Determination of Habitable Zones in Extrasolar Planetary Systems: Where are Gaia's Sisters?

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Abstract

A general modeling scheme for assessing the suitability for life of extrasolar planets is presented. The scheme focuses on the identification of the "habitable zone" in main-sequence star planetary systems accommodating Earth-like components. Our definition of habitability is based on the long-term possibility of photosynthetic biomass production under geodynamic conditions. Therefore, all the pertinent astrophysical, climatological, biogeochemical, and geodynamic processes involved in the generation of photosynthesis-driven life conditions are taken into account. Implicitly, a co-genetic origin of the central star and the orbiting planet is assumed. A geostatic model version is developed and investigated in parallel for demonstration purposes. The numerical solution of the advanced geodynamic model yields realistic look-up diagrams for convenient habitability determination. As an illustration, the MACHO-98-BLG-35 event is scrutinized. It is shown that this event is definitely not tantamount to the discovery of one of Gaia's sisters.

Introduction

Within the last few years, the search for extrasolar planets has become increasingly successful. Up to now about 20 objects have been identified with the help of novel techniques, but most of them are giants on orbits surprisingly close to the central stars [*Schneider,* 1999].

At the 193rd meeting of the American Astronomical Society (AAS) two international teams of astronomers presented observational evidence for the existence of an Earth-like planet in the center of our galaxy, some 30,000 light years away from the Sun [*Rhie et al.,* 1998]. The mass of that object appears to be in the range delimited by Earth and Neptune, and its distance to the gravitational center seems to have a value between 1 and 4 astronomical units (AU).In other words, the search might have tracked down a sister of "Gaia", i.e., a planet which supports life quite similar to the Earth's biosphere.

The reported discovery results from one of those astronomical observing programs, launched in the early 1990s, that rely on planet detection in the Milky Way via gravitational microlensing observation and other techniques [*Bennet and Rhie,* 1996]. The most important programs are MACHO (MAssive Compact Halo Objects), PLANET (Probing Lensing Anomalies Network), EROS (Experience pour la Recherche d'Objets Sombres), and OGLE (Optical Gravitational Lensing Experiments).

Gravitational microlensing events occur when a faint or dark star passes the line of sight of a more distant, brighter star. The light rays emanating from the latter are bent by the gravitational field of the closer, fainter star. This results in a discernible magnification of the image of the brighter object. A planet orbiting the faint star can cause a minor extra peak in the magnification record. The event which we are concerned with here refers to an observation classified as MACHO-98-BLG-35, i.e., the 35th microlensing observation registered towards the Galactic Bulge in 1998 by the MACHO search program. The slight brightness variation involved

there is consistent with a signal expected for an object possessing between 0.002 and 0.01% of the mass of the central star, which in turn is estimated to be between 20% and 60% of one solar mass. These findings and complementary data indicate the Earth-like characteristics of the "MACHO-35" planet as summarized above [*MPS Collaboration,* 1999; *Rhie et al.*, 1999]. It is clear, on the other hand, that even more sophisticated search techniques are needed for attaining a sufficiently high level of certainty in the detection of an Earth sibling [*Rhie et al., 1998*].

The habitable zone (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 advanced life forms. 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 and Sagan* [1966], respectively. *Hart* [1978; 1979] calculated the hypothetical evolution of the terrestrial atmosphere over geologic time for varying orbital radius. He found that the HZ, i.e. the "ecological niche" between runaway greenhouse and runaway glaciation processes, is amazingly narrow for G2 stars like our Sun: it is delimited from below by R_{inner} = 0.958 AU, and from above by R_{outer} = 1.004 AU.

A main disadvantage of those calculations was the neglect of the negative feedback between atmospheric CO_2 partial pressure and mean global surface temperature via the carbonate-silicate cycle as discovered by *Walker et al.* [1981]. The inclusion of that feedback by *Kasting et al.* [1988] produced the interesting result of an almost constant inner boundary of the HZ, but a remarkable extension of its outer boundary. In subsequent years, the HZ approach experienced a number of refinements and the extension to other classes of main-sequence stars [*Kasting et al.,*1993; *Kasting*, 1997; *Williams*, 1998]. A thorough state-of-the-art overview is provided by the proceedings of the First International Conference on Circumstellar Habitable Zones [*Doyle*, 1996]. Recent studies conducted by our group (see, particularly, *Franck et al.*, 1999a; 1999b) have generated a rather comprehensive characterization of habitability, based on the possibility of photosynthetic biomass production under large-scale geodynamic conditions. Thus not only the availability of liquid water on a planetary surface is taken into account, but also the suitability of CO_2 partial pressures.

In this paper, we employ our habitability concept for assessing the probability of the existence of photosynthetic life on extrasolar planets. To this end we calculate the HZ for planetary systems with a single central star, possessing a mass in the range between 0.2 and 2.2 M_S and with Earth-sized planets. As already mentioned, our methodology is derived from the dynamic Earth system science approach that determines the past and future evolution of our planet under the influence of increasing solar luminosity [*Franck et al.*, 1999a; 1999b]. A major element involved there is long-term climate regulation as realized by an intricate global carbon cycle across the Earth system. The general modeling philosophy is sketched in the following section.

