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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.

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 10 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,

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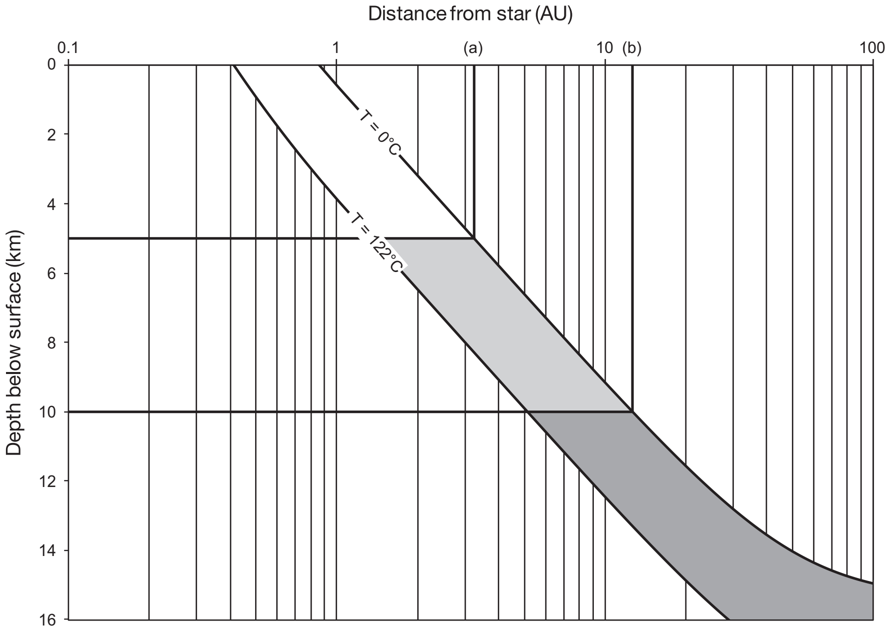

Fig. 1. Circumstellar subsurface-habitability zones (SSHZ). Habitable layers and SSHZ outer edges for two values of z_{max}, a stipulated maximum habitable depth (where a planet within the SSHZ for $z_{max}=x$ can sustain liquid water at some depth $\leq x$). For $z_{max}=5$ km, the outer edge of the 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 15.4 km. Calculations assume the Earth's current size, bulk density, heat production per unit mass, albedo and emissivity.

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} (Fig. 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:

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

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_{CO2} and τ_{H2O} are given by $0.029 \times \rho_{CO2}T$ and $0.087 \times \rho_{H2O}T$ respectively, where ρ_i is the partial pressure of gas i in the atmosphere, which is itself a function of temperature:

$$\rho_i = \frac{n_i RT}{N_A} \tag{2}$$

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