LIMITS OF PHOTOSYNTHESIS IN EXTRASOLAR PLANETARY SYSTEMS FOR EARTH-LIKE PLANETS

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ABSTRACT

We present a general modeling scheme for investigating the possibility of photosynthesis-based life on extrasolar planets. The scheme focuses on the identification of the habitable zone in main-sequence-star planetary systems with planets of Earth mass and size. Our definition of habitability is based on the long-term possibility of photosynthetic biomass production as a function of mean planetary surface temperature and atmospheric CO_2-content. All the astrophysical, climatological, biogeochemical, and geodynamic key 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. The numerical solution of an advanced geodynamic model yields realistic look-up diagrams for determining the limits of photosynthesis in extrasolar planetary systems, assuming minimum CO_2 levels set by the demand of C_4 photosynthesis.

INTRODUCTION

The question of extraterrestrial life is one of the most basic ones in the history of science. For many years scientists have been very attracted to the idea of the possibility of life on other planets in our solar system and in other planetary systems. On the basis of our knowledge about life existing on Earth we assume that extraterrestrial life has a carbon-based structure and needs liquid water. These are the main assumptions for limiting photosynthesis in extrasolar planetary systems. In this sense a habitable planet is defined as a planet capable of supporting such life. 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 photosynthesis based life forms. The conventional definition of the HZ is the region in space around a star where liquid water can exist on a planet's surface (e.g. Doyle, 1996). The HZ concept was introduced by Huang (1959, 1960) and extended by Shklovskii and Sagan (1966), respectively. Hart (1978, 1979) calculated the HZ for G2 stars like our Sun to be amazingly narrow (between 0.958 AU and 1.004 AU). Through the inclusion of the negative feedback between atmospheric CO_2 partial pressure and mean global temperature via the carbonate-silicate cycle by Kasting et al. (1988) the outer boundary of the HZ was remarkably extended. Later on the HZ approach was modified 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 Doyle (1996). Recent studies by Franck et al. (2000a, 2000b) have generated a rather comprehensive characterization of the possibility of photosynthetic biomass production. Thus not only the availability of liquid water on a planetary surface is essential but also the suitability of CO_2 partial pressures.

MODEL DISCRIPTION

Our modeling approach is based on a simulation of the coupling between increasing central star luminosity, silicate rock weathering, and the global energy balance (Caldeira and Kasting, 1992; Franck *et al.*, 2000b). As a direct result, the partial pressure of atmospheric carbon dioxide P_{atm} and the biological productivity Π can be estimated as functions of time t throughout planetary past and future.

The luminosity evolution of a main-sequence central star in the mass range between 0.8 and 2.5 solar masses (M_s) was calculated by polynomial fitting of detailed stellar evolution models and presented in the form of a Hertzsprung-Russell diagram (Franck *et al.*, 2000b). For stellar masses between 0.2 and 0.8 M_s the luminosity L can be extrapolated with the help of the luminosity-mass relation, $L \sim M^{3.88}$ (Kippenhahn and Weigert, 1990).

The global energy balance governing the climate of candidate planets is based on a formula given by Williams (1998):

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

where R is the distance from the central star, a the planetary albedo, T_{surf} the mean surface temperature of the planet, T_{eff} the stellar radiation temperature, and I the outgoing infrared flux.

The weathering process has the potential to stabilize the planet's surface temperature by a negative feedback that is strongly modulated by the biosphere (Walker *et al.*, 1981; Schwartzman and Volk, 1989; Schneider and Boston, 1991). The total process of weathering embraces first the reaction of silicate minerals with carbon dioxide, second the transport of weathering products, and third the deposition of carbonate minerals in sediments. Following Walker *et al.* (1981) and Caldeira and Kasting (1992), the global mean silicate-rock weathering rate F_{wr} can be formulated via the following equation:

$$\frac{F_{wr}}{F_{wr,0}} = \left(\frac{a_{H^+}}{a_{H^+,0}}\right)^{0.5} \exp\left(\frac{T_{surf} - T_{surf,0}}{13.7\ \mathrm{K}}\right). \tag{2}$$

Here the pre-factor outlines the role of CO_2 concentration in the soil, P_{soil}. a_{H^+} is the activity of H^+ in fresh soil-water. The quantities $F_{wr,0}$, $a_{H^+,0}$, and $T_{surf,0}$ are the present-day values for the weathering rate, the H^+ activity, and the surface temperature, respectively.

