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Hypothesis Article

Habitability of Super-Earth Planets Around Other Suns: Models Including Red Giant Branch Evolution

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Abstract

The unexpected diversity of exoplanets includes a growing number of super-Earth planets, *i.e.*, exoplanets with masses of up to several Earth masses and a similar chemical and mineralogical composition as Earth. We present a thermal evolution model for a 10 Earth-mass planet orbiting a star like the Sun. Our model is based on the integrated system approach, which describes the photosynthetic biomass production and takes into account a variety of climatological, biogeochemical, and geodynamical processes. This allows us to identify a so-called photosynthesis-sustaining habitable zone (pHZ), as determined by the limits of biological productivity on the planetary surface. Our model considers solar evolution during the main-sequence stage and along the Red Giant Branch as described by the most recent solar model. We obtain a large set of solutions consistent with the principal possibility of life. The highest likelihood of habitability is found for "water worlds." Only mass-rich water worlds are able to realize pHZ-type habitability beyond the stellar main sequence on the Red Giant Branch. Key Words: Extrasolar terrestrial planets—Habitable zone—Planetary atmospheres—Modeling studies. Astrobiology 9, 593–602.

Introduction

A pivotal part in the ongoing search for extrasolar planets is the quest to identify planetary habitability, *i.e.*, the principal possibility of life. In a previous paper, Kasting *et al.* (1993) presented a one-dimensional climate model to define a zone of habitability (HZ) around the Sun and other main-sequence stars that assumed as a basic premise an Earth-like model planet with a $CO_2/H_2O/N_2$ atmosphere and the presence of liquid water on the planetary surface.

Other definitions of HZs have been proposed, which include the galactic HZ, the UV-HZ, and the photosynthesis-sustaining HZ (pHZ). The galactic HZ (Lineweaver *et al.*, 2004) caters to the requirement that a sufficient amount of heavy elements (notably those contained in carbon and silicate compounds) must be present for the buildup of planets and life, a condition easily met in the solar neighborhood. The UV-HZ (Buccino *et al.*, 2006; Cuntz *et al.*, 2008) is based on the premise that no lethal amounts of stellar UV flux are produced (regarding life-forms assuming carbon-based biochemistry), a condition that tends to favor the environment of old main-sequence stars and giants (Guinan and Ribas, 2002) as well as planets with appreciable atmospheres and significant ozone layers (Segura *et al.*, 2003).

Another definition of habitability first introduced by Franck *et al.* (2000a, 2000b) is associated with the photosynthetic activity of the planet, which critically depends on the planetary atmospheric CO_2 concentration. This type of habitability is, thus, strongly influenced by the planetary geodynamics and encompassing climatological, biogeochemical, and geodynamical processes ("Integrated System Approach"). This concept has previously been used in studies of fictitious planets around 47 UMa (Cuntz *et al.*, 2003; Franck *et al.*, 2003) and 55 Cnc (von Bloh *et al.*, 2003), as well as detailed studies of observed super-Earth planets in the Gliese 581 system (von Bloh *et al.*, 2007b). The latter investigation showed that Gliese 581c is clearly outside the HZ, since it is too close to the star, whereas Gliese 581d, which is located near the outer edge of the HZ, is probably habitable, at least for certain types of primitive life-forms (see also Selsis *et al.*, 2007). Moreover, von Bloh *et al.* (2007a) used this type of model to compile a detailed ranking of known star-planet systems regarding the principal possibility of life, which led to the conclusion that the Solar System is not the top-tier system ("Principle of Mediocrity").

In the case of Earth-mass planets ($1\,M_\oplus$), a detailed investigation of geodynamic habitability was presented by Franck *et al.* (2000b) with respect to the Sun as well as to stars

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of somewhat lower and higher mass as central stars. Franck *et al.* determined that Earth will be rendered uninhabitable after 6.5 Gyr as a result of plate tectonics, notably the growth of the continental area (enhanced loss of atmospheric CO_2 by an increase in the weathering surface) and the dwindling spreading rate (diminishing CO_2 output from the solid Earth).

This implies that there is no merit in investigating the future habitability of Earth during the post-main-sequence evolution of the Sun in the framework of pHZ models, because the lifetime of habitability is limited by terrestrial geodynamic processes. However, this situation is expected to be significantly different for super-Earth planets due to inherent differences compared to Earth-mass planets (*e.g.*, Valencia *et al.*, 2007a). A further motivation for this type of work stems from the ongoing discovery of super-Earths in the solar neighborhood, for which the Gliese 876 (Rivera *et al.*, 2005) and Gliese 581 (Udry *et al.*, 2007) systems are prime examples.

In the following, we discuss the definition of the pHZ, including the relevant geodynamic assumptions, and describe the most recent model of solar evolution, which was used as a basis for our study. We present our results, including comparisons to previous work, and then present our summary and conclusions.

A New Model of Solar Evolution

A key element of our study was to consider a star akin to the Sun as the central object of the star-planet system. Schröder and Smith (2008) obtained a new model of solar evolution that will be adopted in the following. This model is based on a well-tested stellar evolution code that allows us to follow the change of solar properties at the main sequence, along the Red Giant Branch (RGB) and beyond. It is the Eggleton evolution code in the version described by Pols *et al.* (1995, 1998), which has updated opacities and an improved equation of state.

Among other desirable characteristics, the code uses a self-adapting mesh and a proper treatment of "overshooting" that has been tested and calibrated with giant and supergiant stars in eclipsing binary systems. The code also considers a detailed description of the mass loss following Schröder and Cuntz (2005), which has been tested based on a set of well-observed stars (Schröder and Cuntz, 2007). Thus, it permits an accurate description of the time-dependent solar luminosity along the RGB (see Fig. 1). A further consequence of the steadily increasing mass loss is the increase of the orbital distances R of any putative planets, given as $R \propto M_\odot^{-1}$ with $M_\odot$ as solar mass.

The solar evolution model by Schröder and Smith (2008) suggests an age of the Sun as 4.58 (±0.05) Gyr, and the RGB tip is reached after 12.167 Gyr, which is also the point in time where our computations are suspended. This model also confirms some well-established facts: (1) The main-sequence Sun has already undergone significant changes, *i.e.*, the present solar luminosity $L_\odot$ exceeds the zero-age value by $0.30\,L_\odot$, and the zero-age solar radius has been 11% smaller than the present value. (2) There was an increase of effective temperature from 5596 K to 5774 (±5) K. (3) The present Sun is increasing its average luminosity at a rate of 1% in every 110 million years or 10% over the next billion years. All these findings are consistent with established solar models such as that of Gough (1981) and subsequent investigators.

