Circumstellar habitable zones for deep terrestrial biospheres

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Abstract

The *habitable zone* (HZ) is conventionally the thin shell of space around a star within which liquid water is thermally stable on the surface of an Earth-like planet (Kasting et al., 1993). However, life on Earth is not restricted to the surface and includes a "deep biosphere" reaching several km in depth. Similarly, subsurface liquid water maintained by internal planetary heat could potentially support life well outside conventional HZs. We introduce a new term, *subsurface-habitability zone* (SSHZ) to denote the range of distances from a star within which rocky planets are habitable at any depth below their surfaces up to a stipulated maximum, and show how SSHZs can be estimated from a model relating temperature, depth and orbital distance. We present results for Earth-like, Mars-like and selected extrasolar terrestrial planets, and conclude that SSHZs are several times wider and include many more planets than conventional surface-based habitable zones.

Keywords: habitable zone, deep biosphere, subsurface, astrobiology, exobiology, extrasolar planets

1. Introduction

1.1 Habitable zones and deep biospheres

The concept of a circumstellar habitable zone (HZ) was formalised by Kasting et al. (1993) and is widely employed in the planetary sciences. Within the conventional HZ, global average planetary surface temperatures—buffered by a CO_2 weathering cycle—fall between the limits of runaway greenhouse warming at the inner edge and runaway cooling driven by CO_2 condensation at the outer edge. Outside these limits, planetary surfaces are thought to be unable to sustain liquid water and therefore life. In our own solar system, however, some of the most promising candidates for habitable extraterrestrial environments are in the subsurface of planets and moons outside the conventional HZ, such as Mars and Jupiter's moon Europa (e.g. Boston et al., 1992; Fisk and Giovannoni, 1999; Gaidos et al., 1999).

It has long been recognised that subsurface life on Earth provides a model for understanding how life could adapt to conditions deep within a colder rocky planetary body (e.g. Gold, 1992). Micro-organisms inhabit pores and fractures at depths of up to several km in the Earth's crust, constituting a "deep biosphere" with a total biomass that may be similar to the "surface biosphere" (Whitman et al., 1998). Much of the deep biosphere relies on buried photosynthetic organic matter and dissolved oxidants from the surface. However, some organisms (chemolithoautotrophs) obtain nutrients and energy from geochemical sources that are largely independent of surface conditions (Lin et al., 2006). Nutrients and redox couples for metabolism are widespread in rocks, minerals and circulating fluids (e.g. Fisk and Giovannoni, 1998; Popa et al., 2012). Hence, deep aquifers and hydrothermal systems in crystalline and sedimentary rocks

provide a habitable environment that could persist beyond the outer edge of the conventional habitable zone. This scenario has been widely discussed in relation to Mars, where aquifers could exist less than ten km below the surface (Travis et al., 2003). Similarly, many workers have discussed whether Jupiter's moons Europa, Callisto and Ganymede, Saturn's moon Titan, and other icy moons of the outer solar system may provide habitable conditions in deep oceans beneath their outer ice shells (see Raulin et al., 2010 for review). Here, we extend the widely used quantitative model of Kasting et al. (1993) for circumstellar habitable zones to include terrestrial (rocky) planets with habitable temperatures in the subsurface down to a stipulated depth. The possibility of adapting the model for icy bodies is also discussed.

1.2 Subsurface-habitability zones

We introduce a new term**,** "subsurface-habitability zone" (SSHZ) to denote the range of distances from a star within which terrestrial planets are habitable at any depth below their surfaces up to a certain maximum, z_{max} (for instance, within the "SSHZ for 2 km depth", planets can support liquid water at a depth of 2 km or less). SSHZs directly extend the conventional habitable zone, which is reproduced by setting z_{max} equal to 0. In this paper, we show how SSHZs can be estimated from a model of how the global average temperature (1) decreases with increasing orbital distance, and (2) increases with depth in the crust.

The "habitable layer" is placed where global average temperatures fall between T_{min}, the freezing point of water, and T_{max}, the upper limit of viability for known life, until the base is truncated by z_{max} (**Figure 1**). We find the thickness and depth of the habitable layer by coupling a conventional model for planetary surface temperature (as a function of orbital distance) with a geothermal gradient. The outer edge of the SSHZ is placed at the heliocentric distance where the

habitable layer pinches out at z_{max}; in other words, the temperature at z_{max} passes below T_{min}. The inner edge of the SSHZ can be placed either where the average surface temperature reaches T_{max}, or—because a planet too hot to maintain surface water would probably vent and lose subsurface water on a geologically short timescale—at the conventional HZ inner edge. It should be noted that both the conventional HZ and the SSHZ are determined by planetary average temperatures although in reality temperature and other controls on habitability vary regionally (see *Section 4.1*).

1.3 The maximum habitable depth

If desired, the maximum depth (z_{max}) can be used to represent a physical obstacle to deeper infiltration by the biosphere. Fractures and pores are compacted under high lithostatic pressures and occluded by secondary mineral growth. Thus, this obstacle could be a minimum threshold in porosity, permeability or hydraulic connectivity. The upper pressure limit for known microbial survival is on the order of GPa and is therefore unlikely to be encountered in pore water at a shallower depth than these geophysical barriers or T_{max}. (Sharma et al., 2002; Vanlint et al., 2011). However, relationships between pressure, temperature, rock rheology, permeability, porosity, fluid flow and other controls on habitability are not well constrained; on Earth, the depth of penetration by the biosphere is probably limited by temperature (for discussion, see Jones et al., 2011). A physically meaningful z_{max} would be temperature-dependent and therefore vary with orbital distance, potentially failing to truncate the habitable layer (as defined in *1.2*) and hence to define an SSHZ outer edge. In any case, z_{max} can be used more generally to limit a depth range of interest; the SSHZ outer edge is simply the maximum orbital distance of a planet habitable at that particular depth.