Model description

Our modeling approach [*Franck et al.*, 1999a; 1999b] is based on the ideas introduced by *Caldeira and Kasting* [1992]. Therefore, a careful simulation of the coupling between increasing solar luminosity, the silicate-rock weathering as parameterized by the mean rate F_{wr}, and the global energy balance forms the corner stone of the investigation. As a direct product, the partial pressure of atmospheric carbon dioxide, P_{atm}, and the biological productivity, Π, can be estimated as function of time t throughout planetary past and future. Here are the crucial elements of the causal web employed:

Luminosity evolution of the central star on the main sequence in the mass range between 0.8 and 2.5 M_S can be conveniently calculated by polynomial fitting of detailed stellar evolution models like the one presented by *Schaller et al.* [1992]. Thus

$$\log \frac{L}{L_S} = \sum_{i=0}^{3} \lambda_i \left(\frac{t}{\tau_H} \right)^i. \tag{1}$$

Here L denotes stellar luminosity, τ_H the nuclear time span (the time a star spends on the main sequence while burning its hydrogen fuel), and the λ_i represent fit parameters. If the stellar mass, M, is in the lower range, i.e. $0.2\ M_S \leq M \leq 0.8\ M_S$, then the luminosity data can be extrapolated with the help of the luminosity-mass relation, $L \sim M^{3.88}$, as given by *Kippenhahn and Weigert* [1990]. In that low-mass regime evolutionary variations over a time scale of 5 to 6 Ga may be neglected. The parameters λ_i in Eq. 1 depend on M in the following way:

$$\lambda_i = \sum_{j=0}^{3} C_{ij} \left(\frac{M}{M_S} \right)^j, \tag{2}$$

where the C_{ij} are auxiliary parameters. τ_H (in Ga units) can be expressed as a function of the stellar mass as follows:

$$\log \tau_H = \sum_{i=0}^{3} \alpha_i \left(\log \left(\frac{M}{M_S} \right) \right)^i. \tag{3}$$

The effective central-star temperature, T_{eff}, is approximated in a similar way:

$$\log T_{eff} = \sum_{i=0}^{4} \mu_i \left(\frac{t}{\tau_H} \right)^i , \tag{4}$$

where

$$\mu_i = \sum_{j=0}^{4} D_{ij} \left(\frac{M}{M_S} \right)^j . \tag{5}$$

The values of all auxiliary parameters, i.e. C_{ij} and D_{ij}, are displayed in Tab. 1, and the values of auxiliary parameter α_i are 9.9707, -3.8727, 4.3784, and -5.7728 for i = 0, 1, 2, and 3, respectively. The resulting stellar luminosities and effective temperatures are summarized in the Hertzsprung-Russell diagram of Fig. 1.

The global energy balance governing the climate of candidate planets is based on the Arrhenius equation [*Arrhenius,* 1896]:

$$(1 - a)(L/(4\pi R^2)) = 4\sigma T_{bbr}^4 , \tag{6}$$

where a denotes planetary albedo, R is the (average) distance between planet and central star, σ represents the Stefan-Boltzmann constant, and T_{bbr} symbolizes the effective black-body radiation temperature. The mean surface temperature, T_{surf}, of the planet is related to T_{bbr} via the greenhouse warming factor ΔT, i.e.

$$T_{surf} = T_{bbr} + \Delta T . \tag{7}$$

Usually, ΔT is parameterized as a function of T_{surf} and P_{atm} [*Caldeira and Kasting,* 1992; *Franck et al.,* 1999b]. The main drawback of this parameterization is its limitation to atmospheric CO_2 pressures below 0.1 bar. As our model has to account for values of P_{atm} as high as 10 bar [*Kasting and Ackerman*, 1986; *Tajika and Matsui*, 1992], we employ the global energy balance formulation as given by *Williams* [1998]: it is also valid for $P_{atm} > 0.1$ bar and implicitly includes the CO_2 greenhouse effect through the formula

$$\frac{L}{4\pi R^2}(1 - a(T_{surf}, P_{atm})) = 4I(T_{surf}, P_{atm}), \tag{8}$$

where I denotes the outgoing infrared flux. For the entities I and a polynomial approximations within the framework of a radiative-convective climate model can be used. The albedo function, a, can be modified properly to incorporate its explicit dependence on the stellar temperature, i.e. $a \equiv a(T_{surf}, P_{atm}, T_{eff})$. Following *Kasting et al.* [1993], this is achieved by gauging

the radiative balance with respect to the solar case: For relatively hotter stars ($T_{eff} > T_{eff,S}$) the planetary albedo is increased due to diffusive Rayleigh scattering; for cooler stars it is reduced due to stronger near-infrared absorption by CO_2. A linear interpolation for the specific dependence of a on T_{eff} can be constructed along that line of reasoning with the help of Fig.11 of *Kasting et al.* [1993].

As for the process of weathering, three crucial aspects have to be taken into account: First, the reaction of silicate minerals with carbon dioxide, second, the transport of weathering products, and third, the deposition of carbonate minerals in sediments. The basic assumptions and limitations involved in a stylized description of this intricate dynamics are discussed in some details in *Franck et al.* [1999a]. For the purpose of the present investigation the following insight is important: The direct temperature effect on the weathering reactions, the weak temperature influence on river runoff, and the dependence of weathering on soil CO_2 partial pressure, P_{soil}, can be combined to yield an implicit equation for the global mean silicate-rock weathering rate [*Walker et al.*, 1981; *Caldeira and Kasting*, 1992]. This equation relates the weathering rate F_{wr}, the activity of protons in fresh soil-water a_{H+}, and the planetary surface temperature T_{surf} at some arbitrary point in time to the respective present-day values $F_{wr,0}$, $a_{H+,0}$, and $T_{surf,0}$:

$$\frac{F_{wr}}{F_{wr,0}} = \left(\frac{a_{H^+}}{a_{H^+,0}}\right)^{0.5} \exp\left(\frac{T_{surf} - T_{surf,0}}{13.7 \text{ K}}\right). \tag{9}$$

We emphasize that a_{H+} by itself depends explicitly on T_{surf} as well as on P_{soil}, so the prefactor on the right-hand side of Eq. 9 accounts for the role of CO_2 enrichment of the soil. Equilibrium constants for the chemical activities of the involved carbon and sulfur systems have been taken from *Stumm and Morgan* [1981]. Note that also the sulfur content in the soil does contribute to the global weathering rate, but its influence is not temperature-dependent. Therefore, it can be regarded as an overall weathering bias, which has to be taken into account when the present-day value is determined.