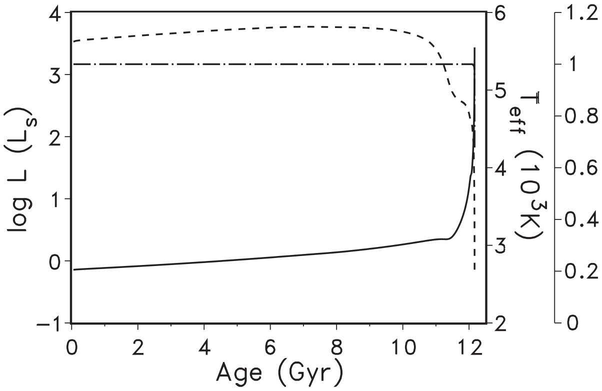

FIG. 1. Solar evolution model following Schröder and Smith (2008), depicting the luminosity (solid line), the effective temperature (dashed line), and the mass (dash-dotted line).

During the solar main sequence, the consequences of evolution for Earth-type planets (as well as other types of planets) are extremely slow, compared to natural or human-driven climate changes on Earth. Nonetheless, solar-type evolution will force global warming upon any planet, which has been the subject of detailed previous investigations concerning both the climatic HZ (*e.g.*, Underwood *et al.*, 2003; Jones *et al.*, 2005) and the pHZ of the Sun (*e.g.*, Franck *et al.*, 2000b). According to the evolution model by Schröder and Smith (2008), the tip-RGB evolution will be reached with a luminosity of 2730 $L_\odot$, an effective temperature of 2602 K, and a radius of $256\,R_\odot$. At that time, the Sun will have lost $0.332\,M_\odot$ of its initial mass. There is an ongoing debate as to that point in time when a planet originally located at 1 AU and equivalent in size to $215\,R_\odot$ will be engulfed as a consequence. Contrary to the previous model by Sackmann *et al.* (1993), which is based on a less accurate description of the solar mass loss, Schröder and Smith (2008) concluded that such an engulfment will happen during the late phase of the solar RGB evolution. In fact, the minimal orbital radius for a planet able to survive is found to be about 1.15 AU.

The evolution of the central star, as well as its effects on planetary orbits, has significant consequences for planetary habitability. This property has previously been investigated for different types of climatic HZs by Kasting *et al.* (1993), Underwood *et al.* (2003), Jones *et al.* (2005), and others. Furthermore, a previous assessment of the spatial and temporal evolution of climatic HZs for different types of stars beyond the main sequence has been given by Lopez *et al.* (2005). They showed that, for a $1\,M_\odot$ star at the first stages of its post-main-sequence evolution, the temporal transit of the HZ is estimated to be several times 10^9 years at 2 AU and about 10^8 years at 9 AU. Lopez *et al.* (2005) concluded that, under these circumstances, life could develop at distances in the range of 2 to 9 AU in the environment of subgiant or giant stars. This view is consistent with our current understanding that terrestrial life existed at least as early as 7×10^8 years after the Earth formed, which tends to imply that life may be able to form over time intervals from 5×10^8 to 10^9 years. The short time window ($\approx10^8$ years) for the origin of life is bounded by the last ocean-vaporizing impact and the earliest evidence for life on Earth ($\approx$3.8–3.9×10^9 years ago). This window might be extended if the origin of life occurred close to 3.5×10^9 years ago (Chyba and Hand, 2005).

The main goal of our study was to investigate habitability in the framework of the pHZ for stars like the Sun with special consideration of the post-main-sequence evolution. Our study focused on super-Earth planets, and we considered a significant set of geodynamic processes. Our findings will also be compared with the previous work by Lopez *et al.* (2005).

Habitability of Super-Earths

Definition of the photosynthesis-sustaining habitable zone

To assess the habitability of terrestrial planets, including super-Earth planets, an Earth-system model was applied to calculate the evolution of the temperature and atmospheric CO_2 concentration. On Earth, the carbonate-silicate cycle is the crucial element for a long-term homeostasis under increasing solar luminosity. The role of weathering for the Earth's climate was first described by Walker *et al.* (1981). They found that an increase in luminosity leads to a higher mean global temperature, which causes an increase in weathering. As a consequence, more CO_2 is extracted from the atmosphere, which thus weakens the greenhouse effect. Overall, the temperature is lowered, and homeostasis is achieved.

On geological timescales, however, the deeper parts of the Earth are considerable sinks and sources for carbon. As a result, the tectonic activity and the continental area change considerably. Therefore, Tajika and Matsui (1992) favored the so-called "global carbon cycle." In addition to the usual carbonate-silicate geochemical cycle, it also contains 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. In particular, the potential of weathering to stabilize the surface temperature of a terrestrial planet by a negative feedback mechanism is also strongly modulated by the biosphere.

Our numerical model couples the solar luminosity L, the silicate-rock weathering rate F_{wr}, and the global energy balance to obtain estimates of the partial pressure of atmospheric carbon dioxide P_{CO_2}, the mean global surface temperature T_{surf}, and the biological productivity Π as a function of time t (Fig. 2). The main point is the persistent balance between the CO_2 (weathering) sink in the atmosphere-ocean system and the metamorphic (plate-tectonic) sources. This is expressed through the dimensionless quantities

$$f_{\mathrm{wr}}(t)\cdot f_A(t)=f_{\mathrm{sr}}(t) \tag{1}$$

where $f_{\mathrm{wr}}(t)\equiv F_{\mathrm{wr}}(t)/F_{\mathrm{wr},0}$ is the weathering rate, $f_A(t)\equiv F_A(t)/F_{A,0}$ is the continental area, and $f_{\mathrm{sr}}(t)\equiv F_{\mathrm{sr}}(t)/F_{\mathrm{sr},0}$ is the areal spreading rate, which are all normalized by their present values of Earth. Equation (1) can be rearranged by introducing the geophysical forcing ratio GFR (Volk, 1987) as