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}:

$$\frac{P_{soil}}{P_{soil,0}} = \frac{\Pi}{\Pi_0}\left(1 - \frac{P_{atm,0}}{P_{soil,0}}\right) + \frac{P_{atm}}{P_{soil,0}}, \tag{3}$$

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:

$$\frac{\Pi}{\Pi_{\max}} = \left(1-\left(\frac{T_{\mathrm{surf}}-50^{\circ}\mathrm{C}}{50^{\circ}\mathrm{C}}\right)^{2}\right)\left(\frac{P_{\mathrm{atm}}-P_{\mathrm{min}}}{P_{1/2}+(P_{\mathrm{atm}}-P_{\mathrm{min}})}\right). \tag{4}$$

Here $\Pi_{\max}$ denotes the maximum productivity, which is assumed to amount to twice the present value Π_0 (Volk, 1987). $P_{1/2}+P_{\mathrm{min}}$ 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 C_4-photosynthesis (Pearcy and Ehleringer, 1984; Larcher, 1995). The evolution of teh biosphere and its adaption to even lower CO_2 partial pressures are not taken into account in our model. The evolution of CO_2 concentrating mechanisms in C_4 photosynthesis in the past (some time after the end of the late Cretaceous) shows that this is an open possibilty for the future. For a given P_{atm}, Eq. 4 yields maximum productivity at T_{surf} = 50˚C and zero productivity for $T_{surf} \leq 0^{\circ}\mathrm{C}$ and $T_{surf} \geq 100^{\circ}\mathrm{C}$. At this point we should emphasize that all calculations are done for a planet with Earth mass and size, and the sameoactive heating in its interior.

In this way, the HZ is defined 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 photosynthesis. This is equivalent to a nonvanishing biological productivity, i.e. $\Pi > 0$:

$$HZ := \{R \,|\, \Pi(P_{atm}(R,t),\, T(R,t)) > 0\}. \tag{5}$$

Our model has also an upper limit for atmospheric CO_2 at 10 bar (Kasting and Ackerman, 1986; Tajika and Matsui, 1992).

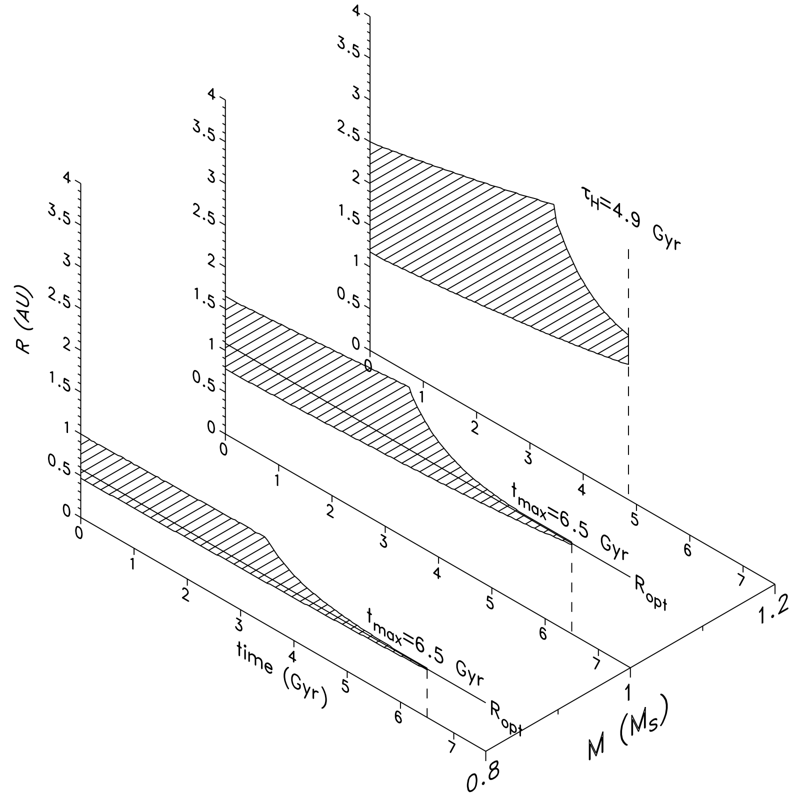

Fig 1. Width and position of the HZ (shaded) as a function of time for three different central-star masses (M = 0.8, 1.0, 1.2 M_S) for an Earth-like planet. R_{opt} is the optimum position with maximum life span of the photosynthesis-based biosphere.