2. Methods

2.1 Surface temperature

Surface temperature, T_s, is estimated from the combined solar and geothermal heat flux on the assumption of thermal equilibrium at the surface of the planet (heat absorbed = heat emitted). From the Stefan-Boltzmann law, the total heat radiated from the surface is given by $Q_{total} = 4\pi R^2 \varepsilon \sigma T_s^4$, where R is the planetary radius, σ is the Stefan-Boltzmann constant, ε is emissivity and T_s is surface temperature. At equilibrium, Q_{total} = internal heat (Q_{int}) + solar heat (Q_{sol}). Solving for T_s:

$$T_s = \sqrt[4]{\frac{Q_{\mathrm{int}} + Q_{\mathrm{sol}}}{4\varepsilon\sigma\pi R^2}} \quad (1)$$

Q_{sol} is equal to $(1 - a)\pi R^2 H_0$, where a is the planetary albedo and H_0 is the solar irradiance (power density) at the orbital distance of the planet. For Earth-like atmospheres, we modify T_s using simple temperature-dependent fluxes of the greenhouse gases H_2O and CO_2. The partial optical thicknesses τ_{CO_2} and τ_{H_2O} are given by $0.029 \times \rho_{CO_2} T$ and $0.087 \times \rho_{H_2O} T$ respectively, where ρ_i is the partial pressure of gas i in the atmosphere, which is itself a function of temperature:

$$\rho_i = \frac{n_i R T}{N_A} \quad (2)$$

where n_i is the number density of the gas molecules in 1 m^3 of the atmosphere, R is the universal gas constant and N_A is Avogadro's constant. The partial pressures of H_2O and CO_2 in the atmosphere are accounted for following the conventions of Caldeira and Kasting (1992) and Kasting et al. (1993), using the updated boundary conditions of Kopparapu et al. (2013). Replacing T_{eff}, the effective temperature due to solar radiation (i.e. $(Q_{sol}/4\pi\varepsilon\sigma R^2)^{¼}$) with $T_{eff}(1 + 0.75\tau)^{¼}$ gives a surface temperature that overshoots the actual value because it assumes a perfect greenhouse. A final surface temperature is estimated by calculating the energy losses from the system.

Q_{int}, the planetary internal heat, is assumed for simplicity to scale linearly with mass and is given by $= (4/3)\pi R^3 \rho Q_M$, where Q_M is the heat production per unit mass and ρ is the bulk density. Except when stated otherwise, Q_M and ρ were given terrestrial values (7.4×10^{12} W kg^{-1} [Pollack et al., 1993] and 5.515×10^3 kg m^{-3} respectively). The assumption that heat production scales linearly with mass is justified if most heat production is radiogenic (whereas accretional heat should scale with M^2/R [Selsis et al., 2008] and tidal heating depends on orbital configurations); the relative contributions of the Earth's heat sources are currently poorly constrained.

2.2 Habitable layers and SSHZs

The flux of internal heat to the surface, q, is obtained by dividing Q_{int} by the surface area of the planet. The increased lag time for internal heat to reach the surface of larger planets is not taken into account; this increase may be small given that mantle convection rates are expected to scale with $M^{1.19}$ (Valencia et al., 2007). A depth interval Δz corresponding to a temperature increase $T_1 - T_0$ is found by:

$$\Delta z = \frac{\int_{T_0}^{T_1} K(T)dT}{q} \quad (3)$$

where $K(T)$ is the temperature-dependent thermal conductivity of the medium, assumed to be similar to basalt. We do not consider other influences on $K(T)$ such as pressure, rock porosity, water saturation, clathrates, ammonia or solutes in water. Since no data exist for *K(T)* of basalt at very low temperatures, we follow Clifford et al. (2010) in approximating it by an empirical relation derived for water ice (Petrenko and Whitworth, 1999) which closely matches the $K(T)$ of basalt at higher temperatures. At 246 K, this function intersects the empirical relation of Clauser and Huenges (1995) for the thermal conductivity of basaltic rocks verified between 323 and 1273 K, which we therefore use for temperatures higher than 246 K. The use of these two relations together results in a smoothly continuous $K(T)$ curve for basalt throughout the desired temperature range. We thereby find both the top of the habitable layer and its base as a function of surface temperature and hence orbital distance.

The top of the habitable layer is placed at the shallowest depth where temperature is equal to or higher than T_{min}. The base is placed at the depth of T_{max} (395 K; Takai et al., 2008) except where that depth exceeds the stipulated maximum depth, z_{max}, in which case the base is placed at z_{max}. This allows the calculation of SSHZ inner and outer edges as noted in *1.2* and illustrated by Figure 1. As noted in *1.2*, the inner edge of the SSHZ can be placed either where T_s reaches T_{max} (the maximum temperature known to support life), or at the conventional HZ inner edge; for Earth-like atmospheres there is very little difference between these two values because of runaway global warming at the inner edge. The outer edge of the SSHZ is placed at the distance beyond which temperature does not exceed T_{min} (the freezing point of water) at any depth

shallower than the chosen z_{max}. Thus, any planet within the SSHZ can sustain liquid water at some depth $\leq z_{max}$.

3. Results

3.1 General results

SSHZs expand several-fold the range of heliocentric distances designated "habitable". The relationship between orbital distance and the position of the habitable layer is illustrated for the most general case (i.e. with no atmospheric feedbacks) by **Figure 1**. In this example, the planet is given Earth's radius, bulk density, and estimated internal heat production, as well as a fixed albedo and emissivity with Earth's values. Because atmospheric feedbacks are not included, the HZ and SSHZ are shifted towards the sun compared to a planet with an Earth-like atmosphere.

SSHZ outer-edge positions are highly sensitive to the maximum habitable depth, z_{max}; outer edges for z_{max} = 5 and 10 km are marked on Figure 1. In this example, the SSHZ is only limited when z_{max} is shallower than ~15.4 km (the asymptote in the top of the habitable layer). For higher z_{max}, SSHZs are unbounded; the planet's internal heat production is such that subsurface temperatures are within habitable limits even without additional heat from a star.

Higher albedos reduce surface temperature, shifting the habitable zone towards the star and reducing its width (**Figure 2**). The effect on the SSHZ outer-edge position is stronger for higher values of z_{max}, because the difference in the depth of the habitable layer (forced by surface temperature) corresponds to a larger shift towards the star. However, the asymptote in the depth

of the habitable layer is determined where solar irradiation approaches zero and is therefore independent of albedo.

3.2. Effect of planetary size

Planetary masses (M) 0.1 – 10 × Earth-mass ($M_\oplus$) were modelled, with bulk density and heat production per unit mass held constant at bulk-Earth values. Larger radii generate steeper geothermal gradients and proportionally shallower and thinner habitable layers less sensitive to solar radiation (**Figure 3**). For $M/M_\oplus = 10$, a habitable layer ~1.5 km thick is supported less than 6 km below the surface in interstellar space. However, if z_{max} is related to a minimum threshold in porosity or permeability (see *1.3*) then it must decrease with increasing lithostatic pressure, which is proportional to gravitational field strength and hence planetary radius. Increasing the planetary radius can therefore reduce both the depth of the habitable layer and z_{max} at the same rate, such that the SSHZ is unaffected. This result only applies when the internal heat flux negligibly affects surface temperature; within the limits of Figure 2, it applies within ~7 AU.