Eq. 9 is the key relation for our modeling approach. For any given weathering rate, the surface temperature and the CO_2 partial pressure in the soil can be calculated self-consistently. Following *Volk* [1987], P_{soil} can be assumed to be linearly related to the terrestrial biological productivity Π, defined as biomass production per unit time and per unit area, and to the atmospheric CO_2 partial pressure P_{atm}. This implies

$$\frac{P_{soil}}{P_{soil,0}} = \frac{\Pi}{\Pi_0}\left(1 - \frac{P_{atm,0}}{P_{soil,0}}\right) + \frac{P_{atm}}{P_{soil,0}}, \tag{10}$$

where $P_{soil,0}$, Π_0, and $P_{atm,0}$ are again present-day values.

The main role of the biosphere in the context of our model is to enrich P_{soil}, relative to the atmospheric value P_{atm}, in proportion to the biological productivity Π. Π is considered to be a function of temperature and CO_2 partial pressure in the atmosphere only:

$$\frac{\Pi}{\Pi_{max}} = \left(1 - \left(\frac{T_{surf} - 50°C}{50°C}\right)^2\right)\left(\frac{P_{atm} - P_{min}}{P_{1/2} + (P_{atm} - P_{min})}\right). \tag{11}$$

Here Π_{max} denotes the maximum productivity, which is assumed to amount to twice the present value Π_0 [*Volk*, 1987]. $P_{1/2} + P_{min}$ is the value at which the pressure-dependent factor is equal to 1/2, and P_{min} is fixed at 10^{-5} bar, the presumed minimum value for C4-photosynthesis [*Pearcy and Ehleringer*, 1984; *Larcher*, 1995]. The adjustment of the biosphere to even lower CO_2 partial pressures is an open question. For a given P_{atm}, Eq. 11 yields maximum productivity at $T_{surf} = 50°C$ and zero productivity for $T_{surf} \leq 0°C$ and $T_{surf} \geq 100°C$.

The system of equations (1) through (11) may be solved under the assumption that the weathering rate F_{wr} remains equal to the present-day value $F_{wr,0}$ at all points in time. This is clearly a rough approximation, which we call the geostatic model (GSM).

In order to achieve a more realistic description of the carbonate-silicate cycle under varying insolation, *Franck et al.* [1999a; 1999b] have introduced the so-called geodynamic model (GDM). The main difference to GSM consists in the consideration of time-dependent continent areas and seafloor spreading rates. Using an idea of *Kasting* [1984], the balance between the CO_2 sinks in the atmosphere-ocean system and the sources provided by metamorphic processes can be expressed with the help of dimensionless quantities in the following way:

$$f_{wr} \cdot f_A = f_{sr} \tag{12}$$

where $f_{wr} \equiv F_{wr}/F_{wr,0}$ 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 $f_{sr} \equiv S/S_0$ is the spreading rate normalized by the present value.

Eq.12 allows us to determine the weathering rate directly from geodynamical theory. The main idea behind this scheme is the coupling of the thermal and the degassing history of the Earth. To formalize the connection we need a relation between the mantle heat flow, expressing the thermal evolution, and the sea-floor spreading rate, characterizing tectonics and volatile exchange. According to boundary layer theory, the spreading rate can be expressed as a function of the mantle heat flow calculated via the cooling process for an oceanic plate, which is approximated by the cooling of a semi-infinite domain. The derivation of this formula is given in the well-known textbook on geodynamics by *Turcotte and Schubert* [1982]. The spreading rate as a function of time, *S(t)*, is related to the mantle heat flow, $q_m(t)$, by general boundary layer theory of mantle convection [*Mc Govern and Schubert*, 1989]. We have

$$S(t) = \frac{q_m(t)^2 \pi \kappa A_{oc}(t)}{[2k(T_m(t) - T_{surf,0})]^2}, \tag{13}$$

where k is the thermal conductivity, T_m is the average mantle temperature, κ is the thermal diffusivity, and $A_{oc}(t)$ is the total area of ocean basins at time t. $T_{surf,0}$ can be computed as the constant outer temperature of the upper boundary layer in the parameterized convection approximation [*Franck*, 1998]. Within the framework of our approximation, Eq. 13 works well both for the past and for the future of the Earth. In applying this equation to other planets we have to presume that these planets are Earth-like with respect to crucial features like mass, presence of plate tectonics, etc..

The area of the planet's surface, A_p, is obviously the sum of $A_{oc}(t)$ and the area of continents, $A_c(t)$, introduced above:

$$A_p = A_{oc}(t) + A_c(t). \tag{14}$$

Eqs. 13 and 14 can be used to introduce continental growth models into the equations for the volatile cycle. For the present purpose, however, namely the investigation of habitability of Earth-like planets, we will not employ a detailed growth model as in *Franck. et al*. [1999a] but the simple linear constant-growth model considered by *Franck and Bounama* [1997].

Now we have assembled all the pertinent relationships for determining the HZ in extrasolar planetary systems governed by simple main sequence stars: with the help of Eqs.12 to14 the weathering rate can be calculated for every time step of the evolution of an Earth-like planet, and the strategic climate parameters as well as the biological productivity can be extracted from the solution of the system of Eqs. 1 to 11.