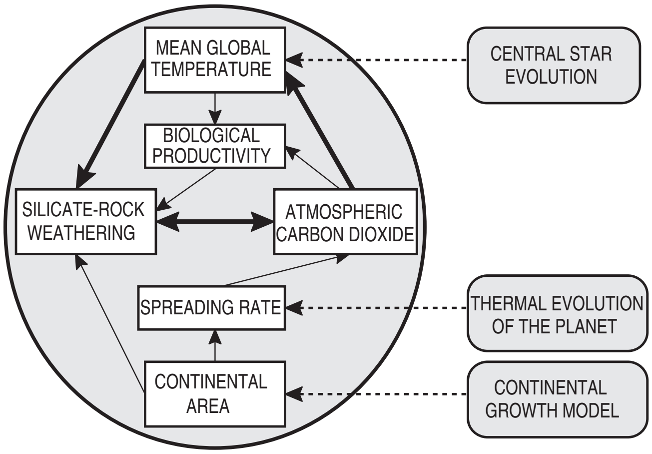

FIG. 2. Box model of the integrated system approach adopted in our model. The arrows indicate the different types of forcing, which are the main feedback loop for stabilizing the climate (thick solid arrows), the feedback loop within the system (thin solid arrows), and the external and internal forcings (dashed arrows).

$$f_{\mathrm{wr}}(T_{\mathrm{surf}},P_{CO_2})=\frac{f_{\mathrm{sr}}}{f_A}=:\mathrm{GFR}(t) \tag{2}$$

Here, we assume that the weathering rate depends only on the global surface temperature and the atmospheric CO_2 concentration. For the investigation of a super-Earth under external forcing, we adopt a model planet with a prescribed continental area. The fraction of continental area relative to the total planetary surface c is varied between 0.1 and 0.9.

The connection between the stellar parameters and the planetary climate can be formulated by using a radiation balance equation

$$\frac{L}{4\pi R^2}[1-a(T_{\mathrm{surf}},P_{CO_2})]=4I_R(T_{\mathrm{surf}},P_{CO_2}) \tag{3}$$

where L denotes the stellar luminosity, R the planetary distance, a the planetary albedo, and I_R the outgoing infrared flux of the planet. Following Williams (1998), I_R has been approximated by a third-order polynomial and a by a second-order polynomial. These approximations have been derived from 24,000 runs of a radiation-convection model by Kasting and Ackerman (1986) and Kasting (1988). They are valid in a range of 10^{-9} bar $<P_{CO_2}<10$ bar. Equations (2) and (3) constitute a set of two coupled equations with two unknowns, T_{surf} and P_{CO_2}, if the parameterization of the weathering rate, the luminosity, the distance to the central star, and the geophysical forcing ratio are specified. Therefore, a numerical solution can be attained in a straightforward manner.

The pHZ is defined as the spatial domain of all distances R from the central star, *e.g.*, the Sun, where the biological productivity is greater than zero, *i.e.*,

$$\mathrm{pHZ}:=\{R|\Pi(P_{CO_2}(R,t),T_{\mathrm{surf}}(R,t))>0\} \tag{4}$$

In our model, biological productivity is considered to be solely a function of the surface temperature and the CO_2 partial pressure in the atmosphere. Our parameterization yields maximum productivity at $T_{\mathrm{surf}} = 50^{\circ}\mathrm{C}$ and zero productivity for $T_{\mathrm{surf}} \leq 0^{\circ}\mathrm{C}$ or $T_{\mathrm{surf}} \geq 100^{\circ}\mathrm{C}$ or $P_{CO_2} \leq 10^{-5}$ bar (Franck *et al.,* 2000a). A photosynthesis-based biosphere of a super-Earth may, however, use methane to produce CO_2, because hydrogen is less likely to escape to space. The inner and outer boundaries of the pHZ do not depend on the detailed parameterization of the biological productivity within the temperature and pressure tolerance window. Hyperthermophilic life-forms can tolerate temperatures somewhat above 100°C. However, these chemoautotrophic organisms are outside the scope of this study.

Silicate rock weathering

Weathering plays an important role in Earth's climate because it provides the main sink for atmospheric carbon dioxide. The overall chemical reactions for the weathering process are

$$CO_2 + CaSiO_3 \rightarrow CaCO_3 + SiO_2$$
$$CO_2 + MgSiO_3 \rightarrow MgCO_3 + SiO_2$$

The total process of weathering embraces (1) the reaction of silicate minerals with carbon dioxide, (2) the transport of weathering products, and (3) the deposition of carbonate minerals in the oceanic crust. The available thickness of crust where $CaCO_3$ is stable in the presence of silicate scales inversely with the thermal gradient and, hence, inversely with surface gravity. Therefore, there may be a problem for storing carbonates in the crust of super-Earth planets. Additionally, there is an exchange with the mantle via alteration of the oceanic crust.

When combining all these effects, the normalized global mean weathering rate f_{wr} can be calculated as

$$f_{\mathrm{wr}} = \left(\frac{a_{\mathrm{H}^+}}{a_{\mathrm{H}^+,0}}\right)^{0.5} \exp\left(\frac{T_{\mathrm{surf}} - T_{\mathrm{surf},0}}{13.7\mathrm{K}}\right) \tag{5}$$

following Walker *et al.* (1981). Here, the first factor reflects the role of the CO_2 concentration in the soil, P_{soil}, with a_{H^+} as the activity of H^+ in fresh soil water that depends on P_{soil} and the global mean surface temperature T_{surf}. The quantities $a_{\mathrm{H}^+,0}$ and $T_{\mathrm{surf},0}$ are the present-day values for the H^+ activity and the surface temperature, respectively. The activity a_{H^+} is itself a function of the temperature and the CO_2 concentration of the soil. The concentration of CO_2 in the soil water $[CO_2(aq)]$ can be obtained from the partial pressure of CO_2 in the soil according to

$$[CO_2(aq)] = K_{\mathrm{H}} P_{\mathrm{soil}} \tag{6}$$

where K_{H} is Henry's law constant. We assume that $[CO_2(aq)] = [H_2CO_3^*]$. H_2CO_3 dissociates in two steps, which are