3.3. Application to Earth, Mars and exoplanets

SSHZ outer edges for Earth, Mars and a selection of exoplanets are presented (**Table 1**). Mars (~0.1 $M_\oplus$) is approximated by the general (equilibrium) model. The habitable layer is found to extend from 5.3 km to 14.0 km below the surface (unless limited by z_{max}). A hypothetical Mars-average-salinity melting point of −10 °C (Jones et al., 2011) raises the top of the habitable layer to 4.5 km below the surface. These results are similar to other recent estimates (e.g. Clifford et al., 2010) despite the use of Earth's heat production per unit mass.

For Earth, the model is adjusted to include some simple, temperature-dependent greenhouse gas fluxes, as described in *2.1*. These introduce sharp changes in surface temperature, and consequently in the depth of the habitable layer, at both edges of the conventional HZ (**Figure 4)**. For the most Earth-like case, the SSHZ is ~3 and ~14 times wider than the conventional HZ for a biosphere shallower than 5 and 10 km respectively. In Earth's present position, the average base of the biosphere is predicted to occur at 2.8 km depth, corresponding to a predicted average thermal conductivity of ~2.3 W m^{-1} K^{-1}.

Four low-mass super-earths were selected for investigation based on their low mass and variety of positions with respect to the surface HZ (Schneider, 2010; Vogt et al., 2010). As in the calculation of conventional (surface) habitable zones, an Earth-like atmosphere is assumed (see *2.1*); we also assume Earth values for bulk density and heat production per unit mass. Since these assumptions are only partially valid, the results are best regarded as illustrative. HD 85512 b is outside the inner edge of the conventional HZ (T_s = 181 °C), Gliese 667 Cc lies within the conventional HZ but close to the inner edge (T_s = 75 °C), Gliese 581g (unconfirmed; T_s = −11 °C) is just beyond the outer edge; and Gliese 581 d is far beyond the outer edge (T_s = −84 °C). However, all but HD 85512 b, which cannot support liquid water at any depth, are found to lie within the SSHZ for 2 km depth, i.e., they possess temperatures suitable for liquid water less than 2 km below the surface.

4. Discussion

4. 1 Uncertainties and limitations

To constrain both HZs and SSHZs for real planetary bodies requires modelling of surface temperature based on incoming solar radiation, atmospheric composition, and (bio)geochemical

feedbacks. For SSHZs, additional modelling is required to estimate heat production, transport and loss due to accretion, radioactive decay, tidal and other gravitational effects in planets of different compositions, sizes, ages, and tectonic regimes. Small terrestrial planets without surface liquid water probably cannot support plate tectonics and should therefore lose internal heat less efficiently than the Earth. Nevertheless, the present model yields both an appropriate geotherm for Earth and a Mars geotherm similar to those of other studies (e.g. Clifford et al. 2010).

The age and hence accretional heat reserves of exoplanets of known mass might be very broadly constrained by the spectroscopic and activity profiles of their host stars (Lachaume et al., 1999). Planetary radiogenic heat production depends on both age and the initial abundance of radioactive isotopes of U, Th and K. 70 – 90% of stars surveyed formed in clusters within gas or dust clouds; 75% of these clusters contain massive stars, implying a high likelihood of contamination by supernova explosions (Lada and Lada, 2003). While U/O and Th/O ratios should be relatively constant for planets forming within 10 Ga of a supernova explosion, K enrichments may be more variable (Valencia et al., 2007).

Both conventional HZs and SSHZs are necessarily based on global average temperatures despite the potential for large regional variations and for habitable micro-habitats on broadly hostile planets (Nisbet et al. 2007). Deeper and shallower habitable regions can result from variations in connected pore space, nutrient and energy availability and heat flux, the latter expressing latitude, climate, composition, geodynamic processes, and impact events. On Mars, for example, localised convection cells may carry liquid water in aquifers several km above the background T_{min} isotherm (Travis et al., 2003), and seasonal surface features have been tentatively interpreted as briny flows (McEwen et al., 2011).

On Earth, the thick continental crust supports a gentler geothermal gradient than the thin basaltic oceanic crust. Our model predicts that Earth's biosphere should extend on average 2.8 km below the surface. This may be a reasonable average across Earth's two crustal types, although data for comparison are sparse. Prokaryotes have been found in the oceanic crust at 1.6 km depth and ~100 °C (Mason et al., 2010). On the continents, the three deepest boreholes searched for life (to the authors' knowledge) have yielded, respectively, living organisms at 3.6 km (48 °C) and 5.3 km (70 °C) and sterile waters at 4 km depth (110 °C) (Szewzyk et al., 1994; Borgonie et al., 2011; Huber et al., 1994). Substituting the higher conductivity of continental crust into our model predicts an average continental biosphere thickness of ~4 km.

We have not considered the effects of impurities (e.g. ammonia) and ultra-high pressures on the phase transitions of water. Lower values of T_{min} than 0 °C can be considered for impure water, raising the top of the habitable layer and expanding the SSHZ. Cell growth has been reported at −20 °C (Canganella and Wiegel, 2007); however, we regard liquid water as essential for habitability. The choice of 122 °C as T_{max} might be made obsolete by future studies of thermophiles. Raising T_{max} lowers the base of the habitable layer but does not affect SSHZ outer edge positions.

4. 2 Adaptation to icy bodies

Icy bodies are of particular interest because SSHZs extend much further than solar system frost lines, beyond which planetary bodies are volatile-rich. We note that our model for terrestrial planets could be adapted to find SSHZs for icy bodies by treating sub-ice oceans as habitable layers. For instance, treating Titan as a shell of pure water/ice around a heat-generating core (Grasset et al., 2000) and accounting for the pressure-dependent melting point and temperature-dependent thermal conductivity of water ice (Chizhov, 1993; Petrenko and Whitworth, 1999), we

obtain an ice thickness of ~85 km at Titan's present position and an SSHZ outer edge of ~1 AU for 10 km depth. A sophisticated treatment of the internal structure of icy bodies is beyond our purposes here but should take account of: (a) convection, and (b) the effects of clathrates, impurities (notably ammonia) and high-pressure ice phases on thermal conductivity and melting points. The forthcoming ESA JUICE mission should determine useful information about these parameters and direct measurements of ice-thickness for Ganymede, Europa and Callisto (Dougherty et al., 2011). However, it is doubtful whether circumstellar habitable zones are appropriate tools for locating habitable icy moons, whose dominant heat source may be tidal rather than solar energy.