We re-emphasize that we define the HZ as the spatial domain around a central star where the planetary surface temperature stays between 0°C and 100°C, and where the atmospheric CO_2 partial pressure is higher than 10^{-5} bar to allow for non-vanishing biological productivity (i.e., $\Pi > 0$). In our definition, there is also an upper limit for atmospheric CO_2 at 10 bar. All these specifications are based on the prerequisite that the planet is "Earth-like" in the sense that the plate-tectonics machinery is active to operate the global carbonate-silicate cycle as the negative feedback mechanism that compensates for the gradual brightening of the central star during its "life" on the main sequence. Without plate tectonics, the preconditions for a photosynthesis-based biosphere are much more restrictive. Furthermore, we implicitly assume a co-genetic origin of the central star and the orbiting planet as described, for example, by the Safronov Model [*Safronov*, 1969; *Newsom and Jones*, 1990].

Results and Discussion

Our model equations are solved numerically according to the strategy outlined above. We can calculate the HZ for any value of the stellar mass, but for the sake of illustration we initially restrict ourselves to $0.8\,M_S$, $1.0\,M_S$, and $1.2\,M_S$, respectively. The HZ for an Earth-like planet is determined for these masses with the linear continental-growth approach for the different geophysical models GSM and GDM. The results are presented in Fig. 2 in the form of domain diagrams, which identify the "habitable" range of mean planet-star distances R as a function of stellar evolution time.

In the geostatic modeling case (GSM) we observe a slight widening and outward shift of the HZ over time for all masses considered. This is in agreement with the findings by *Kasting et al.* [1993] and *Kasting* [1997]. We also observe the trivial effect that the inner boundary of the HZ moves outward with increasing stellar mass, while the concurrent widening trend is not so self-evident. Thus our GSM results for the habitable zone are qualitatively similar to the previous findings based on the non-photosynthetic definition of habitability [*Kasting et al.,* 1993; *Jakosky*, 1998]: for small stellar masses, the HZ is a narrow band near the central star that is moving slightly outward with time. When the central star mass increases, the HZ becomes broader, moves significantly outward with time, and is limited by the star's lifetime on the main sequence.

Our geodynamic modeling (GDM) approach exhibits completely different behavior. Up to 4.6 Ga of stellar evolution the HZ in the GDM case is broader than in the GSM case. Note, in particular, that in the early stage of co-genetic evolution (i.e., up to about 3.6 Ga) the outer zone boundary is determined by the upper CO_2 threshold, i.e. 10 bar. At the present time (4.6 Ga) the HZ of GSM and GDM coincide by construction: the GSM operates with the present values for spreading rate, continental area, and weathering rate (Eq. 12). Beyond 4.6 Ga, however, the HZ becomes smaller than in the GSM case. The geodynamically derived zone even collapses for central stars with $M \leq M_S$ at $t_{max} = 6.5$ Ga due to plate tectonics for the hypothetical Earth-like planet! For $M = M_S$ (Fig 2b), the actual position of our Earth (1 AU) is remarkably close to the optimum position (1.08 AU) at which any Earth-like planet would enjoy maximum biosphere life span. This was already found by *Franck et al.* [1999a]. By way of contrast, the existence of a HZ is limited in the GSM case only by the lifetime of the central star on the main sequence (time period of central hydrogen burning, symbolized by τ_H).

Thus, for stars not heavier than the Sun, GDM defines an optimum planet-star distance, R_{opt}, which guarantees the maximum life span of the biosphere: $R_{opt} = 0.58$ AU for $M = 0.8 M_S$ (Fig. 2a), and $R_{opt} = 1.08$ AU for $M = M_S$ (Fig. 2b). As illustrated in Fig. 2c, the HZ for heavier central stars is limited by the stellar life time on the main sequence irrespective of the geophysical model employed. In the GDM case, the sharp temporal decrease of the outer HZ boundary is a consequence of growing continental area (enhanced loss of atmospheric CO_2 by enlarged weathering surface) and dwindling spreading rate (diminishing CO_2 output from the solid Earth).

An alternative way to present the insights provided by our simulation-modeling approach is to delineate the HZ for an Earth-like extrasolar planet at a given (but arbitrary) distance R in the stellar mass-time plane. To be specific, the mass axis measures the ratio of M over M_S.

The HZ is limited in this case by the following effects:

(I)   Stellar life time on the main sequence decreases strongly with mass. Using Eq. 3 we estimated the central hydrogen burning period and got $\tau_H < 0.8$ Ga 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 about 0.8 Ga 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 Ga [*Jakosky*, 1998]. If we perform calculations with $\tau_H < 0.5$, we obtain 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 1.1M_S the maximum life span of the biosphere is determined exclusively by planetary geodynamics which is independent (in a first approximation, but see IV) from R. So we obtain the limitation $t < t_{max}$.

(IV)   There have been discussions about the habitability of tidally locked planets. We take this complication into account and indicate the domain where an Earth-like planet on a circular orbit experiences tidal locking [*Peale, 1977, Kasting et al., 1993*]. 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.

As an illustration of the multiple factors involved, we depict the HZ for $R = 2$ AU and the GDM approach in Fig. 3. Under these circumstances, the habitable zone is restricted to a stellar mass range between 1.1 and 1.5 M_S, and to stellar ages below 4.7 Ga.

The question raised in the introduction - whether an Earth-sized planet discovered outside the solar system may accommodate higher life - can be answered if the mass and age of the central star is known as well as the planet's orbit. When these data are given, then the assessment is conveniently carried out using Figs. 4 and 5.

