with a biosphere interacting with its environment on a global scale, denoted by $\mathcal{N}_{\text{Gaia}}$. The number of civilizations, $\mathcal{N}_{\text{CIV}}$, is given by:

$$\mathcal{N}_{\text{CIV}} = \mathcal{N}_{\text{Gaia}} \times f_{\text{CIV}} \times \delta, \tag{4}$$

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

$$\mathcal{N}_{\text{Gaia}} := N_{\text{MW}} \times f_P \times n_{\text{CHZ}} \times f_L. \tag{5}$$

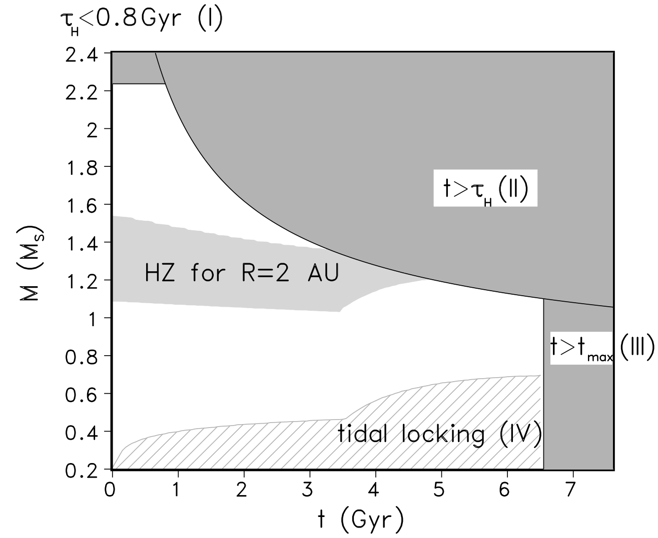

Figure 5. Shape of the GDM HZ (light grey shading) in the mass-time plane for an Earth-like planet at distance $R = 2$ AU from the central star. The potential overall domain for accommodating the HZ for planets at some arbitrary distance is limited by a number of factors that are independent of R: (I) 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))

Let us discuss the specific factors in detail:

- $N_{\rm MW}$ denotes the total number of stars in the Milky Way.
- f_P is the fraction of stars with Earth-like planets.
- $n_{\rm CHZ}$ 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).
- $f_{\rm CIV}$ 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 lifetime 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 5 is n_{CHZ}. For the assessment of n_{CHZ} it is necessary to investigate the habitability of an extra-solar planetary system.

Based on Equation 3 we introduce the continuously 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. 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 6) 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 $[\tilde{R}_{\mathrm{inner}}(\tau, t), \tilde{R}_{\mathrm{outer}}(\tau, t)]$ of an extra-solar planetary system can be formulated as follows (Whitmire & Reynolds 1996):

$$P_{\mathrm{hab}}(M, t) = C \int_{\tilde{R}_{\mathrm{inner}}(M,\tau,t)}^{\tilde{R}_{\mathrm{outer}}(M,\tau,t)} p(R)dR. \tag{6}$$

In order to estimate n_{CHZ}, the following assumptions are made:

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, $M \in [0.4M_s \ldots 2.2M_s]$, 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 $N_p / \int_{R_{\mathrm{min}}}^{R_{\mathrm{max}}} p(R)dR$, where $N_p = 10$ is the average number of planets per stellar system, and $R_{\mathrm{min}} = 0.1$ AU and $R_{\mathrm{max}} = 20$ AU define the boundaries of the planetary system.

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

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

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 $n_{\mathrm{CHZ}} = 0.012$. Figure 6 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 5.

For the total number of starts we assume $N_{\mathrm{NW}} \approx 4 \times 10^{11}$ (Dick 1998). According to Gonzalez et al. (2001) there exist also a so-called galactic habitable zone, which may reduce the number of stars where an Earth-like planet can be habitable at all. Until now, Gonzalez et al. (2001) have investigated only the outer limit quantitatively. Therefore a full quantitative estimate is not possible and we are still using the total number of stars, N_{MW}.

Current extra-solar planet detection methods are sensitive only to giant planets. According to Marcy et al. (2000) and Marcy & Butler (2000) approximately 5% of Sun-like stars surveyed possess giant planets. Up to now, the fraction of stars with Earth-like planets can be estimated only by theoretical considerations. In such an approach Lineweaver (2001) combines star and Earth formation rates based on the metalicity of the host star. Using his results we can find a rough approximation for the fraction of stars with Earth-like planets from the ratio of Earth formation rates to star formation rates. Since the Sun was formed this ratio has always been between 0.01 and 0.014. As a conservative approximation the value $f_P \approx 0.01$ has been used.

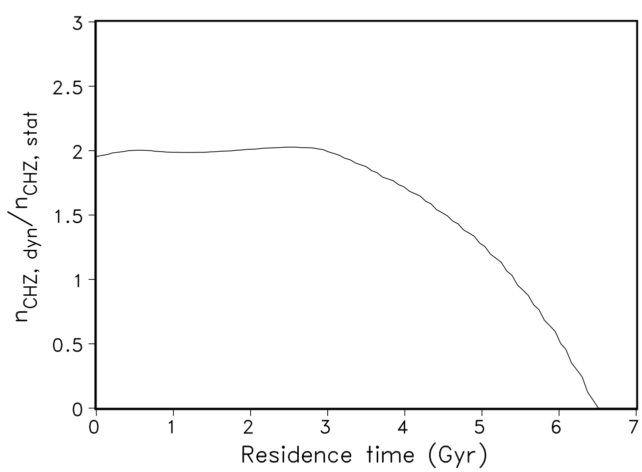

Figure 6. Geodynamic/geostatic abundance ratio as a function of time-of-continuous-residence, τ, in the habitable zone.

The fraction of habitable planets where life emerges and a full biosphere develops is a topic of controversial discussions The main question is whether biochemistry on a habitable planet would necessarily lead to replicating molecules ($f_L \equiv 1$, see, e.g., Dick 1998). On the other hand there are also suggestions that f_L is an extremely low number (Hart 1995). We use $f_L \approx 10^{-2}$ as a mid-way between the predominant optimistic view and pessimistic estimations sketched above. Combining these factors we finally get

$$\mathcal{N}_{\rm Gaia} \approx 4.8 \times 10^5, \tag{8}$$

which is indeed a rather large number. The number of habitable planets in the Milky Way is even larger, we expect 50 million habitable extra-solar Earth-like planets.

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