4.3 Conclusions

The example of our own solar system suggests that most planets in the universe are beyond the outer edge of conventional surface habitable zones, although exoplanets closer to their stars are easier to detect. Moreover, surface habitability may commonly be precluded by ionizing solar and cosmic radiation, especially under thin atmospheres and weak geomagnetic fields; or by corrosive atmospheres, while the subsurface is insulated from these hazards by layers of rock (Fisk and Giovannoni, 1998; Dartnell et al., 2007). Besides a favourable temperature, pressure and radiation environment, life requires long-term nutrient and energy supplies. Subsurface environments in both rocky and icy bodies are likely to meet these requirements for at least low levels of biological activity while partially or even completely isolated from surface (Gaidos et al., 1999; Lin et al., 2006; Sleep, 2012). These considerations, together with our results, suggest that habitable environments may occur much more commonly deep within planets and moons than on their surfaces. Deeper biospheres are probably much less likely to produce planetary

biosignatures amenable to remote sensing, although potential search targets include atmospheric chemistry, cryovolcanic plume chemistry (McKay et al., 2008), and the compositions of hydrothermal and cryovolcanic surface residues. However, if life can originate in the subsurface of cold planets, then the probability of detecting a deep biosphere on a randomly selected terrestrial planet might be comparable to the probability of detecting a (more readily apparent but rarer) surface biosphere.

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FIGURE 1

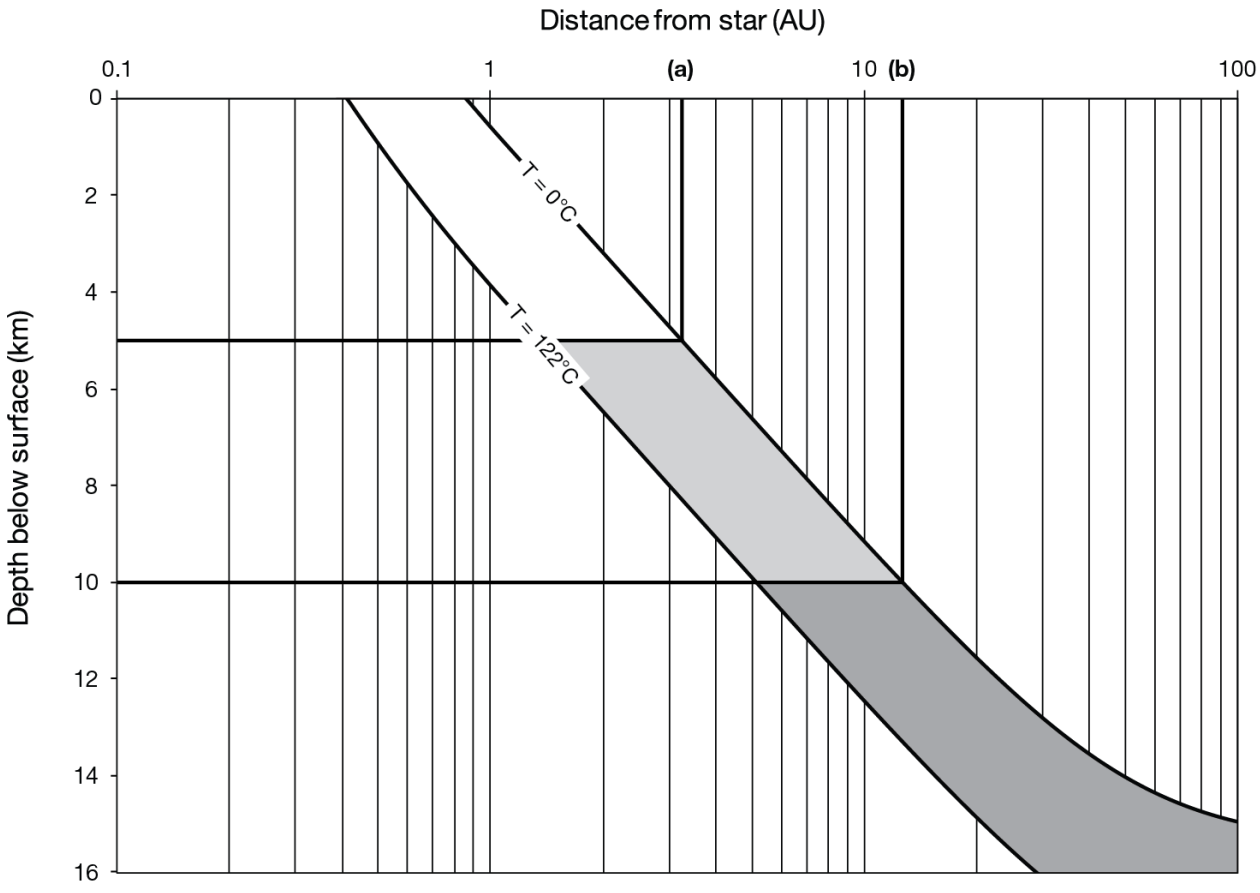


Figure 1. Circumstellar subsurface-habitability zones (SSHZ). Habitable layers and SSHZ outer edges for two values of z_{max}, a stipulated maximum habitable depth (where a planet within the SSHZ for $z_{max} = x$ can sustain liquid water at some depth $\leq x$). For z_{max} = 5 km, the outer edge of the SSHZ **(a)** falls at 3.2 AU; for z_{max} = 10 km, the outer edge **(b)** falls at 12.6 AU. The outer-edge position tends to infinity as z_{max} approaches about 15.42 km. Calculations assume the Earth's current size, bulk density, heat production per unit mass, albedo and emissivity.