$$H_2CO_3^* \rightarrow H^+ + HCO_3^-$$
$$HCO_3^- \rightarrow H^+ + CO_3^{2-}$$

The corresponding concentrations can be calculated from the law of masses as

$$[HCO_3^-] = \frac{K_1}{[H^+]} K_{\mathrm{H}} P_{\mathrm{soil}} \tag{7}$$

$$[CO_3^{2-}] = \frac{K_1 K_2}{[H^+]^2} K_{\mathrm{H}} P_{\mathrm{soil}} \tag{8}$$

where K_1 and K_2 are (temperature-dependent) equilibrium constants. An additional constraint for the concentrations is given by the charge balance

$$[H^+] = [HCO_3^-] + 2[CO_3^{2-}] + [OH^-] \tag{9}$$

Here, $[H^+]$ and therefore a_{H^+} can be derived from a simultaneous solution of Eqs. (7) to (9) as a function of P_{soil}. The sulfur content of the soil can be taken into account analogously. The equilibrium constants for the chemical activities of the carbon and sulfur systems involved are taken from Stumm and Morgan (1981). Note that the sulfur content of the soil also contributes to the global weathering rate, but its influence does not depend on the temperature. It can be regarded as an overall weathering attribute that has to be taken into account for the estimation of the present-day value.

For any given weathering rate, the surface temperature and the CO_2 concentration of the soil can be calculated in a self-consistent manner. P_{soil} is assumed to be linearly related to the terrestrial biological productivity Π (see Volk, 1987) and the atmospheric CO_2 concentration P_{CO_2}. Thus, we find

$$\frac{P_{\mathrm{soil}}}{P_{\mathrm{soil},0}} = \frac{\Pi}{\Pi_0}\left(1 - \frac{P_{CO_2,0}}{P_{\mathrm{soil},0}}\right) + \frac{P_{CO_2}}{P_{\mathrm{soil},0}} \tag{10}$$

where $P_{\mathrm{soil},0}$, Π_0 and $P_{CO_2,0}$ are again present-day values. Note that the present-day concentration of CO_2 in the soil is 10 times the present-day concentration of CO_2 in the atmosphere, *i.e.,* $P_{\mathrm{soil},0} = 10 P_{CO_2,0}$.

Thermal evolution model

Parameterized convection models are the simplest models for investigating the thermal evolution of terrestrial planets and satellites. They have successfully been applied to the evolution of Mercury, Venus, Earth, Mars, and the Moon (Stevenson *et al.,* 1983; Sleep, 2000). Franck and Bounama (1995) investigated the thermal and volatile history of Earth and Venus in the framework of comparative planetology. The internal structure of massive terrestrial planets with 1 to 10 Earth masses has been investigated by Valencia *et al.* (2006) to obtain scaling laws for the total radius, mantle thickness, core size, and average density as a function of mass. Further scaling laws were found for different compositions. We used such scaling laws for mass-dependent properties of our 10 $M_{\oplus}$ super-Earth model as well as for mass-independent material properties given by Franck and Bounama (1995) (see Table 1).

The thermal history and future of a super-Earth has to be determined to calculate the spreading rate for solving Eq. (1). A parameterized model of whole mantle convection,

Table 1. Parameter Values for the Evolution Model of the Mantle Temperature and Water

Parameter	*Value*		*Unit*	*Description*
	1 $M_\oplus$	*10* $M_\oplus$		
d_{bas}	5×10^3	5×10^3	m	Average thickness of the basalt layer
f_{bas}	0.03	0.03	…	Mass fraction of water in the basalt layer
ρ_{bas}	2,950	4,569	$kg\,m^{-3}$	Density of the basalt
f_w	0.194	0.194	…	Degassing fraction of water
d_m	40×10^3	40×10^3	m	Melting depth
k	4.2	4.2	$J\,s^{-1}\,m^{-1}\,K^{-1}$	Thermal conductivity
R_c	$3{,}471\times10^3$	$6{,}463\times10^3$	m	Inner radius of the mantle
R_m	$6{,}271\times10^3$	$11{,}667\times10^3$	m	Outer radius of the mantle
$M_w(0)$	4.2×10^{21}	4.2×10^{21}	kg	Initial amount of mantle water
$T_m(0)$	3,000	3,000	K	Initial mantle temperature
K_H	3.36×10^{-4}	3.36×10^{-4}	$mol\,J^{-1}$	Henry's law constant at 25°C
$\log K_1$	-6.3	-6.3	…	Equilibrium constant in Eq. (7), Eq. (8) at 25°C
$\log K_2$	-10.3	-10.3	…	Equilibrium constant in Eq. (8) at 25°C
κ	10^{-6}	10^{-6}	$m^2\,s^{-1}$	Thermal diffusivity
ρc	4.2×10^6	4.2×10^6	$J\,m^{-3}\,K^{-1}$	Density×specific heat
R_T	2.98×10^{-4}	2.98×10^{-4}	K^{-1}	Temperature dependence of regassing ratio
α	3×10^{-5}	3×10^{-5}	K^{-1}	Coefficient of thermal expansion
β	0.3	0.3	…	Empirical constant in Eq. (13)
Ra_{crit}	1,100	1,100	…	Critical Rayleigh number
λ	0.34	0.34	Gyr^{-1}	Decay constant
E_0	1.46×10^{-7}	1.46×10^{-7}	$J\,s^{-1}\,m^{-3}$	Initial heat generation per time and volume
g	9.81	28.26	$m\,s^{-2}$	Gravitational acceleration

including the volatile exchange between the mantle and surface reservoirs (Franck and Bounama, 1995; Franck, 1998), is applied. Assuming conservation of energy, the average mantle temperature T_m can be obtained by solving

$$\frac{4}{3}\pi\rho c\left(R_m^3 - R_c^3\right)\frac{dT_m}{dt} = -4\pi R_m^2 q_m + \frac{4}{3}\pi E(t)\left(R_m^3 - R_c^3\right) \quad (11)$$

where ρ is the density, c is the specific heat at constant pressure, q_m is the heat flow from the mantle, $E(t)$ is the energy production rate by decay of radiogenic heat sources in the mantle per unit volume, and R_m and R_c are the outer and inner radii of the mantle, respectively. The radiogenic heat source per unit volume is parameterized as

$$E(t) = E_0 e^{-\lambda t} \quad (12)$$

where λ is the decay constant and the constant E_0 is obtained from the present heat flux of $q_m = 0.007\,Wm^{-2}$ for an Earth-sized planet at 4.6 Gyr.