RESULTS AND DISCUSSION

We can calculate the limits of photosynthesis in extrasolar planetary systems for any value of the central star mass between 0.2 and 2.5 M_s. In Figure 1 we have plotted the width and position of the HZ for our geodynamic model (Franck *et al.*, 1999, 2000a, 2000b) 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 the C_4-type photosynthesis 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 the C_4-type photosynthesis would be limited up to 6.5 Gyr after starting cogenetic evolution because continental growth and decline in spreading rate force atmospheric CO_2 content below 10^{-5} bar. In these cases, there is an optimum position R_{opt} with maximum biospheric life span.

An alternative way to present our results about the limits of photosynthesis in extrasolar planetary systems is to delineate the HZ for an Earth-like extrasolar planet at a given (but arbitrary) distance in the stellar mass-time plane (see Figure 2). In this presentation the limits for photosynthesis are connected with the following effects (Franck *et al.*, 2000b):

(I) Stellar life time on the main sequence decreases strongly with mass. We estimated the central hydrogen burning period and got $\tau_H < 0.8$ 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 about 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). 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 1.1 M_s the maximum life span of the biosphere is determined by planetary geodynamics which is independent (in a first approximation, but see limiting effect 4) of 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; Joshi et al., 1997). 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.

In Figure 2 we depict the HZ for $R = 2$ AU. Under these circumstances, the limits of photosynthesis are given by stellar masses below 1.1 M_s and above 1.5 M_s, and to stellar ages above 4.7 Gyr.

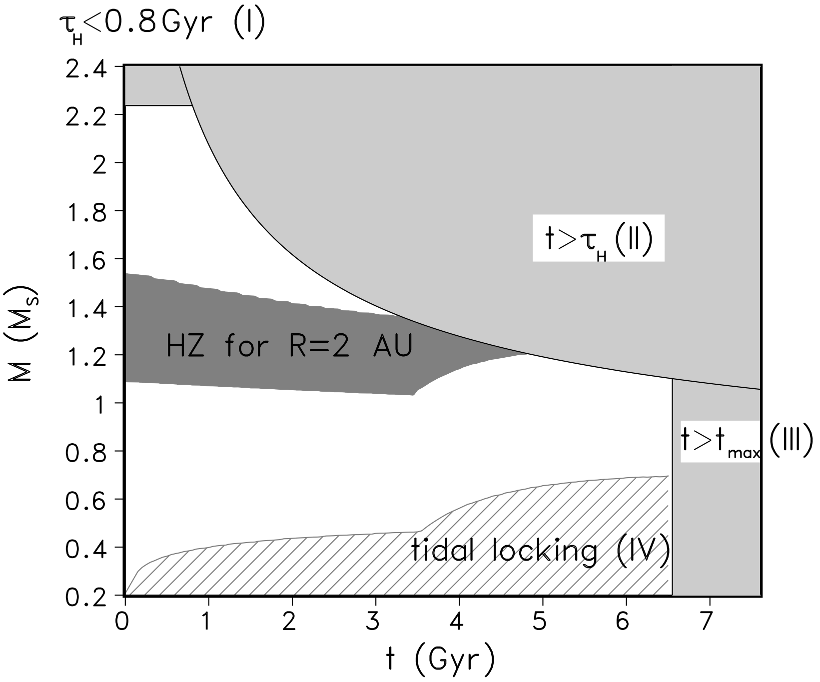

Fig 2. Shape of the HZ (dark grey) in the mass-time plane for an Earth-like planet with photosynthesis at distance R = 2 AU from the central star. The potential overall domain for accommodating the HZ of planets at some arbitrary distance is limited by a number of R-independent factors that are explained in detail in the text. Figure is taken with slight changes from Franck et al., 2000b, copyright by the American Geophysical Union.

As we have shown above, our model provides a convenient filter for picking candidates for photosynthesis-based life from all the extrasolar planets that will be discovered in the future. Knowing the age and the mass of the central star and the distance between the star and an Earth-like planet one can decide whether the planet is habitable for photosynthesis-based life or not.

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