FIGURE 2

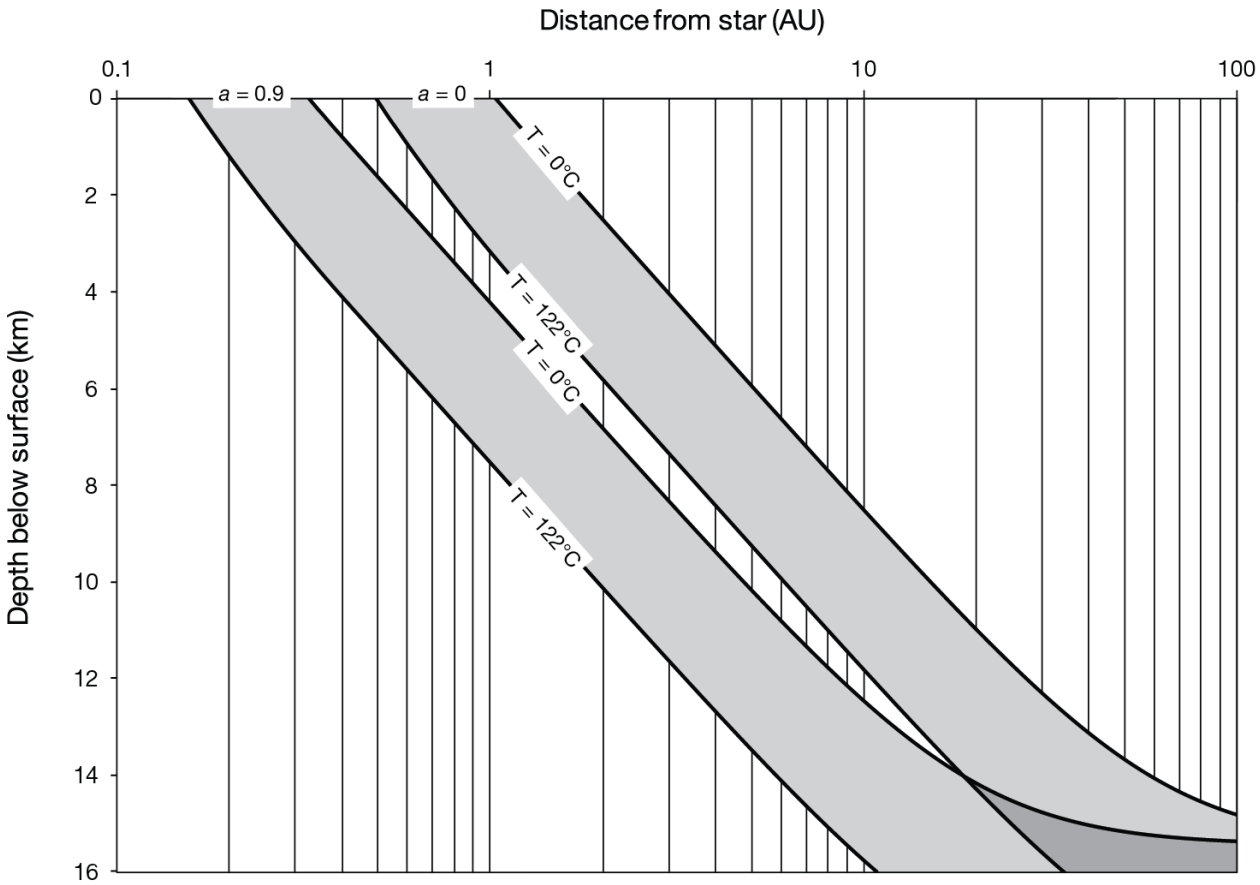


Figure 2. The relationship between subsurface habitability and surface albedo. Top Habitable-layer depth as a function of heliocentric distance for two extremes of planetary Bond albedo (*a*). For $a = 0.9$, the SSHZ is narrower and closer to the star than for $a = 0$. Calculations assume the Earth's current size, bulk density, heat production per unit mass and emissivity.

FIGURE 3

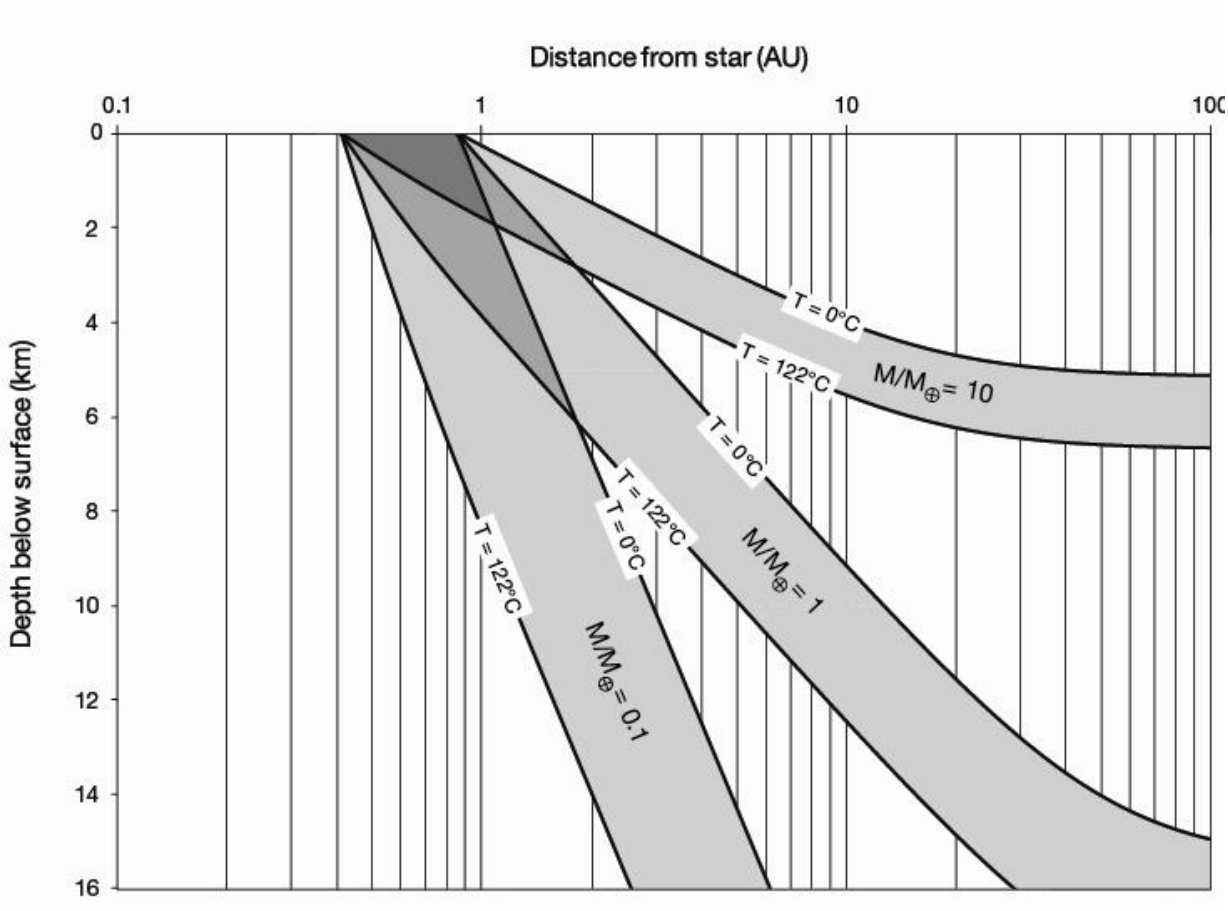


Figure 3. Habitable layers for three planetary masses. $M_{\oplus}$ = Earth-mass. The differences in internal heat production are insufficient to shift significantly the position of the surface HZ but become significant in the subsurface. Consequently, subsurface habitable layers are thinner, shallower and less sensitive to the solar heat flux for larger planets. Calculations assume the Earth's bulk density, heat production per unit mass, albedo and emissivity.

