Naturwissenschaften (2001) 88:416–426
DOI 10.1007/s001140100257

REVIEW ARTICLE

S. Franck · A. Block · W. von Bloh · C. Bounama
I. Garrido · H.-J. Schellnhuber

Planetary habitability: is Earth commonplace in the Milky Way?

Published online: 23 August 2001

Abstract Is there life beyond planet Earth? This is one of the grand enigmas which humankind tries to solve through scientific research. Recent progress in astronomical measurement techniques has confirmed the existence of a multitude of extra-solar planets. On the other hand, enormous efforts are being made to assess the possibility of life on Mars. All these activities have stimulated several investigations about the habitability of cosmic bodies. The habitable zone (HZ) around a given central star is defined as the region within which an Earth-like planet might enjoy the moderate surface temperatures required for advanced life forms. At present, there are several models determining the HZ. One class of models utilises climate constraints for the existence of liquid water on a planetary surface. Another approach is based on an integrated Earth system analysis that relates the boundaries of the HZ to the limits of photosynthetic processes. Within the latter approach, the evolution of the HZ for our solar system over geological time scales is calculated straightforwardly, and a convenient filter can be constructed that picks the candidates for photosynthesis-based life from all the extra-solar planets discovered by novel observational methods. These results can then 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. extra-solar terrestrial planets with a globally acting biosphere) is estimated. This leads to the thoroughly educated guess that there should exist half a million Gaias in the Milky Way.

S. Franck (✉) · A. Block · W. von Bloh · C. Bounama · I. Garrido
H.-J. Schellnhuber
Potsdam Institute for Climate Impact Research (PIK),
PF 60 12 03, 14412 Potsdam, Germany
e-mail: Franck@pik-potsdam.de
Tel.: +49-331-2882659, Fax: +49-331-2882660

Introduction

The extra-terrestrial life debate stretches from the ancient Greek world of Democritus over the 18th century European world of Immanuel Kant to the recent discoveries of extra-solar planets. Concerning the search for life in our planetary system, Schiaparelli's observation of a system of "canali" on the Martian surface in 1877 was the beginning of an epochal effort to reveal planetary conditions relevant to life with the refinement of observational techniques. The detection, by McKay et al. (1996), of the chemical biomarkers and possible microfossils in a meteorite from Mars called ALH 84001 (found in 1984 in Antarctica) has stimulated research in the newly emerging field of astrobiology. Mars holds great interest for the latter and presently stands centre stage in the plans to explore the inner solar system for signs of past or present life. Already it can be stated that the search for extra-terrestrial life will be one of the predominant themes of science in the 21st century.

The definition of habitability is closely related to the very definition of life. Up to now, we only know terrestrial life, and therefore the search for extra-terrestrial life is the search for life, as we know it from our home planet. Life can be defined as a self-sustained system of organic molecules in liquid water immersed in a source of free energy. It is well known that organic molecules are rather common in the solar system and even in interstellar clouds. There is also no problem in finding any source of free energy for extra-terrestrial life. Therefore, the existence of liquid water is the central point in the search for extra-terrestrial life and in the definition of habitability. Nevertheless, it is evident that liquid water and basic nutrients are essential, but not sufficient requirements for life.

The histories and fates of the three "terrestrial planets" – Venus, Earth and Mars – suggest that a combination of factors such as distance from the Sun, planetary size, as well as geological and perhaps biological evolution, will control the existence of liquid water on a planetary surface. Earth-like planets cannot have liquid surface water if they are much closer to the Sun than one astronomical unit (as defined by Earth's orbit), because of unfavourably high temperatures and loss of water by photo-dissociation would be unavoidable in this case. On the other hand, an Earth-like planet, which is quite distant from the Sun, would have permanent surface temperatures below the freezing point of water, and therefore would not be habitable either.

In general, the habitable zone (HZ) around the Sun can be defined as the region within which an Earth-like planet might enjoy the moderate surface temperatures needed for advanced life forms. The more specific definition related to the existence of liquid water at the planet's surface was introduced by Huang (1959, 1960) and extended by Dole (1964) and Shklovskii and Sagan (1966). Hart (1978, 1979) calculated the evolution of the terrestrial atmosphere over geologic time at varying distances. He found that the HZ between "runaway greenhouse" and "runaway glaciation" is surprisingly narrow for G2 stars like our Sun: R_{inner}=0.958 AU, R_{outer}= 1.004 AU, where AU denotes the astronomical unit. A main drawback of those calculations is the neglect of the negative feedback between atmospheric CO_2 content and mean global surface temperature as discovered later by Walker et al. (1981). The full consideration of this feedback by Kasting et al. (1988) provided the interesting result of an almost constant inner boundary, yet a remarkable extension of the outer boundary. Later on, the calculations of the HZ were improved and extended to other main sequence stars (Kasting et al. 1993; Kasting 1997; Williams 1998). A comprehensive overview can be found in the proceedings of the first international conference on circumstellar HZs (Doyle 1996).

Recent studies conducted by the authors of this review (see, for example, Franck et al. 2000a, b) have generated a rather general characterisation of habitability, based on the possibility of photosynthetic biomass production under large-scale geodynamic conditions. Thus not only is the availability of liquid water on a planetary surface taken into account but also the suitability of CO_2 partial pressure. Our definition of habitability is described in detail in the next section.

In fact, the same type of stability calculations sketched above for the solar system, with the Sun as the central star, can also be performed for other stars. The basic results for the HZ around these other central bodies are relatively simple: in order to have a surface temperature in the terrestrial range, a planet orbiting a central star with lower mass would have to be closer to the star than 1 AU, whereas a planet orbiting a brighter star having more mass than our Sun would have to be farther away than 1 AU from the star. But the problem is a bit more complicated than that. One also has to take into account the different times that stars spend on the so-called main sequence. Such stars receive their energy mainly from hydrogen burning, i.e. the fusion of hydrogen to helium (see, for example, Kippenhahn and Weigert 1990; Sackmann et al. 1993).

The success of highly sophisticated detection techniques for extra-solar planets has led astronomers to forecast the imminent dawning of a golden age of astronomy. Up to now, about 60 extra-solar planets have been discovered. Questions that scientists once considered beyond the reach of observation may soon find at least partial answers. In particular, is there life on planets found beyond the solar system, or are they at least habitable? Fundamental work in these fields has been performed by Lovelock (1965, 1975), and Hitchcock and Lovelock (1967). They discuss the general interactions between life and its planetary environment. Later on, discussing the possibility of self-regulation by and for the biosphere, Lovelock and Margulis (1972) (see also Lovelock 1987) put forward the Gaia hypothesis. Beyond the discussion of extra-terrestrial life, there is an ongoing debate about other civilisations outside the solar system. The Drake equation, which was first presented by Drake in 1961 (see, for example, Dick 1998) and which identifies the relevant factors for a statistical estimation, can provide further information about the abundance of possible extra-terrestrial civilisations. Although several factors are highly speculative, a subset of them – determining the selection of contemporary biospheres interacting with their environment on a global scale ("Gaias") – can be investigated rather rigorously. Based on investigations by Franck et al. (2001) on the HZ for extra-solar planets, one can calculate the probability for the existence of an Earth-like planet in the HZ as one factor of this subset.