The mantle heat flow is parameterized in terms of the Rayleigh number Ra as

$$q_m = \frac{k(T_m - T_{surf})}{R_m - R_c}\left(\frac{Ra}{Ra_{crit}}\right)^{\beta} \quad (13)$$

with

$$Ra = \frac{g\alpha(T_m - T_{surf})(R_m - R_c)^3}{\kappa\nu} \quad (14)$$

where k is the thermal conductivity, Ra_{crit} is the critical value of Ra for the onset of convection, β is an empirical constant, g is the gravitational acceleration, α is the coefficient of thermal expansion, κ is the thermal diffusivity, and ν is the water-dependent kinematic viscosity. The viscosity ν can be calculated with the help of a water fugacity-dependent mantle creep rate. It strongly depends on the evolution of the mass of mantle water M_w, and the mantle temperature T_m, that is, $\nu \equiv \nu(T_m, M_w)$ and is parameterized according to Franck and Bounama (1995).

The evolution of the mantle water can be described by a balance equation between the regassing flux F_{reg} and outgassing flux F_{out} as

$$\begin{aligned}\frac{dM_w}{dt} &= F_{reg} - F_{out}\\ &= f_{bas}\rho_{bas}d_{bas}SR_{H_2O} - \frac{M_w}{\frac{4}{3}\pi\left(R_m^3 - R_c^3\right)}d_m f_w S\end{aligned} \quad (15)$$

where f_{bas} is the water content in the basalt layer, ρ_{bas} is the average density, d_{bas} is the average thickness of the basalt layer before subduction, S is the areal spreading rate, d_m is the melt generation depth, and f_w is the outgassing fraction of water. R_{H_2O} is the regassing ratio of water, *i.e.*, the fraction of subducting water that actually enters the deep mantle. The average thickness of the basalt layer, as well as the melt-generation depth, scales inversely with surface gravity g, that is, $d_{bas} \propto 1/g$ and $d_m \propto 1/g$. The pressure closing of cracks in the deeper parts of the basalt layer also scales inversely with g and thus reduces the storage capacity of volatiles for a super-Earth planet. Therefore, the ratio F_{reg}/F_{out} is independent of g. According to Eq. (15), gravity influences only the timescale of mantle water evolution. Therefore, as a first approximation the melt generation depth d_m does not depend on mantle temperature. However, there is a temperature dependence of d_m (McKenzie and Bickle, 1988; Langmuir *et al.*, 1992). The regassing ratio depends linearly on the mean mantle temperature T_{m} that is derived from the thermal evolution model via

$$R_{\mathrm{H_2O}}(t) = R_T \cdot (T_{\mathrm{m}}(0) - T_{\mathrm{m}}(t)) + R_{\mathrm{H_2O},0} \tag{16}$$

The factor R_T is adjusted to obtain the correct modern amount of surface water (one ocean mass) for an Earth-sized planet, and $R_{\mathrm{H_2O},0}$ is fixed at 0.001. This value is obviously very low at the beginning of the planetary evolution because of the enhanced loss of volatiles resulting from back-arc volcanism at higher temperatures.

The areal spreading rate S is a function of the average mantle temperature T_{m}, the surface temperature T_{surf}, the heat flow from the mantle q_{m}, and the area of ocean basins A_{o} (Turcotte and Schubert, 1982), given as

$$S = \frac{q_{\mathrm{m}}^2 \pi \kappa A_{\mathrm{o}}(t)}{4k^2 (T_{\mathrm{m}} - T_{\mathrm{surf}})^2} \tag{17}$$

To calculate the spreading rates for a planet with several Earth masses, the planetary parameters have to be adjusted accordingly. We assume

$$\frac{R_{\mathrm{p}}}{R_{\oplus}} = \left(\frac{M}{M_{\oplus}}\right)^{0.27} \tag{18}$$

and with R_{p} as planetary radius: see Valencia *et al.* (2006). The total radius, mantle thickness, core size and average density are all functions of mass, with subscript $\oplus$ denoting Earth values. The exponent of 0.27 has been obtained for super-Earths ($M > 1\,M_{\oplus}$) and has already been used by von Bloh *et al.* (2007b) in their models of Gliese 581c and 581d. The values of R_{m}, R_{p}, A_{o}, the density of the planet, and the other planetary properties are also scaled accordingly.

The source of CO_2 to the atmosphere is expressed in mass of carbon outgassed at the spreading zones, $C_{\mathrm{sr}} \propto S$. It has to be converted to an equivalent concentration of CO_2 in the atmosphere. This can be done by the following equation

$$P_{\mathrm{CO_2}} = \frac{g}{4\pi R_{\mathrm{p}}^2} \frac{\mu_{\mathrm{CO_2}}}{\mu_{\mathrm{C}}} C_{\mathrm{sr}} \tag{19}$$

where $\mu_{\mathrm{CO_2}}$ and μ_{C} are the molar weights of CO_2 and C, respectively. The mass dependent pre-factor g/R_{p}^2 scales as $M^{-0.08} \approx M^0$ and has therefore been neglected in our study. Therefore, the conversion does not depend on the planetary mass, and the spreading rate S can be directly used to calculate f_{sr} in Eq. (1).

In Table 1, we give a summary of the selected values for the parameters used in the thermal evolution model of the $10\,M_{\oplus}$ super-Earth planet, while also depicting an Earth-sized planet for comparison. Consistent with Valencia *et al.* (2007b), we assume that a more massive planet is likely to convect in a plate tectonic regime similar to Earth. Thus, the more massive the planet is, the higher the Rayleigh number that controls convection, the thinner the top boundary layer (lithosphere), and the faster the convective velocities. This is the so-called boundary-layer limit of convection. From this limit, it follows that the interior of a super-Earth is always hotter and less viscous than that of an Earth-mass planet. Nevertheless, friction is the rate-limiting process for subduction. Increasing the planetary radius acts to decrease the ratio between driving forces and resistive strength (O'Neill and Lenardic, 2007). Thus, a super-sized Earth might be in an episodic or stagnant lid regime.