FIGURE 4

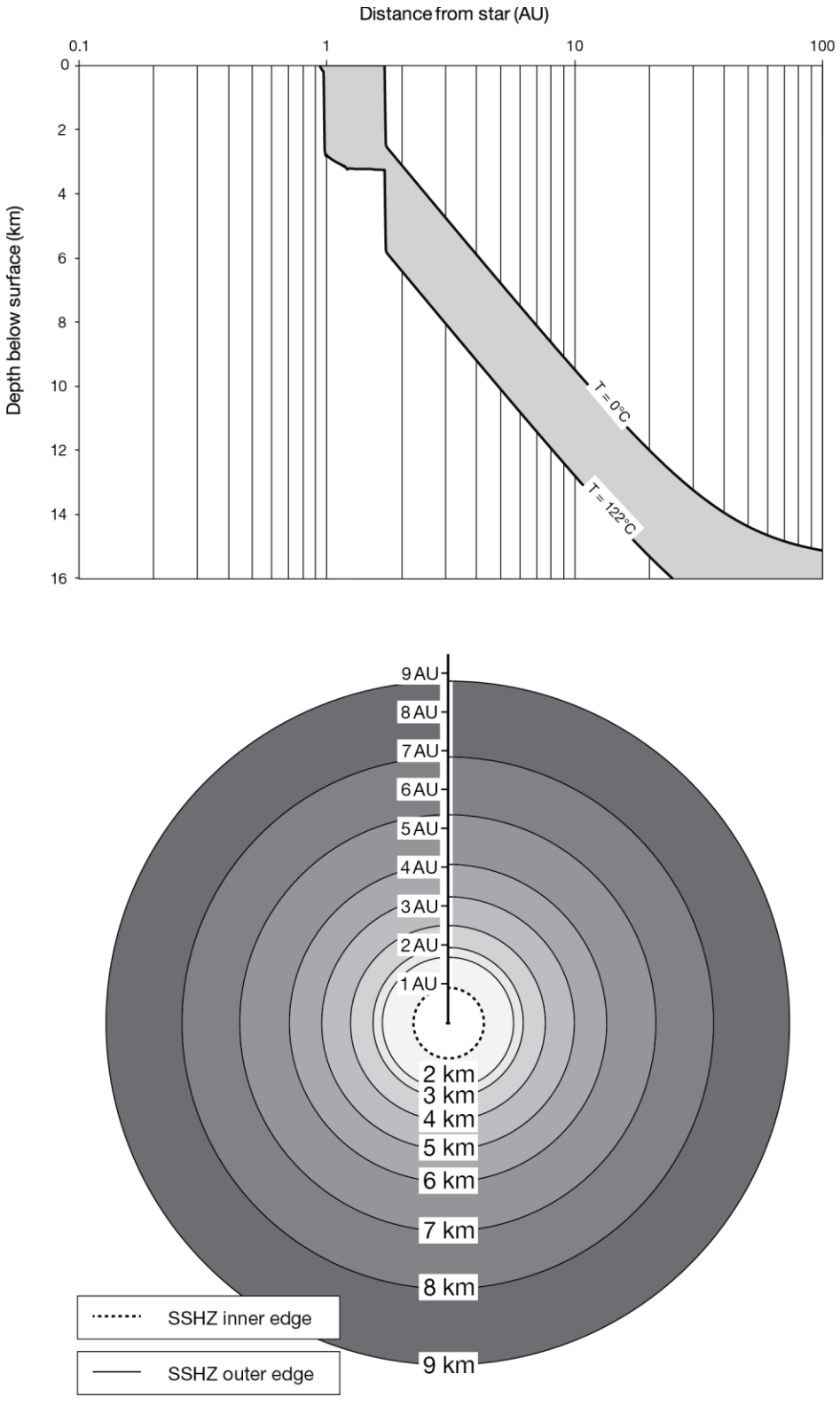

Distance from star (AU)
0.1
1
10
100
Depth below surface (km)
0
2
4
6
8
10
12
14
16
T = 0°C
T = 122°C
9 AU
8 AU
7 AU
6 AU
5 AU
4 AU
3 AU
2 AU
1 AU
2 km
3 km
4 km
5 km
6 km
7 km
8 km
9 km
SSHZ inner edge
SSHZ outer edge

Figure 4. Circumstellar subsurface-habitability zones (SSHZ) for a deep biosphere on an Earth-like planet. Top: The depth of a habitable layer on an Earth-like planet as a function of orbital distance. Sharp downward steps indicate greenhouse feedbacks in the atmosphere model. **Below:** The same model output represented as SSHZ outer edges in the first 10 AU at 1 km intervals of z_{max}, the maximum habitable depth (where a planet within the SSHZ for $z_{max} = x$ can sustain liquid water at some depth $\leq x$). Calculations assume the Earth's current size, bulk density and heat production per unit mass, so should be regarded as illustrative.

TABLE 1

Estimated circumstellar subsurface-habitability zone (SSHZ) outer edges for selected planetary bodies. SSHZ outer edges are shown for an appropriate range of maximum habitable depths, z_{max} (such that any planet within a SSHZ for $z_{max} = x$ can sustain liquid water at some depth $\leq x$). Subscript $\oplus$ denotes Earth. Orbital distances are semi-major axes. M = mass. ρ = density. a = albedo. T_s = surface temperature. * = at semi-major axis orbital distance. Gliese 581 g is unconfirmed. † = minimum mass. Calculations for Earth and exoplanets use Earth's bulk density and an Earth-like atmosphere model; all calculations use Earth's heat production per unit mass.