All these cross-disciplinary studies concerning the origin, distribution, and future of life in the universe may be summarised by the term "astrobiology" as the scientific discipline for the study of life as part of cosmic evolution. Some fundamental questions in current astrobiological research are the following: How do habitable worlds form and how do they evolve? How did living systems emerge? How can we recognise other biospheres? How have the physical Earth and its biosphere influenced each other over time? How do changes in the environment affect emergent ecosystems and their evolution? What is the potential for biological evolution beyond Earth? At the beginning of the new millennium the answers to some of these questions are within our reach (see, for example, Brack 1998; Dick 1998; Jacosky 1998; Schopf 1999; Horneck 2001). We can expect that important new insights will emerge as space-age technology is intensively used in astronomical, planetological, and biological research.

In the present paper, the possibility of the existence of life on an Earth-like planet at various distances from the Sun is investigated. The method is based on the Earth system science approach (Schellnhuber 1999) that calculates the past and future evolution of a dynamic Earth under the influence of an increasing solar luminosity (Franck et al. 1999, 2000a). Such long-term climate regulation is thought to be governed by the global carbon cycle and its effect on atmospheric CO_2 content and biological productivity. Our methodological apparatus is sketched out in the next section, and results for the HZ for our solar system are presented after this. The model is extended to extra-solar planetary systems with central

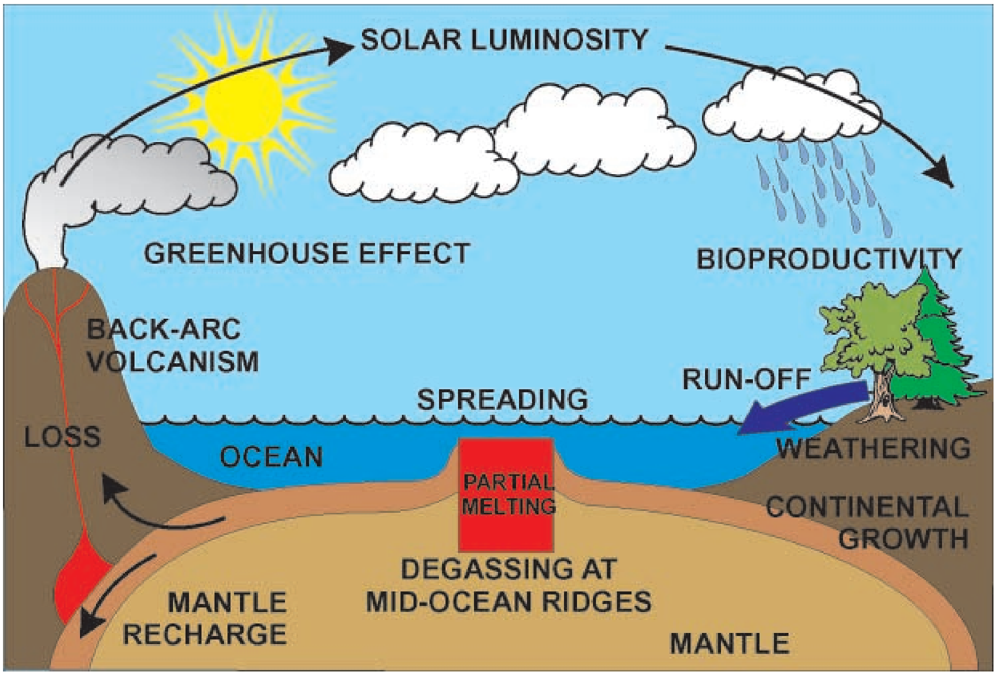

Fig. 1 The global carbon cycle as part of the general volatile exchange between mantle and surface reservoirs

stars different from our Sun, and the insights obtained there are used to estimate the number of Gaias in the Milky Way.

Earth system modelling

The Earth system model employed here is a stylised geosphere–biosphere model to analyse the evolution of this complex on a global scale from the geological past to the planetary future in 1.5 billion years. The model consists of the components solid Earth, hydrosphere, atmosphere and biosphere. It couples the increasing solar luminosity, the silicate-rock weathering rate, and the global energy balance to estimate the partial pressure of atmospheric and soil carbon dioxide, the mean global surface temperature, and the biological productivity as a function of time. The crucial point is the long-term balance between the CO_2 sink in the atmosphere–ocean system and the metamorphic (plate-tectonic) sources. In the following, the respective features of our Earth system model are described in some detail.

Climate

The climate of a planet is governed by the energy balance equation between incoming and outgoing radiation. The pertinent equation is based on the simple zero-dimensional model of climate that was introduced by Arrhenius (1896). In this model, the surface temperature of planet Earth is the sum of the effective (black body) radiation temperature depending on insolation and the greenhouse warming depending on atmospheric CO_2 content. The increased insolation results from the increase in the main-sequence hydrogen-burning rate, and can be well described by rather simple formulae (see, for example, Gough 1981). During the Earth's history, the luminosity of the Sun has increased to the present level at a rate of about 10% per Gyr, and will increase in the future (up to the next 5 Gyr) at approximately the same rate.

Carbon cycle

The carbon cycle is the main process for the regulation of the atmospheric composition and climate with respect to increasing insolation. Walker et al. (1981), Berner (1993), Berner et al. (1983) and Lasaga et al. (1985), as well as many others, have investigated the so-called carbonate–silicate geochemical cycle between the atmosphere, the ocean, and the continents. On geological time scales, however, the deeper parts of the Earth are considerable sinks and sources for carbon and tectonic activity, as well as the continental area, changes markedly. Therefore, Tajika and Matsui (1992) have favoured the so-called global carbon cycle. In addition to the usual carbonate–silicate geochemical cycle, it also involves the subduction of large amounts of carbon into the mantle with descending slabs and the degassing of carbon from the mantle at mid-ocean ridges. The global carbon cycle is sketched in Fig. 1.

Weathering rate

Weathering plays an important role in Earth's climate because it provides the main sink for atmospheric CO_2. The question as to what extent the biota are actually able to play a key role in stimulating this sink is crucial for an understanding of the dynamic properties of the overall Earth system. The total process of weathering embraces (1) the reaction of silicate minerals with CO_2, (2) the transport of weathering products, and (3) the deposition of carbonate minerals in sediments. Combining all theses effects, the global mean weathering rate can be formulated via an implicit equation introduced by Walker et al. (1981).

Biological productivity

The biological productivity, Π, is the amount of biomass that is produced by photosynthesis per unit time and per unit of continental area. In reality, Π itself is a function of various parameters such as water supply, photosynthetically active radiation, nutrients, atmospheric CO_2 content (P_{atm}), and surface temperature (T_s). In the framework of the Earth system model employed, Π is considered to be a function of P_{atm} and T_s only. According to Liebig's principle, Π can be represented as a product, i.e.

$$\Pi(T_s, P_{atm}) = \Pi_{max} \cdot \Pi_T(T_s) \cdot \Pi_P(P_{atm}), \tag{1}$$

where Π_{max} is the maximum biological productivity, about twice the present value (Volk 1987). Π_T has a parabolic form (Caldeira and Kasting 1992), and Π_P is a Michaelis-Menten hyperbola (see Fig. 2).