The general make-up of these figures is similar to Fig. 3, i.e. we consider the stellar mass-time plane again. Fig. 4 refers to GSM and accounts for the HZ limitations involved in the geostatic approach, while Fig. 5 refers to GDM and the corresponding geodynamic limitations. In both cases, the HZ is determined for a variety of planet-star distances R by identifying the associated inner and outer t-M boundary lines, respectively. This allows to select some R and to look up the pertinent parameter range.

One can clearly recognize the qualitative difference between the geostatic and the geodynamic description: for GDM (Fig. 5), the probability of finding an Earth-like planet within the HZ - a sister of Gaia [*Lovelock*, 1988] - is significantly higher for young central stars as compared to GSM (Fig. 4). This behavior is reversed for old stars, where the HZ narrows down rapidly in the GDM approach. The entire effect is caused by geodynamic self-regulation as was discovered recently by *Franck et al.* [1999a; 1999b].

Let us emphasize again that we assume that an Earth-like planet possesses tectonics; 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. First theoretical steps to tackle this problem were made by *Solomatov and Moresi* [1997]. And there are recent observations that plate tectonics may have once operated on Mars [*Connerney et al.*, 1999]. As can be seen in Fig. 2b an Earth-like planet at the Martian position would have resided within the HZ up to about 0.8 Ga ago. As for the real planet Mars, we can state that all geological processes caused by the internal cooling of the planet should evolve much faster than for a larger Earth-size planet. Nevertheless, we can speculate that our findings about the HZ are an upper bound for the time that Mars was habitable in the past. By way of contrast, we find that an Earth-like planet at the Venusian position would have never been within the HZ.

Now we are ready for assessing the MACHO-98-BLG-35 event in the context of the search for extraterrestrial life. In Sect. 1, the probable value ranges for the parameters of the associated extrasolar planet-star system have been outlined. Some of the astronomers involved in the discovery made a best parameter guess resulting in the following system characteristics: a planet of one Earth mass is orbiting a single central star of 0.3 M_S at a distance of about 2 AU (http://www.phys.vuw.ac.nz:80/dept/projects/moa/9835/Usenet.htm).

When we check these data for habitability using Fig. 3 we immediately find that the MACHO 35 system is clearly no candidate for extraterrestrial life. For a positive indication the red line in that figure would have to cross the green HZ associated with R = 2 AU, which is obviously not the case. So the search for a sister of Gaia has to go on...

The approach presented in this paper provides a convenient filter for picking candidates for photosynthesis-based life from all the extrasolar planets that will be discovered by novel observational methods. This filter can and should be further improved by devising schemes for diagnosing the presence of plate tectonics on any planet with a given characteristic, by parameterizing the global energy balance for different central-star masses, and by including the biological productivity at extreme CO_2 levels. For the time being, however, we think that our model helps to stimulate the thinking about the fascinating habitable zone issue.

Acknowledgments

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TABLE 1.   Coefficients determining the series expansions (Eqs. 1 to 5) for the hydrogen-burning time span τ_H, the luminosity L, and the effective temperature T_{eff}, respectively, of main-sequence stars.

C_{ij}	i=0	1	2	3
j=0	-3.4612	0.5163	0.2590	1.1240
1	4.7294	-0.1660	-1.0699	-1.4528
2	-1.6571	-0.1208	0.9906	0.4786
3	0.2302	0.0490	-0.2266	-0.0396