In a first-order approximation, we assumed a fixed thickness of the basalt layer and melting depth that corresponds to relatively low values. Furthermore, the initial amount of water $M_{\mathrm{w}}(0)$ scales linearly with the planetary mass. However, this might be an underestimate because more massive planets tend to accrete more volatiles.

Results

Habitability based on the integrated system approach

In the following, we examine the habitability of super-Earth planets based on the integrated system approach, which has been used in various other planetary studies (*e.g.*, Franck *et al.*, 2000b, 2003; Cuntz *et al.*, 2003; von Bloh *et al.*, 2003, 2007a, 2007b). The simulations were carried out for a $10\,M_{\oplus}$ super-Earth with a fixed relative continental area c varied from 0.1 to 0.9. Figure 3 shows the behavior of the pHZ of the Sun for a $10\,M_{\oplus}$ super-Earth planet. The age domain beyond 11 Gyr, which also includes the post-main-sequence evolution, is depicted in Fig. 4. The width of the pHZ during the main-sequence evolution is found to be approximately constant, but for higher ages it increases over time and moves outward, a phenomenon most noticeable beyond 11.5 Gyr. For example, for ages of 11.0, 11.5, 12.0, and 12.1 Gyr, the pHZ is found to extend from 1.41 to 2.60, 1.58 to 2.60, 4.03 to 6.03, and 6.35 to 9.35 AU, respectively.

At relatively high ages, habitable solutions are identified as water worlds, if the Sun as central star has reached the RGB. This is because planets with a considerable continental area have higher weathering rates, which provide the main sink of atmospheric CO_2. Therefore, such planets are unable to build up CO_2-rich atmospheres that prevent the planet

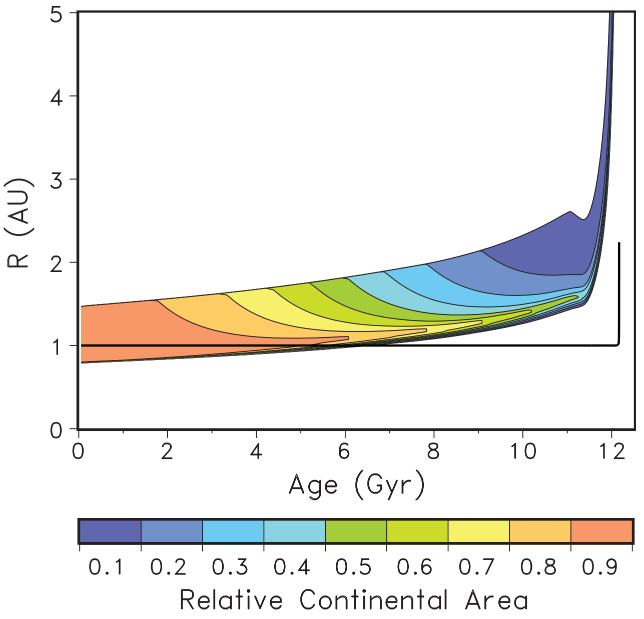

FIG. 3. The pHZ of the Sun for a super-Earth planet with the solar evolution along the RGB taken into consideration. The colored areas indicate the extent of the pHZ for different relative continental areas. The solid line depicts the orbital distance of a planet originally located at 1.0 AU.

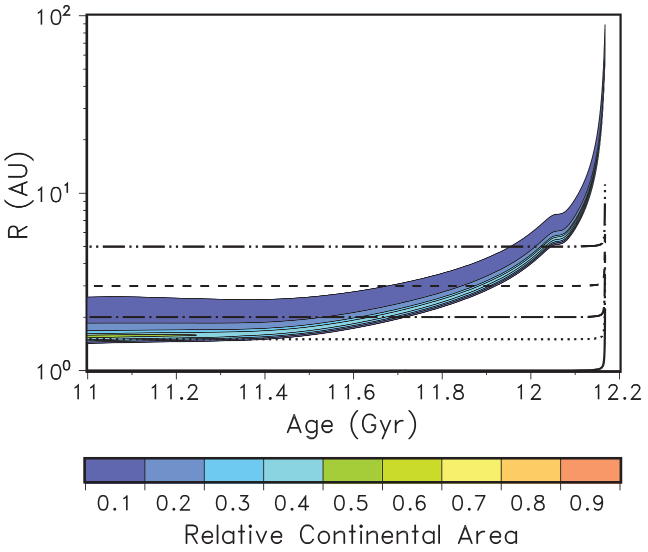

FIG. 4. Same as Fig. 3, but now zoomed-in at the RGB evolution beyond 11 Gyr. We also show the distance evolution of various fictitious planets, originally located at 1.0 AU (solid line), 1.5 AU (dotted line), 2.0 AU (dash-dotted line), 3.0 AU (dashed line), and 5.0 AU (dash–double-dotted line), respectively.

from freezing or allowing photosynthesis-based life. This result is consistent with previous findings for Earth-mass planets around the Sun or stars of similar masses (Franck *et al.*, 2000b; Franck *et al.*, 2003).

Note that the partial pressure of carbon dioxide in the planetary atmosphere is determined by the equilibrium of sources and sinks. The sources are given by volcanic outgassing, while the sinks are given by the weathering of silicates on the continents. As previously found in studies of 1 $M_\oplus$ planets (*e.g.*, Franck *et al.*, 2000b), the rate of outgassing is monotonously decreasing with age because of the decay of long-lived radionuclides and the loss of the initially available accretion energy at the planetary surface. This process starts just after completion of the planetary accretion both for an initially habitable and uninhabitable planet. A planet beyond the outer edge of the pHZ is completely frozen; thus, no weathering will occur on the continents. Therefore, all CO_2 is accumulated in the atmosphere. If the planet becomes habitable due to the increase of the luminosity of the central star, weathering starts, and a new equilibrium of atmospheric CO_2 is established as a consequence.

Furthermore, the interior of a planet with a relatively low mass is known to cool down more rapidly. Therefore, such a planet initially beyond the outer edge of the HZ will not become habitable at a later stage because of the failure to provide a sufficiently dense atmosphere. In contrast, a super-Earth planet might become habitable, depending on the relative size of the continental area. In a recent study, the importance of snowball planets as a possible source of water-rich terrestrial planets was elucidated by Tajika (2008), though the main focus of the paper was the assessment of internal oceans.