Geodynamics

Caldeira and Kasting (1992) have investigated an Earth system model under the assumption that the weathering rate is always equal to the present value. This is clearly a rather rough approximation, and we call this approach the geostatic model. In the framework of a geodynamic-equilibrium approach for the global carbon cycle at longer time scales of about hundred thousands of years, Walker et al. (1981) first proposed a balance between the CO_2 sink in the atmosphere–ocean system and the metamorphic source. Using the balance, one can find a relation between the weathering rate on the one hand, and continental area and spreading rate on the other (Kasting 1984). Therefore, knowing continental area and spreading rate, one can calculate the weathering rate for both the geological history and the planetary future. This is called the geodynamic model that constitutes a significant improvement over the previous approach. Figure 3 depicts the continental growth models fed into the calculations. The spreading rate can be determined according to boundary layer theory of convection as a function of the global mean heat flow (Franck et al. 1999), which is a main result of the so-called parameterised convection models for the Earth's thermal evolution (Franck 1998). The calculation scheme of the applied Earth system model is sketched in Fig. 4.

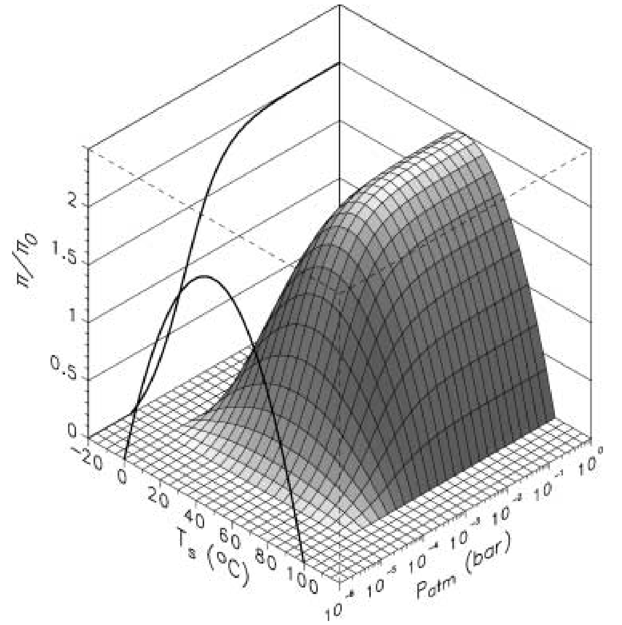

Fig. 2 Biological productivity Π normalised to the present value Π_0 as a function of surface temperature T_s and atmospheric carbon dioxide partial pressure P_{atm}

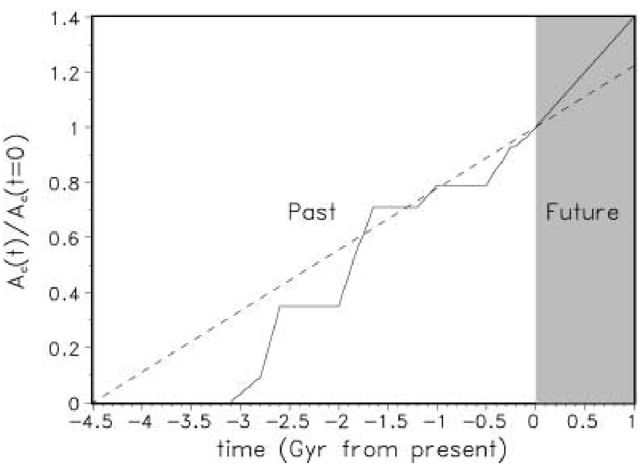

Fig. 3 Cumulative continental growth model of Condie (1990) (*solid line*) and a linear continental growth model (*dashed line*). The continental area A_c is normalised to the present day area $A_c(t{=}0)$. Both models are linearly extrapolated into the future. In our calculations for extra-solar planetary HZs the linear continental growth model has been applied, while for the solar system HZ the Condie model has been used

Models for calculating the HZ in the solar system

Since the early work of Hart (1978, 1979), there have been many improvements regarding the climatic constraints on the inner and outer boundaries of the HZ. One of the most comprehensive studies in this field is the paper by Kasting et al. (1993). The authors define the boundaries of the HZ via so-called critical solar fluxes. For the inner radius of the HZ, they give three different

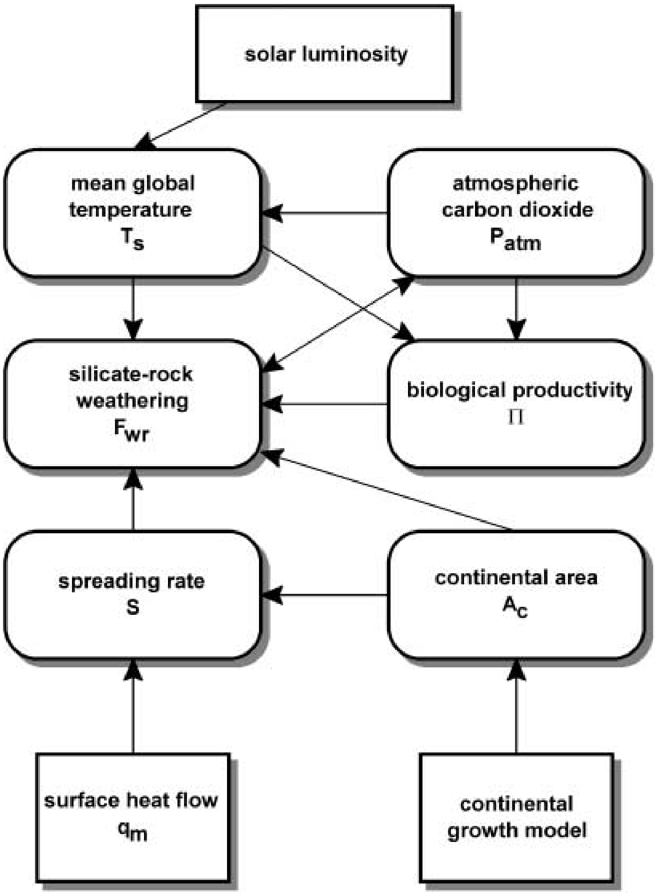

Fig. 4 Earth system box model. The *arrows* indicate the different forcing and feedback mechanisms

estimations. The first assumes the loss of planetary water by a moist greenhouse (Kasting 1988); the second assumes loss of planetary water by a runaway greenhouse; and the third is based on the observation that there was no liquid water on Venus' surface at least for the last 1 Gyr. The outer radius of the HZ is also estimated in three different ways. The first one is based on arguments that early Mars had a warm and wet climate [see also the recent papers by Golombek (1999) and Malin and Edgett (2000)], the second one assumes a maximum possible CO_2 greenhouse heating; and the third one is related to first condensation limit of CO_2 clouds that increase the planetary albedo.

Assuming the possibility of a "cold start", i.e. an originally ice covered planet that was initially beyond the outer HZ boundary could be habitable at a later stage if the outer boundary of the HZ shifts outward to its orbit, Kasting et al. (1993) found the following values for the present HZ in the solar system:

- Most conservative case: 0.95 AU to 1.37 AU,
- Least conservative case: 0.75 AU to 1.90 AU,
- Intermediate case: 0.84 AU to 1.77 AU.