D_{ij}	i=0	1	2	3	4
j=0	2.967	-0.341	2.512	-5.078	3.373
1	1.728	1.025	-6.874	14.730	-9.993
2	-1.460	-0.981	6.849	-15.342	10.584
3	0.608	0.382	-2.964	6.778	-4.746
4	-0.093	-0.054	0.463	-1.065	0.753
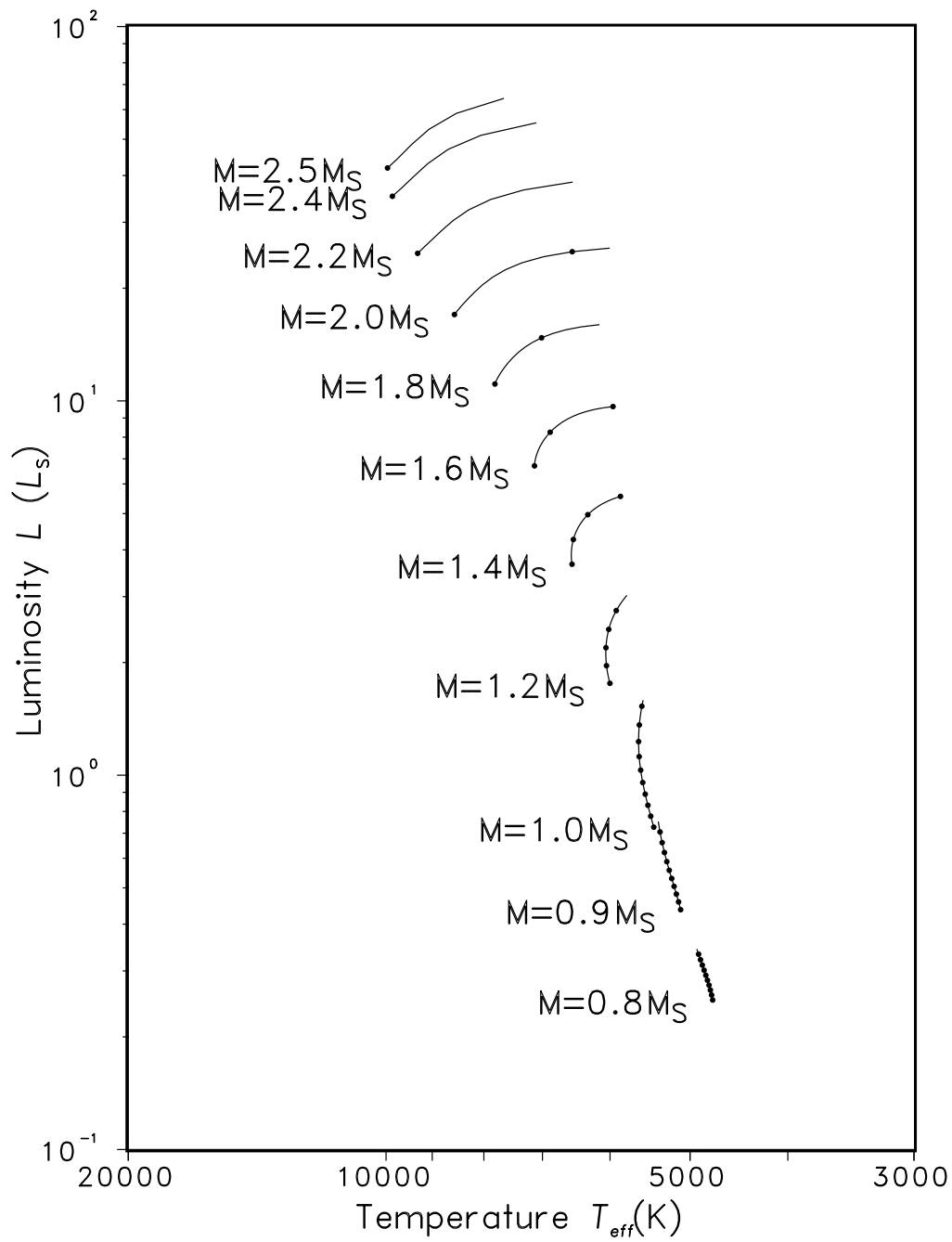
FIGURE 1. Hertzsprung-Russell diagram for central stars in the mass range between 0.8 M_S and 2.5 M_S. Only the main sequence evolution is considered. Successive dots on the mass-specific branches are separated in time by 1 Ga.
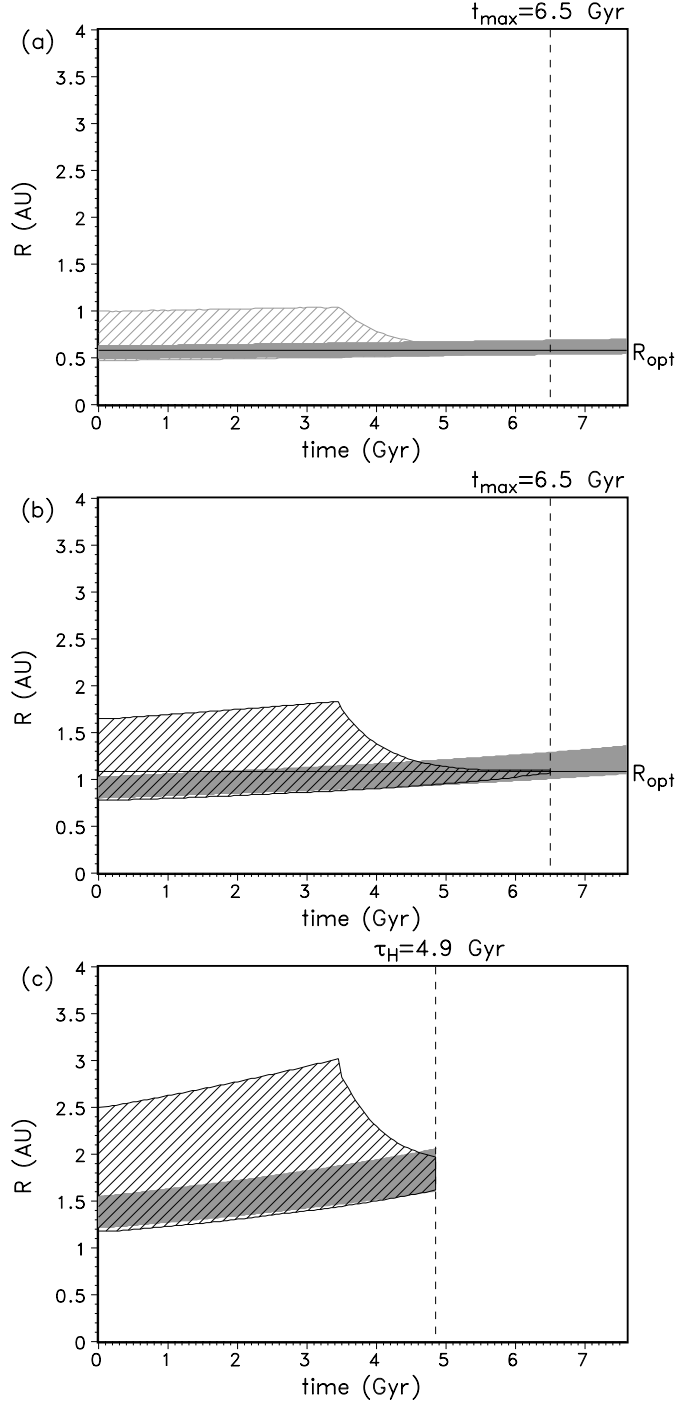
FIGURE 2. Temporal evolution of the HZ for an Earth-like planet orbiting a central star in the following stellar-mass cases: (a) M = 0.8 M$_S$; (b) M = 1.0 M$_S$; (c) M = 1.2 M$_S$. The HZ as obtained via the GSM approach is marked by grey shading, while the result from the GDM approach is identified by hatching. Note that in all cases the GSM-HZ shifts outward in the course of time, and its width increases slightly. The only temporal limitation is given by the hydrogen-burning period, τ_H, which amounts to (a) 24.7 Ga, (b) 9.3 Ga, and (c) 4.9 Ga. The GDM-HZ behaves in drastically different way