Super-Earth–type water worlds are even able to realize pHZ-type habitability beyond solar-type main-sequence evolution. Any model where the mantle vents its water will end up as a water world super-Earth. The height of ridges, volcanoes, and mountains scale with lithosphere thickness and, hence, with $1/g$. As the central star evolves, its pHZ expands outward and moves farther away from the star, particularly for stellar ages beyond 11.8 Gyr (see Fig. 4). Similar to the climatic HZ [see Lopez *et al.* (2005) for details], the pHZ acts like a shell that sweeps progressively outward over a wide range of distances from the star. This results in a significant decrease in the duration of the transit of the HZ for any planet located beyond 1.5 AU (see Fig. 5). We find that for water worlds with $c = 0.1$, the duration of the transit of the pHZ at 2, 3, and 5 AU is given as 3.7, 0.25, and 0.10 Gyr, respectively; whereas for planets at 10 and 20 AU, much smaller durations of the transit are identified.

Figures 3 and 4 also depict various orbital distances of planets originally located between 1 AU and 5 AU. Note that these orbital distances do not change during the stellar main-sequence stage, *i.e.*, below 10 Gyr (Schröder and Smith, 2008),

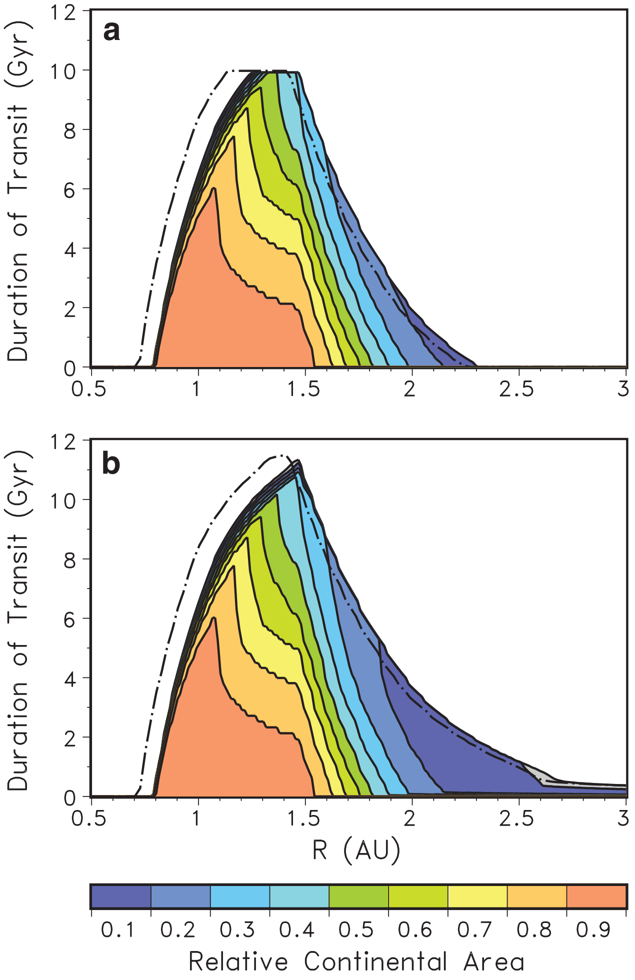

FIG. 5. Duration of the transit of the pHZ for a super-Earth as a function of the distance from the central star *R* for different relative continental areas. Model (**a**) only includes the stellar main-sequence evolution (10 Gyr), whereas Model (**b**) also includes the evolution along the RGB. The gray area indicates the result based on the geostatic approximation (Franck *et al.*, 2000b) that is mostly enveloping the colored area. The dash-dotted line indicates transit times of the general HZ given by the model of Kasting *et al.* (1993).

owing to the lack of significant mass loss in the absence of significant planet-planet interaction as typically encountered in multiple planetary systems. Thereafter, the orbital distances R of any planet increases following $R \propto M_{\odot}^{-1}$ with $M_{\odot}$ as stellar mass.

Comparison with previous results

The existence of habitability around stars that have evolved away from the main sequence has already been the topic of previous investigations. Lopez *et al.* (2005) studied the behavior of the climatic HZ based on the concept of Kasting *et al.* (1993) for stars of different masses, including the Sun. Lopez *et al.* (2005) assumed a HZ based on conservative limits of habitability. The inner limit of their conservative estimate is set by the lowest temperature at which the liquid-solid phase change of water occurs. The estimate of the outer limit assumes the existence of a greenhouse effect involving CO_2 and H_2O gas (Kasting *et al.*, 1993). The less-conservative definition extends the outer edge of the limit of habitability to as large as 2.4 AU, largely depending on the radiative properties of the CO_2 ice clouds [see Forget and Pierrehumbert (1997) and Mischna *et al.* (2000) for detailed studies].

Akin to the pHZ previously discussed, Lopez *et al.* (2005) found that, for the Sun during its evolution, the climatic HZ acts like a shell that sweeps progressively outward over a wide range of distances from the star. The duration of the transit during which the HZ passes over a planet located at 1 AU from the star was found to be on the order of 10^9 years. After the star leaves the main sequence, the climatic HZ progressively moves to 2 AU. The duration of the transit at this location is approximately 10^9 years. A plateau is observed in the curve up to 9 AU (for the conservative limits) and up to 13 AU (for the less-conservative limit), where the durations of habitable conditions last from a few to several times 10^8 years. At 10 AU, the duration is smaller, about 10^8 years. At 15 AU from the star, the duration of habitable conditions lasts more than 10^7 years; and at the largest distances considered in the study by Lopez *et al.* (2005), the duration gradually decreases.

Note that the model of solar evolution considered in the Lopez *et al.* (2005) study is the same one used by Maeder and Meynet (1988). Nonetheless, their results would be quite similar if they had used the subsequent model by Sackmann *et al.* (1993) or the very recent model by Schröder and Smith (2008). This is because the outcome of the Lopez *et al.* (2005) study was much more dependent on the choices made concerning the upper and lower limits of the climatic HZ, mainly having to do with the treatment of the CO_2 atmospheres (*i.e.*, radiative properties, cloud coverage) than the adopted model of solar evolution.