Based on the Earth system model described in the previous section, the HZ for the solar system can be determined in a different way. Here the HZ for an Earth-like planet is the region around the Sun within which the surface temperature of the planet stays between 0°C and 100°C and the atmospheric CO_2 partial pressure is higher than 10^{-5} bar, i.e., suitable for photosynthesis-based life (biological productivity $\Pi>0$):

$$\mathrm{HZ} := \{R \,|\, \Pi(P_{\mathrm{atm}}(R,t), T_{\mathrm{s}}(R,t)) > 0\} = [R_{\mathrm{inner}}, R_{\mathrm{outer}}]. \quad (2)$$

The upper limit of the CO_2 partial pressure is given by the maximum available amount of CO_2 in an Earth-like planet's atmosphere, which is taken as 10 bar. The term "Earth-like" explicitly implies the occurrence of plate tectonics as a necessary condition for the operation of the carbonate–silicate cycle as the mechanism to compensate for the gradual brightening of the Sun during its "life" on the main sequence. The geodynamical evolution of the considered Earth-like planet provides an even stronger constraint. In the geological past, the volcanic input of CO_2 to the atmosphere was much higher and the continental area (available for weathering) was much smaller than today.

The results for the estimation of the HZ via the geodynamic model are summarised in Fig. 5, where we have plotted the width and position of the HZ for three different points in time (past, present, future). In about 500 Myr the inner boundary, R_{inner}, reaches the Earth distance from the Sun (R=1 AU) and the biosphere ceases to exist. The outer boundary, R_{outer}, decreases in a strongly non-linear way. This result is in contrast to the results of Kasting et al. (1993) and Kasting (1997). The calculations show that the inner boundary of the HZ is determined by the 10^{-5} bar limit and the outer boundary by the 0°C limit. From the view of geocybernetics (Schellnhuber and Kropp 1998), the inner and outer boundaries of the HZ can be considered as critical values of an ecological niche for life in general and humanity in particular.

Of course, there may exist chemolithoautotrophic hyperthermophiles that might survive even in a future of higher temperatures, rather independently of atmospheric CO_2 pressures (see, for example, Schwartzman 1999). But, under such conditions, all higher forms of life would certainly be eliminated. The biosphere model (Eq. 1) is actually only relevant to photosynthesis-based life. Therefore, in the time span under consideration, the upper temperature does not affect the results for the HZ.

An Earth-like planet at Martian position would have been within the HZ from about 3.5 Gyr to about 0.5 Gyr ago (Franck et al. 2000c). The outer boundary of the HZ is mainly determined by the total amount of CO_2 that can be in the atmosphere. One should note that the required high atmospheric CO_2 content for a terrestrial planet in the outer HZ would make it less likely for complex aerobic organisms to exist there. The possible extension of the HZ up to the Martian position seems to be realistic for the solar system past. This is a reason for scrutinising planet Mars in some detail. We know that, due to its smaller size, all geological processes caused by the internal cooling of the planet should have faded away much

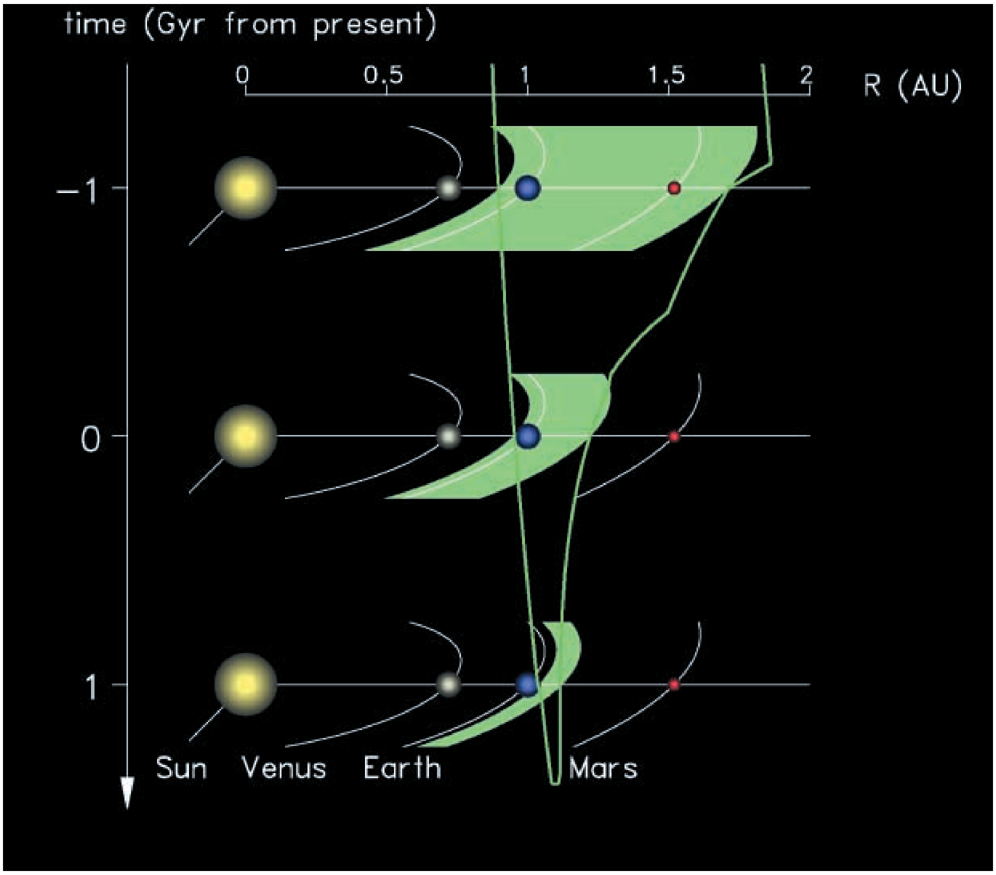

Fig. 5 Habitable zone (*green shading*) for the solar system at three different time steps. The orbits of the three terrestrial planets, Venus, Earth and Mars, are shown. The *solid green lines* describe the evolution of the inner and outer boundary of the HZ

faster than for the Earth. Nevertheless, we can speculate that the results given above about the HZ are an upper bound for the time that Mars was habitable in the past. This is in good agreement with investigations concerning an early warmer and wetter Martian environment (Golombek 1999) and with recent observations that plate tectonics may have once operated on Mars (Connerney et al. 1999). On the other hand, there are theories that the Martian atmosphere was blown away by the solar wind, following the demise of its magnetic field 4 billion years ago. This happened so soon after Mars's formation that it is unlikely that complex life would have had time to evolve (New Scientist 2001b). In contrast to Mars, an Earth-like planet at the Venusian position was never, and will never be, within the HZ.

HZ around other main sequence stars

The same type of HZ calculations, on the basis of climatic constraints as well as on the basis of Earth system modelling, can be performed for stars with masses different from the solar mass.

Kasting et al. (1993) restricted themselves to stellar life times greater than 2 Gyr, which correspond to masses less than 1.5 M_s (1 M_s=one solar mass). At the low-mass end they restricted themselves to masses greater than 0.5 M_s because stars with masses ≤ 0.5 M_s show negligible evolution. Stellar luminosities and temperatures were taken directly from Iben (1967a, b), climatic constraints corresponded to their so-called intermediate case (see above). As expected, stellar HZs for more massive stars are rather short because they have to be truncated at the end of the main sequence. HZs for low-mass stars remain essentially constant over time. In Fig. 6, we show the so-called zero age main sequence HZ from Kasting et al. (1993) as a function of stellar mass.