Planetary body					**Model results**					
Terrestrial planet	Orbital distance (AU)	—	—	a	T_s* (°C)	Habitable layer top (km)*	SSHZ outer edge (AU) for z_{max} =			
							4 km	8 km	16 km	32 km
Earth	1	1	1	N/A	+15	0	2.5	7.3	∞	∞
Mars	1.5	0.1	0.7	0.25	−62	5.3	1.3	2.0	4.5	23
Mars (10% salinity)	1.5	0.1	0.7	0.25	−62	4.5	1.4	2.2	4.9	25
Exoplanet	Stellar luminosity / Solar	Orbital distance (AU)		—	T_s* (°C)	Habitable layer top (km)*	SSHZ outer edge (AU) for z_{max} =			
							1 km	2 km	4 km	8 km
Gliese 581 d	0.013	0.218		5.6	−84	1.6	0.17	0.27	0.64	∞
Gliese 581 g (U)	0.013	0.140		3.1	−11	0.21	0.16	0.23	0.46	2.4
HD 85512 b	0.126	0.26		3.6	+181	N/A	0.49	0.71	1.5	10.7
Gliese 667 Cc	0.0137	0.123		4.5	+75	0	0.18	0.25	0.57	∞

Figure 1

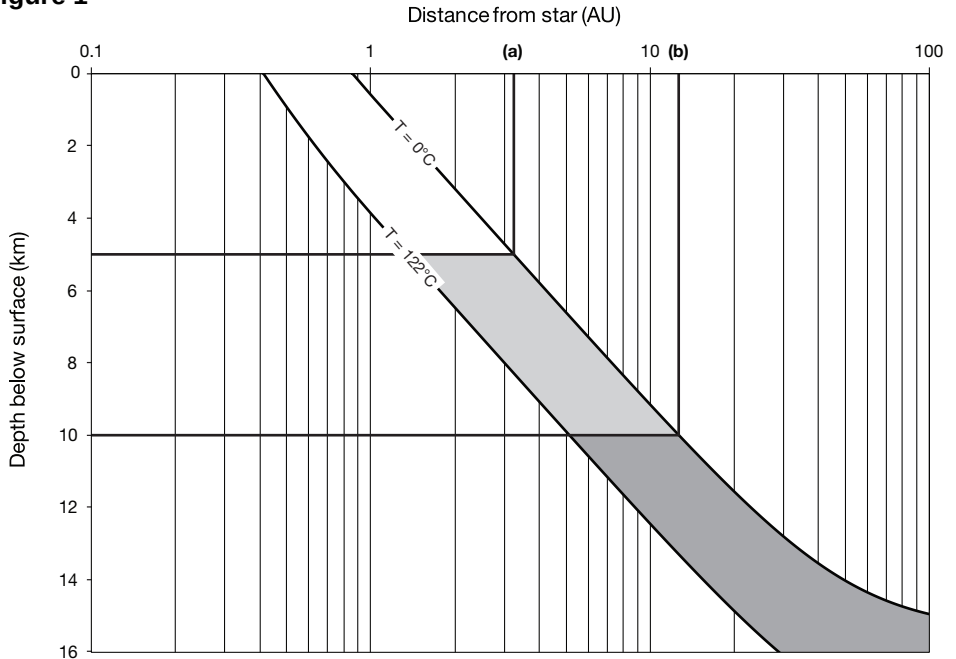

Distance from star (AU)
0.1
1
(a)
10
(b)
100
0
2
4
6
8
10
12
14
16
Depth below surface (km)
T = 0°C
T = 122°C

Figure 2

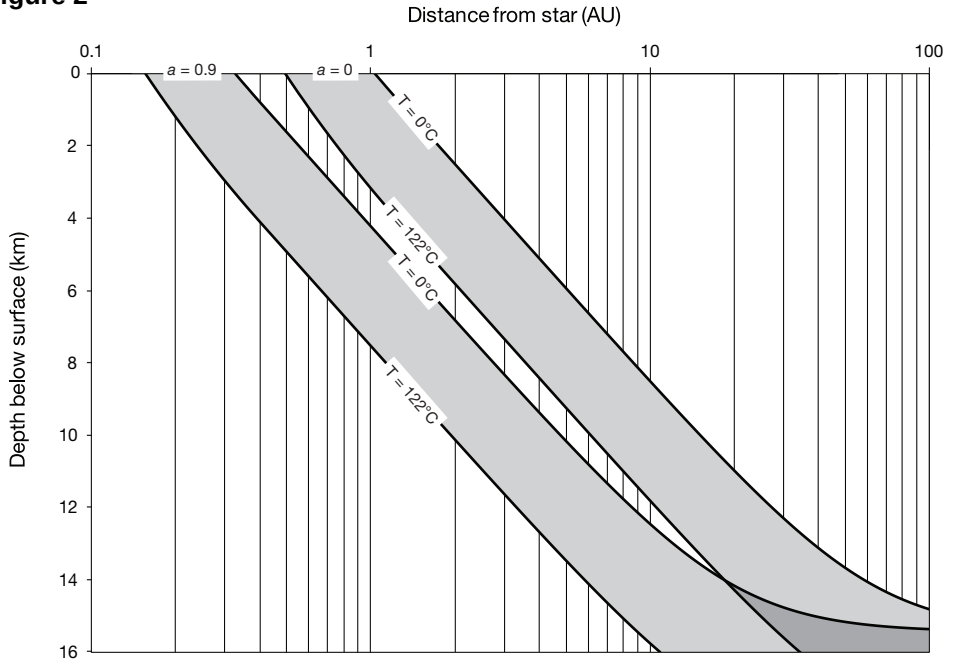

Distance from star (AU)
0.1
1
10
100
Depth below surface (km)
0
2
4
6
8
10
12
14
16
a = 0.9
a = 0
T = 0°C
T = 122°C
T = 0°C
T = 122°C