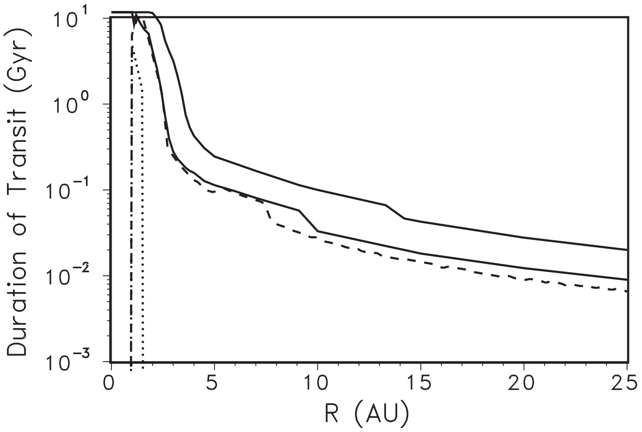

FIG. 6. Duration of the transit of the pHZ for super-Earth planets as a function of the planetary distance R from the center of the star. We depict the results for "water worlds" ($c = 0.1$; dashed line) and "land worlds" ($c = 0.9$; dotted line). In addition, we also show the results by Lopez *et al.* (2005) for terrestrial planets (solid lines) based on the concept of habitability by Kasting *et al.* (1993). Here, the lower line refers to the duration of habitability based on their conservative definition of the HZ, whereas for the upper line the less-conservative definition has been adopted for the outer limit of the HZ, while the inner limit of the HZ was left unchanged.

Figure 6 shows the comparison between the work by Lopez *et al.* (2005) and our current results. We found that, for water worlds ($c = 0.1$), the transit times for photosynthesis-sustaining habitability (pHZ) for planets at a given reference distance from the star is relatively similar to the results obtained for the conservative climatic HZ (Kasting *et al.*, 1993) adopted by Lopez *et al.*, albeit the transit times in our study were typically lower by a factor of up to 1.5. For example, the durations of the transit concerning pHZ-type habitability for water worlds at 2, 3, and 5 AU are identified as 3.7, 0.25, and 0.10 Gyr, respectively; whereas for planets at 10 and 20 AU, the durations of the transit found are as low as 27 and 9 Myr, respectively.

However, significantly smaller transit times are encountered, especially at distances beyond 2 AU, for planets with larger continental areas in terms of all stellar distances, a result consistent with previous findings. For $c = 0.5$, the transit time of the pHZ drops beneath 1 Gyr for planets located at 1.8 AU. For planets with a relative continental area of $c = 0.9$, also referred to as "land worlds," no significant photosynthesis-sustaining habitability was found for planets beyond 1.5 AU.

Summary and Conclusions

We studied the habitability of super-Earth planets based on the integrated system approach, which has previously been used in various theoretical planetary studies (*e.g.*, Franck *et al.*, 2000b, 2003; Cuntz *et al.*, 2003; von Bloh *et al.*, 2003, 2007a, 2007b). This work was motivated by the quest to identify habitability outside the Solar System as well as the ongoing discovery of super-Earths in the solar neighborhood with the Gliese 876 (Rivera *et al.*, 2005) and Gliese 581 (Udry *et al.*, 2007) systems as prime examples.

In agreement with previous studies, it was found that photosynthesis-sustaining habitability strongly depends on the planetary characteristics. For planets of a distinct size, the most important factor is the relative continental area. Habitability was found most likely for water worlds, *i.e.*, planets with a relatively small continental area. For planets at a distinct distance from the central star, we identified maximum durations of the transit of the pHZ. A comparison of planets with different masses revealed that the maximum duration of the transit increases with planetary mass. Therefore, the upper limit for the duration of the transit for any kind of Earth-type planet is found for most massive super-Earth planets, *i.e.*, $10\,M_\oplus$, rather than $1\,M_\oplus$ planets, which are rendered uninhabitable after 6.5 Gyr, as previously pointed out by Franck *et al.* (2000b).

Our study built upon a thermal evolution model for a $10\,M_\oplus$ super-Earth orbiting a star akin to the Sun. The calculations took into account updated models of solar evolution obtained by Schröder and Smith (2008), with a detailed mass loss description provided by Schröder and Cuntz (2005). An appropriate description of mass loss is relevant for the change of luminosity along the RGB as well as the increase of the orbital distances of any putative planets during that phase. By employing the integrated system approach, we were able to identify the sources and sinks of atmospheric carbon dioxide on the planet, which allowed us to describe the pHZ determined by the limits of biological productivity on the planetary surface.

Concerning the pHZ, we identified the following properties:

(1) Geodynamic solutions were identified for different solar ages, including the RGB phase. The pHZ increases in width over time and moves outward. For example, for ages of 11.0, 11.5, 12.0, and 12.1 Gyr, the pHZ was found to extend from 1.41 to 2.60, 1.58 to 2.60, 4.03 to 6.03, and 6.35 to 9.35 AU, respectively.

(2) Habitable solutions for longer time spans, especially for the subgiant and giant phase, are water worlds. This also means that the possibility of water worlds in principle results in an extension of the outer edge of habitability. This is because planets with a considerable continental area have higher weathering rates, which provide the main sink of atmospheric CO_2. Therefore, such planets, contrary to water worlds, are unable to build up CO_2-rich atmospheres that prevent the planet from freezing or allowing photosynthesis-based life.

(3) The total duration of the transit of the HZ is similar to the predictions by Lopez *et al.* (2005) based on the conservative limits of the climatic HZ obtained by Kasting *et al.* (1993). For water worlds with $c = 0.1$, the transit times of the pHZ at 2, 3, and 5 AU are obtained as 3.7, 0.25, and 0.10 Gyr, respectively, whereas for planets at 10 and 20 AU, much smaller transit times were found.

Our results are further motivation to consider super-Earth planets in upcoming or proposed planet search missions, such as Kepler, Terrestrial Planet Finder, or Darwin. Moreover, our results can also be viewed as a reminder that the possibility of habitable planets around red giants, as previously pointed out by Lopez *et al.* (2005) and others, should be seriously considered. For central stars with a higher mass than the Sun, a more rapid evolution will occur that will also affect the temporal and spatial constraints on planetary habitability when the central stars have reached the RGB.

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Abbreviations

HZ, habitable zone; pHZ, photosynthesis-sustaining habitable zone; RGB, Red Giant Branch.

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