In Franck et al. (2000b), the HZ in extra-solar planetary systems is calculated using the luminosity evolution of central stars on the main sequence in the mass range between 0.8 and 2.5 M_s. The results have been obtained by polynomial fitting of detailed stellar evolution models by Schaller et al. (1992). The corresponding Hertzsprung-Russell diagram, i.e. a plot of luminosity versus effective radiating temperature, is shown in Fig. 7. The temperature tolerance window for the biological productivity was again in the range between 0°C and 100°C in order to incorporate thermophiles (Schwartzman et al. 1993), but for this study a linear continental growth model (Fig. 3) was employed.

In principle, it is possible to calculate the HZ for any value of central-star mass shown in Fig. 7. As an illustration, we present the results for central-star masses of 0.8, 1.0, and 1.2 M_s, respectively, in Fig. 8.

An alternative method of presentation is to delineate the HZ for an Earth-like extra-solar planet at a given (but

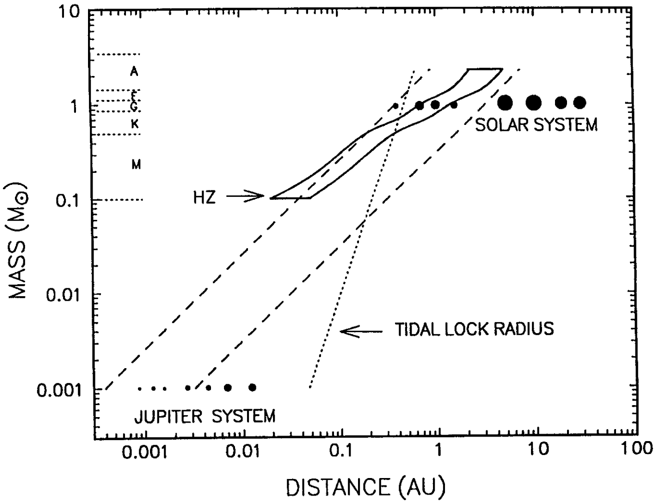

Fig. 6 The zero age main sequence HZ as a function of central star mass (in solar masses M⊙) for the intermediate case of climatic constraints. The *long-dashed lines* delineate the probable terrestrial planet accretion zone. The *dotted line* is the orbital distance for which an Earth-like planet in a circular orbit would be locked into synchronous rotation (tidal locking). Figure from Kasting et al. (1993), with the kind permission of Dr. J.F. Kasting and Academic Press

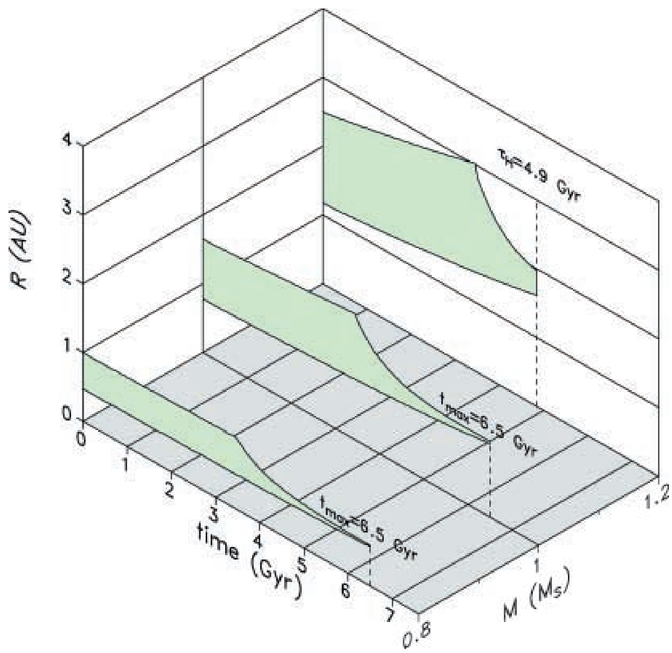

Fig. 8 Graphs of the width and position of the HZ derived from the geodynamic model for three different stellar masses M (0.8, 1.0, 1.2 M_s). t_{max} is the maximum life span of the biosphere limited by geodynamic effects. τ_H indicates the hydrogen burning time on the main sequence limiting the life span of more massive stars

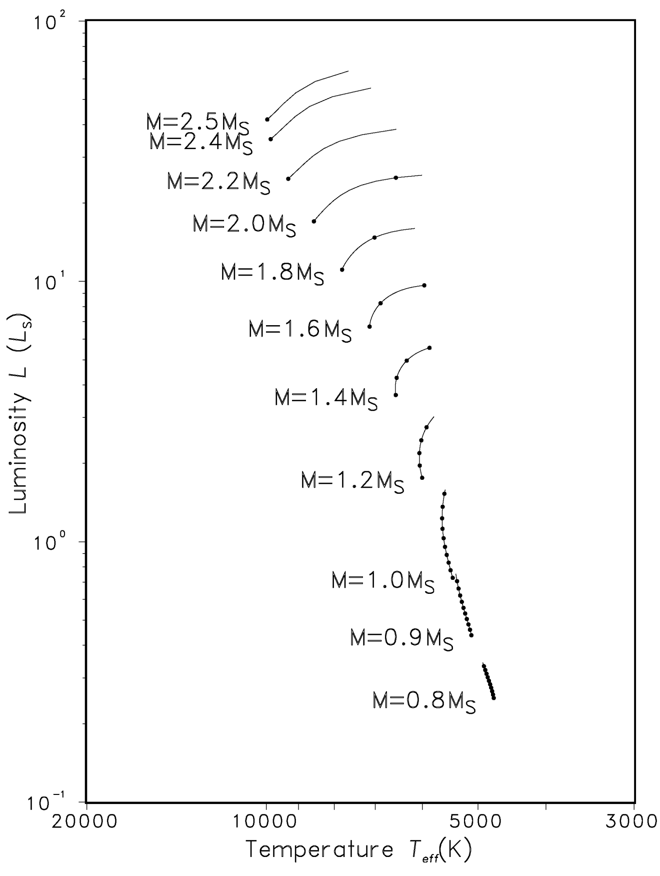

Fig. 7 Hertzsprung-Russell diagram for central stars in the mass range between 0.8 and 2.5 M_s. Only the main sequence evolution is considered. *Successive dots* on the mass-specific branches are separated in time by 1 Gyr. Figure from Franck et al. (2000b)

arbitrary) distance R in the stellar mass–time plane. Here the following effects limit the HZ:

I. Stellar lifetime on the main sequence decreases strongly with mass. Using simple scaling laws (Kippenhahn and Weigert 1990), the central hydrogen burning period is estimated to be τ_H<0.8 Gyr for 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). Quite recently, 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 τ_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 lock-

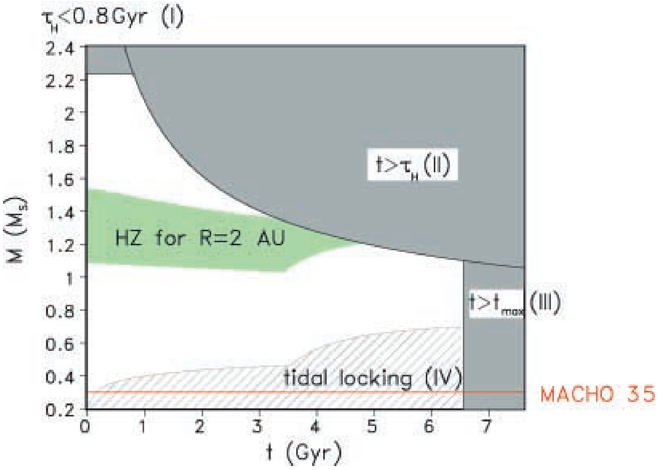

Fig. 9 Shape of the geodynamic model HZ (*green shading*) in the mass–time plane for an Earth-like planet at distance R=2 AU from the central star. The potential overall domain for accommodating the HZ for planets at some arbitrary distance is limited by a number of factors that are independent of R: (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 *grey shading* in the case of the first three factors and by *grey hatching* for the tidal-locking effect. The *horizontal red line* represents the hypothetical MACHO-98-BLG-35 planet, which is assumed to orbit a 0.3 M_s star. Figure from Franck et al. (2000b)

ing. 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. Global climate models of tidally locked planets have indicated that Earth-like planets should not be necessarily precluded from habitability (Joshi et al. 1997).