in all cases: up to 3.4 Ga, its width is nearly constant and much broader than the GSM-HZ. Beyond that point in time, the outer GDM-boundary decreases rapidly and finally joins the inner boundary. In the cases (a) and (b), the GDM-HZ is temporally limited by geodynamics, while in case (c) the limitation is the same as for the GSM-HZ: short hydrogen-burning time span. R is the mean planet-star distance.
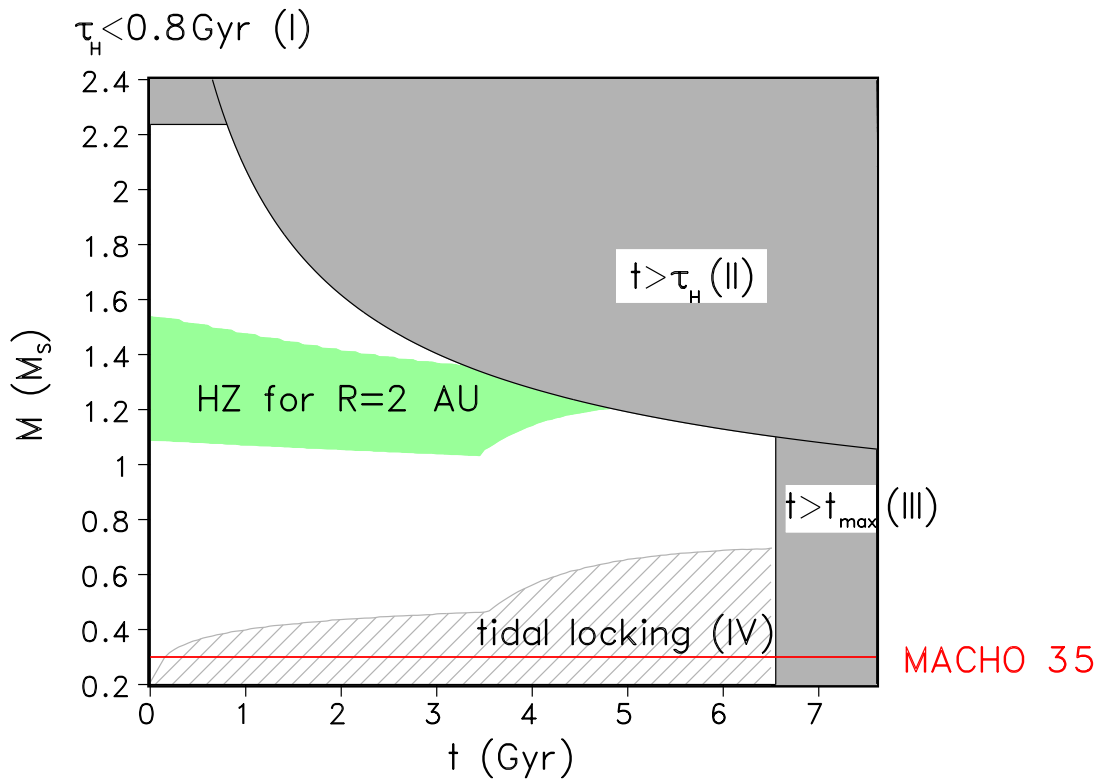
FIGURE 3. Shape of the GDM-HZ (green shading) in the mass-time plane for an Earth-like planet at distance *R* = 2 AU from the central star. The potential overall domain for accommodating the HZ for planets at some arbitrary distance is limited by a number of factors that are independent of *R*: (I) Minimum time for biosphere development (τ_H < 0.8 Ga excluded); (II) Central-star life time on the main sequence (t > τ_H excluded); (III) Geodynamics of the Earth-like planet (t > t$_{max}$ excluded); (IV) Tidal locking of the planet (non-trivial sub-domain excluded). The excluded realms are marked by grey shading in case of the first three factors, and