Figure 3

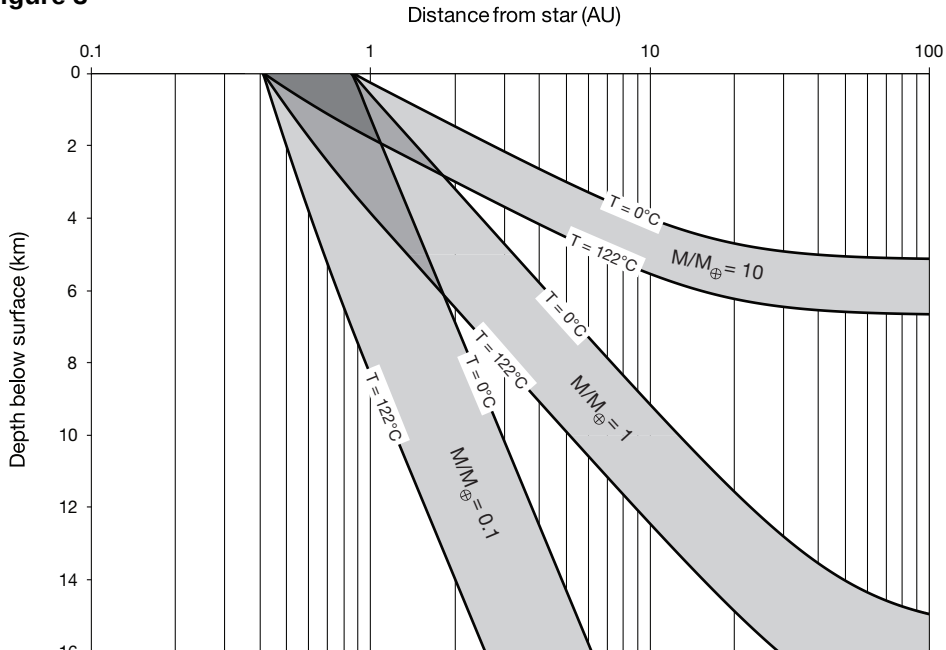
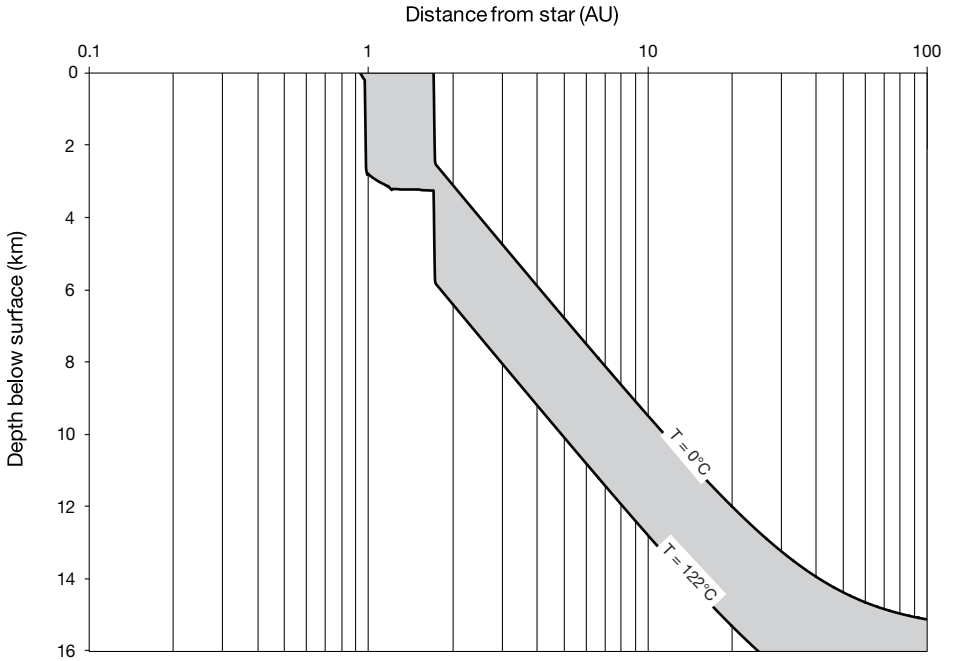
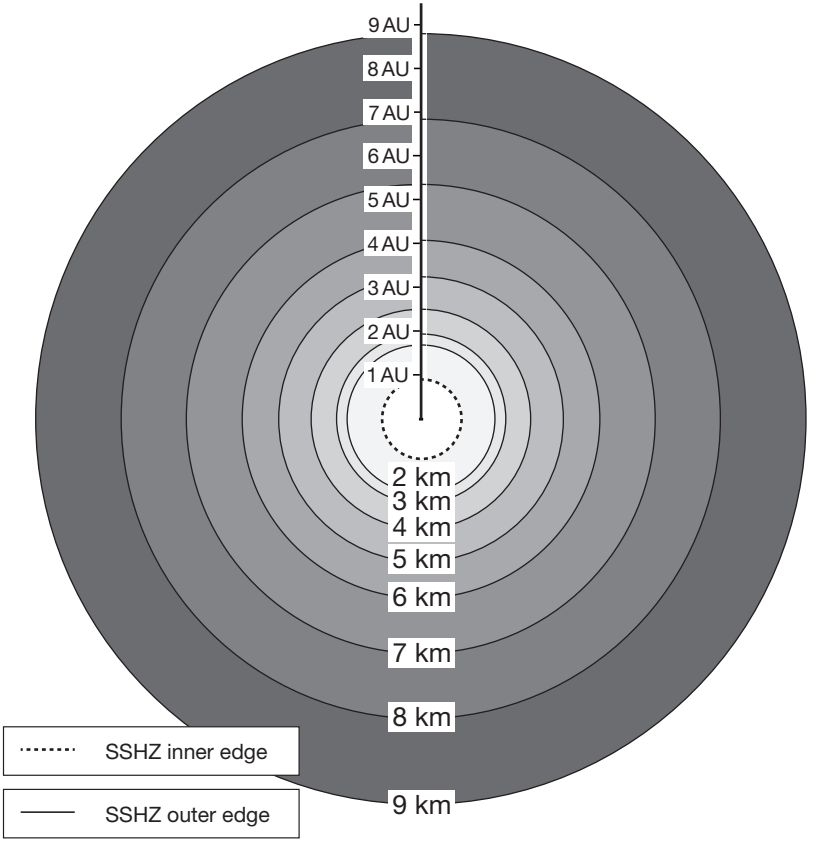

Distance from star (AU)
0.1
1
10
100
Depth below surface (km)
0
2
4
6
8
10
12
14
16
T = 0°C
T = 122°C
M/M⊕ = 10
T = 0°C
T = 122°C
M/M⊕ = 1
T = 0°C
T = 122°C
M/M⊕ = 0.1

Figure 4


Distance from star (AU)
0.1
1
10
100
0
2
4
6
8
10
12
14
16
Depth below surface (km)
T = 0°C
T = 122°C


9 AU
8 AU
7 AU
6 AU
5 AU
4 AU
3 AU
2 AU
1 AU
2 km
3 km
4 km
5 km
6 km
7 km
8 km
9 km
SSHZ inner edge
SSHZ outer edge