As an example, we depict the HZ for R=2 AU in Fig. 9. We have also shown the parameters on the hypothetical MACHO-98-BLG-35 planet, which was assumed to orbit a 0.3 M_s star at a distance of 2 AU (Rhie et al. 1998). Even if the existence of MACHO-98-BLG-35 could be confirmed, this system would not be a candidate for extra-terrestrial life, because it is clearly outside the HZ.

How many Gaias are there?

How can we estimate the number of technological civilisations that might exist "out there"? A convenient scheme for extra-terrestrial intelligence prospecting is the Drake equation, which identifies specific factors considered to play a role in the development of such civilisations and allows estimating at least orders of magnitude:

$$N_{\mathrm{CIV}} = N_{\mathrm{MW}} \cdot f_{\mathrm{P}} \cdot n_{\mathrm{CHZ}} \cdot f_{\mathrm{L}} \cdot f_{\mathrm{CIV}} \cdot \delta. \tag{3}$$

This equation counts the number of contemporary technical civilisations in the Milky Way, N_{CIV}, whose radio emissions may be detectable, but note that some factors in Eq. 3 are highly speculative: Depending on more pessimistic or more optimistic assumptions, one can end up with either no candidates at all or a surprisingly large number of possible entities. Let us discuss the specific factors in detail:

- N_{MW} is the total number of stars in the Milky Way.
- f_{P} is the fraction of stars with Earth-like planets.
- 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 (Gaia's sisters).
- f_{CIV} denotes the fraction of sisters of Gaia developing technical civilisations. Life on Earth began over 3.85 billion years ago (Jakosky 1998). Intelligence took an extremely 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 civilisation lifetime to Gaia lifetime.

As already mentioned above, f_{CIV} and δ are highly speculative items: There is just no information available about the *typical* evolutionary path of life, or the characteristic "life span" of communicating civilisations. Regarding the fate of ancient advanced civilisations on Earth, the typical lifetime was limited by increasing environmental degradation or over-exploitation of natural resources. One can also speculate that the development and utilisation of certain techniques, which facilitate the emergence of a higher civilisation, may be accompanied by new vulnerabilities or hazard potentials that jeopardise the very subsistence of advanced cultures. As a consequence, the lifetime of any communicating civilisation may be limited to the range of few hundreds of years, yet this is not even an educated guess.

On the other hand, f_{L} seems to be assessable by geophysiological theory and observation. And the remaining factors are deducible from biogeophysical science. Therefore, from the view of Earth system analysis, we will focus on estimation for the contemporary sisters of Gaia in the Milky Way, denoted by N_{Gaia}:

$$N_{\mathrm{Gaia}} := N_{\mathrm{MW}} \cdot f_{\mathrm{P}} \cdot n_{\mathrm{CHZ}} \cdot f_{\mathrm{L}}. \tag{4}$$

The key factor in Eq. 4 is n_{CHZ}. For the assessment of this factor it is necessary to investigate the habitability of an extra-solar planetary system. Based on Eq. 2, the continuously habitable zone (CHZ) (Kasting et al. 1993) is defined as the band of orbital distances where the planet is within the HZ for a given time interval τ.

Now we can start to calculate the number of Gaias with the help of Eq. 4 by discussing each of the four factors in Eq. 4:

1. The total number of stars in the Milky Way is quite well known (see, for example, Dick 1998). It can be

derived from the star formation rate (Zinnecker et al. 1993). We pick the value $N_{MW} \approx 4 \times 10^{11}$. According to Gonzalez et al. (2001) there exists also a so-called galactic habitable zone (GHZ), i.e. that region in the Milky Way where an Earth-like planet can be habitable at all. The inner limit of the GHZ is defined by exogenous perturbations destroying life (e.g. supernovae, gamma ray bursts, comet impacts). The outer limit is set by the chemical evolution of the galaxy, in particular the radial disc metallicity gradient. Until now, Gonzalez et al. (2001) have investigated only the outer limit quantitatively. Therefore, a quantitative estimation of the GHZ is still not possible and we cannot reduce the value for N_{MW} given above.

2. Current extra-solar planet detection methods are sensitive only to giant planets. According to Marcy and Butler (2000) and Marcy et al. (2000) approximately 5% of the Sun-like stars surveyed possess giant planets. These discoveries show that our solar system is not typical. Several stars are orbited by giant planets very closely and highly eccentric. Up to now, the fraction of stars with Earth-like planets can be estimated only by theoretical considerations. Lineweaver (2001) combines star and Earth formation rates based on the metallicity 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 rate to star formation rate. Since the Sun was formed this ratio has always been between 0.01 and 0.014. In the framework of a conservative approximation we pick the value $f_P \approx 0.01$.
3. The average number of Earth-like planets per planetary system which are suitable for the development of life, i.e. residing in the CHZ, can be calculated in the following way (Franck et al. 2001): first one computes the probable number of planets, $P_{hab}(M,t)$, which are within the CHZ, $[R_{inner}(\tau), R_{outer}(\tau)]$, of a central star with mass M at a certain time t. For this calculation it is assumed that the planets are distributed uniformly on a logarithmic scale (Kasting 1996). This distribution is a good approximation for the solar system and is not in contradiction of our knowledge of already discovered planetary systems. Knowing $P_{hab}(M,t)$, one has to integrate over all stellar ages t on the main sequence, and after that over all central star masses that are relevant for HZs, i.e. between 0.4 M_s and 2.2 M_s (see Fig. 7). The stellar masses M are distributed according to a power law $M^{-2.5}$ (Scheffler and Elsässer 1988). Introducing certain normalisation constants and using τ=500 Myr as the necessary time interval for the development of life (Jakosky 1998), Franck et al. (2001) find, for the geodynamic model, n_{CHZ}=0.012. This means that only about 1% of all the extra-solar planets are habitable. This calculated number is actually one order of magnitude smaller than the number 1/4 implied by the situation in our solar system.
4. 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. Some scientists hold that if liquid water, carbon, and some nutrients are available then simple microbial life is almost certainly going to occur (New Scientist 2001a). This is equivalent to the suggestion that f_L should be of the order of one: If life can happen, it does (see, for example, Dick 1998). But there are also suggestions that f_L is an extremely low number (Hart 1995). We use $f_L \approx 10^{-2}$ as a conservative approximation in comparison to the predominant optimistic view sketched above.