by grey hatching for the tidal-locking effect. The horizontal red line represents the probable "life time" of the hypothetical MACHO-98-BLG-35 planet, which is assumed to orbit a 0.3 M$_S$ star.
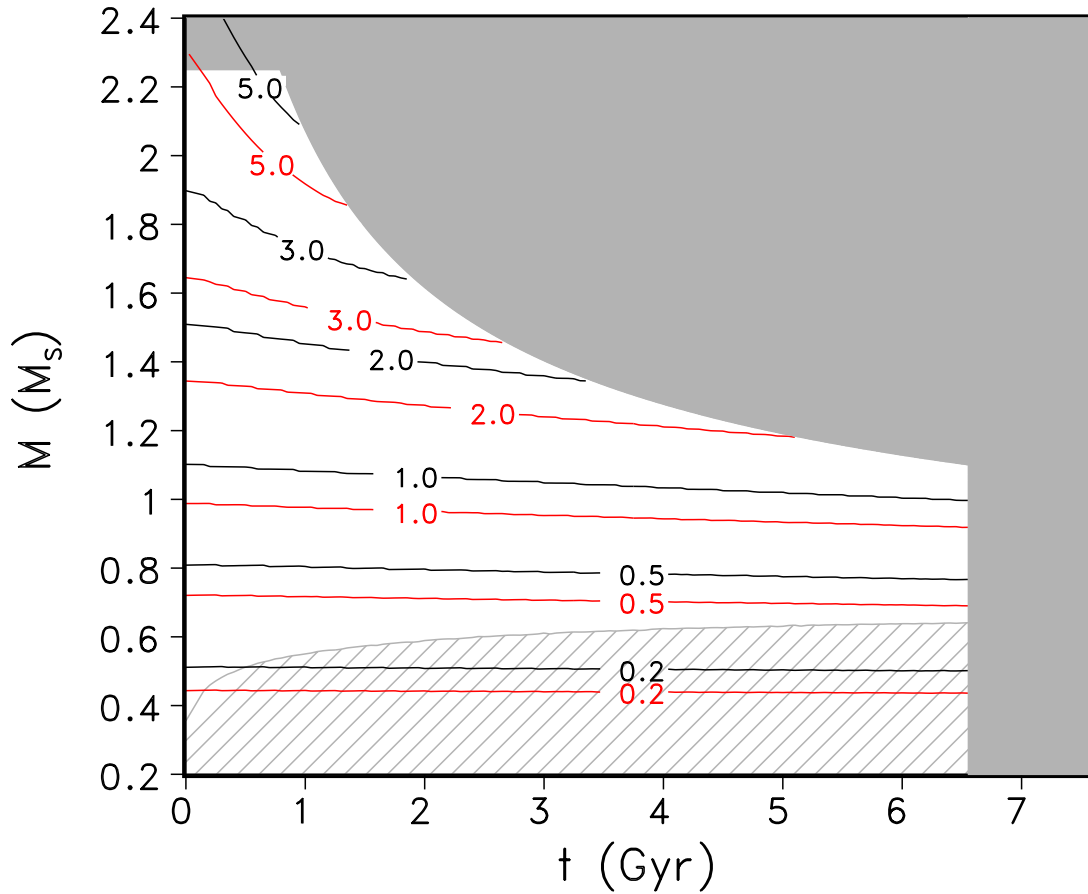
FIGURE 4. GSM approach. Boundary lines for HZ in the mass-time plane for varying planet-star distance (in AU). Note that the "habitable zone" refers to suitable stellar mass for given orbital constellations in this representation. If a specific isodistance line constitutes an inner frontier, it is marked in black, while it is drawn in red in the outer-frontier case. By way of contrast to Fig. 2, the inner frontiers lie above the outer ones! The principally excluded domains are again indicated by grey shading and hatching, respectively. The exclusion evidently differs from the one displayed in Fig. 3, as geodynamical effects are not considered here.
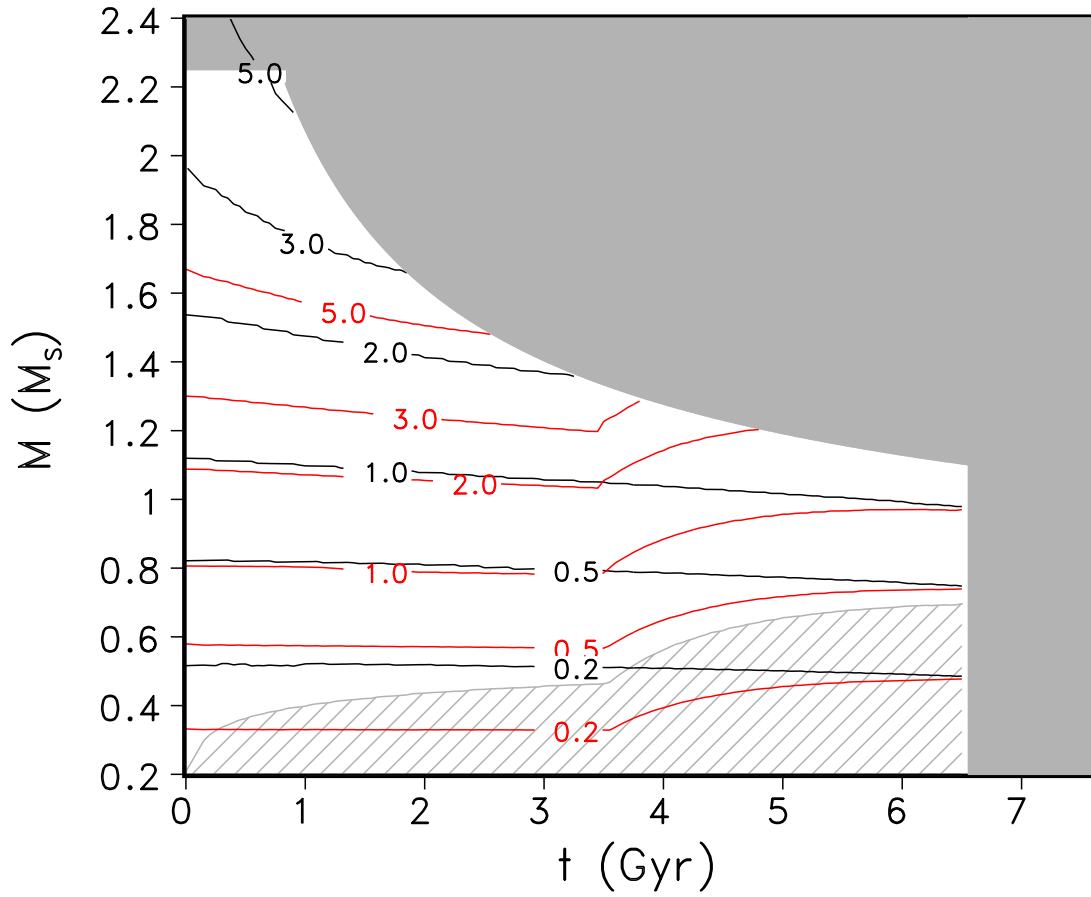
FIGURE 5. GDM approach. Isodistance HZ-boundary lines in the mass-time plane as in Fig. 4, but for the full geodynamical theory. Fig. 5 therefore directly compares to Fig. 3.