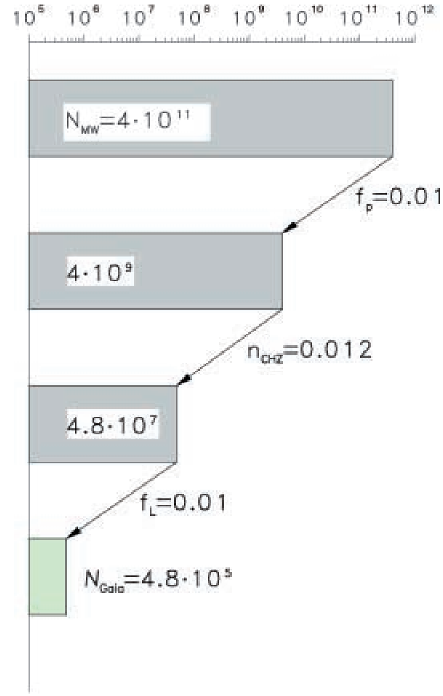

Fig. 10 Determination of the number of Gaias, N_{Gaia}, based on the number of stars in the Milky Way by application of the factors in Eq. 4

With the help of the four numbers just discussed we finally arrive at

$$N_{Gaia} \approx 4.8 \cdot 10^5, \tag{5}$$

which is indeed rather a large number (Fig. 10). It is evident that every of the four involved factors for N_{Gaia} is connected with a more or less large error. Is this sense our number must be considered as a "thoroughly" educated guess.

Now we can raise the question: Are "Earths" commonplace in the Milky Way? Based on the number derived above, the answer is: "Yes!" despite the fact that this estimation does not include other important factors, which may significantly reduce the number of other Gaias. Some of those are:

- The presence of a large moon seems to be necessary to stabilise the planet's obliquity (Laskar et al. 1993).

Furthermore, habitability is tied to the requirement of orbital stability (Laskar 1996; Laughlin and Adams 1998).

- The presence of a giant planet is important to shield the planet from comets and to scatter asteroids to the planet early on to deliver volatiles (Lunine 2001).
- The abundance of long-lived radioisotopes as the primary source of internal heat is necessary for the operation of plate tectonics (Franck 1998).
- There are other destructive cosmic events that may significantly reduce the number of other Gaias. Examples are extinctions from comets and asteroid impacts (Sharpton and Ward 1990), gamma-ray bursts (Király and Wolfendale 2000), and so-called superflares, i.e. suddenly occurring huge eruptions on the central star of planetary systems (Schaefer et al. 2000).

The Search for Extra-Terrestrial Intelligence (SETI; see, for example, Drake and Sobel 1992) is connected to one of the most profound questions: are we alone in the universe? The answer to this question would have tremendous implications for humankind. Turning back to the full Drake equation (Eq. 3) we must specify additionally the last two factors, f_{CIV} and δ, respectively. If intelligence is a common outcome of Darwinian evolution then f_{CIV} should not be too small. The final term, δ, is particularly vexing. If the civilisation life time is determined by the time span between discovery of electromagnetic waves and the capability to destroy this civilisation by a nuclear war or the like (about 100 years only!), then δ can be very small because Gaia's life time (as the normalising factor) is up to 6.5 billion years (see Fig. 9). Therefore, the number of civilisations, N_{CIV}, whose radio emissions may be detectable, could be minute, although not identical to zero. Up until now, it seems to be difficult to assess quantitatively the likelihood of finding extra-terrestrial intelligence. Nevertheless, the new theoretical results about circumstellar HZs and the discovery of new extra-solar planets will combine to make the next decades the most exobiologically promising in the history of astronomy. Quite recently, the new "Rare Earth" hypothesis was published by Ward and Brownlee (2000). According to them, microbial life is common in the universe, but multicellular animal life is rare. We are confident to find Gaia's sisters soon, but to answer the famous question "Where are they?" asked by Enrico Fermi at the dawn of the atomic age will be a central scientific task for our and future generations.

Acknowledgements We thank the two anonymous reviewers for very constructive remarks. This work was supported by the German Science Foundation (DFG, grant number IIC5-Fr910/9-4) and the Federal Government and the Länder agreement (HSPN, grant number 24-04/325;2000).

References

Arrhenius A (1896) On the influence of carbonic acid on the air upon the temperature of the ground. Philos Mag 41:237–276

Berner RA (1993) Paleozoic atmospheric CO_2: importance of solar radiation and plant evolution. Science 262:68–70

Berner RA, Lasaga AC, Garrels RM (1983) The carbonate-silicate geochemical cycle and its effect on atmospheric carbon dioxide over the past 100 million years. Am J Sci 283:641–683

Brack A (ed) (1998) The molecular origins of life: assembling pieces of the puzzle. Cambridge University Press, Cambridge

Caldeira K, Kasting JF (1992) Life span of the biosphere revisited. Nature 360:721–723

Condie KC (1990) Growth and accretion of continental crust: inferences based on Laurentia. Chem Geol 83:183–194

Connerney JEP, Acuna MH, Wasilewski PJ, Ness NF, Rème H, Mazelle C, Vignes D, Lin RP, Mitchell DL, Cloutier PA (1999) Magnetic lineations in the ancient crust of Mars. Science 284:794–798

Dick SJ (1998) Life on other worlds. Cambridge University Press, Cambridge

Dole SH (1964) Habitable planets for man. Blaisdell, New York

Doyle LR (ed) (1996) Circumstellar habitable zones: proceedings of the first international conference. Travis House, Menlo Park, Calif.

Drake F, Sobel D (1992) Is anyone out there? The scientific search for extraterrestrial intelligence. Delta, New York

Franck S (1998) Evolution of the global heat flow over 4.6 Gyr. Tectonophysics 291:9–18

Franck S, Kossacki K, Bounama C (1999) Modelling the global carbon cycle for the past and future evolution of the Earth system. Chem Geol 159:305–317

Franck S, Block A, Bloh W von, Bounama C, Schellnhuber H-J, Svirezhev Y (2000a) Reduction of biosphere life span as a consequence of geodynamics. Tellus 52B(1):94–107

Franck S, Block A, Bloh W von, Bounama C, Steffen M, Schönberner D, Schellnhuber H-J (2000b) Determination of habitable zones in extrasolar planetary systems: where are Gaia's Sisters? JGR-Planets 105(E1):1651–1658

Franck S, Block A, Bloh W von, Bounama C, Schellnhuber H-J, Svirezhev Y (2000c) Habitable zone for Earth-like planets in the solar system. Planet Space Sci 48:1099–1105

Franck S, Block A, Bloh W von, Bounama C, Schellnhuber H-J (2001) Planetary habitability: estimating the number of Gaias in the Milky Way. In: ESA – Proceedings of the 1st European workshop on exo/astrobiology, May 2001, Frascati, Italy (in press)

Golombek MP (1999) A message from warmer times. Science 283:1470–1471

Gonzalez G, Brownlee D, Ward P (2001) The galactic habitable zone: galactic chemical evolution. Icarus 152:185–200

Gough DO (1981) Solar interior structure and luminosity variations. Solar Phys 74:21–34

Hart MH (1978) The evolution of the atmosphere of the Earth. Icarus 33:23–39

Hart MH (1979) Habitable zones about main sequence stars. Icarus 37:351–357

Hart MH (1995) Atmospheric evolution, the Drake equation and DNA: sparse life in an infinite universe. In: Zuckerman B, Hart MH (eds) Extraterrestrials – where are they? Cambridge University Press, Cambridge, pp 215–225

Hitchcock DR, Lovelock JE (1967) Life detection by atmospheric analysis. Icarus 7:140–150

Horneck G (ed) (2001) Lecture notes in physics: astrobiology. Springer, Berlin Heidelberg New York (in press)

Huang S-S (1959) Occurrence of life in the universe. Am Sci 47: 397–403

Huang S-S (1960) Life outside the solar system. Sci Am 202(4): 55–63

Iben I (1967a) Stellar evolution within and off the main sequence. Annu Rev Astron Astrophys 5:571–626

Iben I (1967b) Stellar evolution. VI. Evolution from the main sequence to the red-giant branch for stars of mass 1 $M_\odot$, 1.25 $M_\odot$, and 1.5 $M_\odot$. Astrophys J 147:624–649

Jakosky B (1998) The search for life on other planets. Cambridge University Press, Cambridge

Joshi MM, Haberle RM, Reynolds RT (1997) Simulations of the atmospheres of synchronously rotating terrestrial planets orbiting M dwarfs: conditions for atmospheric collapse and the implications for habitability. Icarus 129:450–465

Kasting JF (1984) Comments on the BLAG model: the carbonate-silicate geochemical cycle and its effect on atmospheric carbon dioxide over the past 100 million years. Am J Sci 284: 1175–1182

Kasting JF (1988) Runaway and moist greenhouse atmospheres and the evolution of Earth and Venus. Icarus 74:472–494

Kasting JF (1996) Habitable zones around stars: an update. In: Doyle LR (ed) Circumstellar habitable zones. Travis House, Menlo Park, Calif., pp 17–18

Kasting JF (1997) Habitable zones around low mass stars and the search for extraterrestrial life. Origins Life 27:291–307

Kasting JF, Toon OB, Pollack JB (1988) How climate evolved on the terrestrial planets. Sci Am 258(2):90

Kasting JF, Whitmire DP, Reynolds RT (1993) Habitable zones around main sequence stars. Icarus 101:108–128

Kippenhahn R, Weigert A (1990) Stellar structure and evolution. Springer, Berlin Heidelberg New York

Király P, Wolfendale AW (2000) Sources of danger and defence systems in our space environment. In: Burdyuzha V, Khozin G (eds.) The future of the universe and the future of our civilization. World Scientific, Singapore, pp 316–325

Lasaga AC, Berner RA, Garrels RM (1985) An improved geochemical model of atmospheric CO_2 fluctuations over past 100 million years. In: Sundquist ET, Broecker WS (eds) The carbon cycle and atmospheric CO_2: natural variations – Archaean to present. (Geophysics monograph 32) AGU, Washington, D.C., pp 397–411

Laskar J (1996) Large-scale chaos and marginal stability in the solar system. Celest Mech Dyn Astron 64:115–162

Laskar J, Joutel F, Robutel P (1993) Stabilization of the Earth's obliquity by the Moon. Nature 361:108–128

Laughlin G, Adams FC (1998) The modification of planetary orbits in dense open clusters. Astrophys Lett 508:171–174

Lineweaver CH (2001) An estimate of the age distribution of terrestrial planets in the universe: quantifying metallicity as a selection effect. Icarus 151:307–313

Lovelock JE (1965) A physical basis for life detection experiments. Nature 207:568–570

Lovelock JE (1975) Thermodynamics and the recognition of alien bisopheres. Proc R Soc Lond B 189:167–181

Lovelock JE (1987) The ages of Gaia: a biography of our living Earth. Oxford University Press, Oxford

Lovelock JE, Margulis L (1972) Atmospheric homeostasis by and for the biosphere: the Gaia hypothesis. Tellus 26:2–14

Lunine JI (2001) The occurrence of Jovian planets and the habitability of planetary systems. Proc Natl Acad Sci USA 98: 809–814

Malin MC, Edgett KS (2000) Evidence for recent groundwater seepage and surface runoff on Mars. Science 288:2330–2335

Marcy GW, Butler RP (2000) Millennium essay: Planets orbiting other suns. Publ Astron Soc Pac 112:137–140

Marcy GW, Cochran WD, Mayor M (2000) Extrasolar planets around main-sequence stars. In: Mannings V, Boss A, Russel S (eds) Protostars and planets IV. University of Arizona Press, Tucson, pp 1285–1311

McKay DS, Gibson EK, Thomas-Keprta KL, Vali H, Rommanek CS, Clemett SJ, Chillier DF, Maechling CR, Zare RH (1996) Search for life on Mars: possible relic biogenic activity in Martian meteorite ALH84001. Science 273:924–930

New Scientist (2001a) Interview with Geoffrey Marcy, planet-hunter. New Sci 169(2273):44–47

New Scientist (2001b) The day the dynamo died. New Sci 169(2277):4

Rhie SH, Bennett DP, Fragile PC, et al (1998) A report from Microlensing Planet Search Collaboration: a possible Earth mass planetary system found in MACO-98-BLG-35? Bull Am Astron Soc 30:1415

Sackmann I-J, Boothroyd AI, Kraemer KE (1993) Our Sun. III. Present and future. Astrophys J 418:457–468

Schaller G, Schaerer D, Meynet G, Maeder A (1992) New grids of stellar models from 0.8 to 120 solar masses at Z=0.020 and Z=0.001. Astron Astrophys Suppl Ser 96:269–331

Schaefer BR, King JR, Deliyannis CP (2000) Superflares on ordinary solar-type stars. Astrophys J 529:1026–1030

Scheffler H, Elsässer H (1988) Physics of the galaxy and interstellar matter. Springer, Berlin Heidelberg New York

Schellnhuber H-J (1999) 'Earth system' analysis and the second Copernican revolution. Nature 402 [Suppl]:C19–C23

Schellnhuber H-J, Kropp J (1998) Geocybernetics: controlling a complex dynamical system under uncertainty. Naturwissenschaften 85: 411–425

Schopf JW (1999) Cradle of life: the discovery of Earth's earliest fossils. Princeton University Press, Princeton, N.J.

Schwartzman D (1999) Life, temperature, and the Earth: the self-organizing biosphere. Columbia University Press, New York

Schwartzman D, McMenamin M, Volk T (1993) Did surface temperatures constrain microbial evolution? BioScience 43:390–393

Sharpton VL, Ward PD (eds) (1990) Global catastrophes in Earth history. Geologic Society of America, Boulder, Colo.

Shklovskii IS, Sagan C (1966) Intelligent life in the universe. Holden-Day, San Francisco

Tajika E, Matsui T (1992) Evolution of terrestrial proto-CO_2 atmosphere coupled with thermal history of the Earth. Earth Planet Sci Lett 113:251–266

Volk T (1987) Feedbacks between weathering and atmospheric CO_2 over the last 100 million years. Am J Sci 287:763–779

Walker JCG, Hays PB, Kasting JF (1981) A negative feedback mechanism for the long-term stabilization of Earth's surface temperature. J Geophys Res 86:9776–9782

Ward PD, Brownlee D (2000) Rare Earth. Copernicus (Springer), New York

Williams DM (1998) The stability of habitable planetary environments. PhD thesis, Pennsylvania State University

Zinnecker H, McCaughrean MJ, Wilking BA (1993) The initial stellar population. In: Levy EH, Lunine JI, Mathews MS (eds) Protostars and planets III. University of Arizona Press, Tucson, pp 429–495