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THE STEPPENWOLF: A PROPOSAL FOR A HABITABLE PLANET IN INTERSTELLAR SPACE

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ABSTRACT

Rogue planets have been ejected from their planetary system. We investigate the possibility that a rogue planet could maintain a liquid ocean under layers of thermally insulating water ice and frozen gas as a result of geothermal heat flux. We find that a rogue planet of Earth-like composition and age could maintain a subglacial liquid ocean if it were ≈3.5 times more massive than Earth, corresponding to ≈8 km of ice. Suppression of the melting point by contaminants, a layer of frozen gas, or a larger complement of water could significantly reduce the planetary mass that is required to maintain a liquid ocean. Such a planet could be detected from reflected solar radiation, and its thermal emission could be characterized in the far-IR if it were to pass within $\mathcal{O}(1000)$ AU of Earth.

Key words: astrobiology – conduction – convection – planetary systems – planets and satellites: surfaces

1. INTRODUCTION

As a planetary system forms, some planets or planetesimals, referred to as "rogue" planets, can enter hyperbolic orbits and be ejected from the system as a result of gravitational interactions with gas giant planets (Lissauer 1987). Furthermore, interaction with passing stars can eject planets from mature systems (Laughlin & Adams 2000). The ability of a rogue planet to support life is of interest as a sort of pathological example of planetary habitability, because such a planet could potentially represent a viable option for interstellar panspermia (Durand-Manterola 2010), and because such a planet could be the closest source of extrasolar life for exploration by humanity in the distant future. Since some sort of starting point is required to discuss the issue, a planet is often defined as habitable if it can sustain liquid water at its surface (Kasting et al. 1993). Stevenson (1999) argued that if a rogue planet had an extremely high-pressure hydrogen atmosphere, pressure broadening of far-infrared absorption by molecular hydrogen could support liquid water on the planet's surface as a result of the geothermal heat flux alone, making the planet potentially habitable. Debes & Sigurdsson (2007) showed that terrestrial planets can be ejected with moons and that the resulting tidal dissipation could increase the geothermal heat flux by up to two orders of magnitude for $\mathcal{O}(10^8$ yr).

Subglacial liquid water oceans sustained by internal heat flux on icy bodies represent an alternative type of habitat. It is well known that subglacial oceans are possible on moons around giant planets and on trans-Neptunian objects in the solar system (Hussmann et al. 2006), as well as water-rich exoplanets in distant orbits (Ehrenreich et al. 2006; Fu et al. 2010). A possible terrestrial analog is Lake Vostok, a ≈125 m deep lake which is sustained by geothermal heat flux under ≈4 km of ice on Antarctica (Kapitsa et al. 1996). Laughlin & Adams (2000) have even argued that a terrestrial rogue planet, not attached to any star and receiving negligible energy at its surface, could sustain a subglacial liquid ocean if it had a thick enough ice layer. We wish to consider this point in more depth, including issues such as the potential for solid-state convection of ice, the potential effect of a thermally insulating frozen gas layer from outgassing of the mantle on an Earth-like rogue planet, the effects of melting point suppression due to contaminants, and observational prospects. By Earth-like, we mean specifically within an order of magnitude in mass and water complement, similar in composition of radionuclides in the mantle, and of similar age. A subglacial ocean on a rogue planet is interesting because it could serve as a habitat for life which could, for example, survive by exploiting chemical energy of rock that is continually exposed by an active mantle. We will refer to a rogue planet harboring a subglacial ocean as a Steppenwolf planet, since any life in this strange habitat would exist like a lone wolf wandering the galactic steppe.

We can imagine that the ice layer on top of an ocean on a Steppenwolf planet will grow until either it reaches a steady state with the ice bottom at the melting point, or all available water freezes. Geothermal heat from the interior of the Steppenwolf planet will be carried through the ice layer by conduction, and potentially by convection in the lower, warmer, and less viscous portion of the ice layer. Since convection transports heat much more efficiently than conduction, the steady-state ice thickness will be much larger if convection occurs, making it harder to maintain a subglacial ocean.

Here we will calculate steady-state ice thicknesses when there is conduction only and when there is convection in the lower portion of the ice, and make the conservative assumption that the thicker solution is valid. We must acknowledge, however, that it is very difficult to establish definitively whether convection would occur, and the resulting ice thickness if it were to occur, without detailed knowledge of conditions in and microscale composition of the ice (Barr & Showman 2009). More generally, we will make many simplifications, including considering the question within the framework of a one-dimensional (vertical) model, since our primary objective is to establish whether or not a Steppenwolf planet is feasible.

2. GEOPHYSICAL CONSIDERATIONS

First we calculate the conductive steady-state thickness, H_{cond}. Above ≈10 K, the temperature dependence of the thermal conductivity of water ice is well approximated by $k(T) = AT^{-1}$, where T is the temperature in Kelvin and $A = 651$ W m^{-1} (Petrenko & Whitworth 2002). Dimensional analysis shows that thermal steady state is reached in $\sim 10^6$ years, much shorter than the timescale of decay of the geothermal heat flux. Geothermal heat flux through the shell will be constant at steady state, since no heat is produced within the ice, as would occur by tidal heating of a frozen moon. Since the Steppenwolf planets we consider would be much larger and drier than the icy moons on which subglacial oceans are typically studied, we can assume that the ice thickness is much less than the planetary radius, yielding an exponential temperature profile through the ice and steady-state thickness, so that

$$H_{\mathrm{cond}} = \frac{A}{F} \log\left(\frac{T_H}{T_0}\right), \tag{1}$$

where T_H is the temperature at the ice–water interface (the melting temperature), T_0 is the temperature at the top of the ice, and F is the geothermal heat flux.

Decay of radioactive elements in Earth's interior and primordial heat remaining from Earth's formation lead to an average geothermal heat flux emanating from Earth's surface of $F_\oplus = 0.087$ W m^{-2} (Pollack et al. 1993). This heat flux decays with time such that Earth's geothermal heat flux may have been roughly twice its present value 3 Gyr ago (Turcotte 1980). In order to consider Steppenwolf planets of different sizes, we use the radius–mass scaling $R \propto M^v$ for super-Earths with $v = 0.27$ (Valencia et al. 2006). Heuristically, this yields a geothermal heat flux that scales as $(M/M_\oplus)^{1-2v}$, or roughly as the square root of the mass.

The pressure at the bottom of the ice layer is $\approx$9 MPa for each kilometer of ice, scaling with mass as $(M/M_\oplus)^{1-2v}$. The melting point of pure ice is 250–270 K at pressures less than 620 MPa (Choukroun & Grasset 2007), although contaminants to pure ice such as chloride salts or ammonia could suppress the melting point by $\approx$50–100 K (Kargel 1991, 1992; Fortes & Choukroun 2010; Grasset & Sotin 1996). The steady-state thickness in the conductive regime is only logarithmically sensitive to T_H, so we will take $T_H = 260$ K in the estimates here, except that we will consider the eutectic point of an ammonia-water ice mixture at 176 K to demonstrate the impact of contaminants. In steady state, the temperature at the surface of a Steppenwolf planet (T_s), i.e., the top of the ice or frozen gas layer, will be set by a balance between thermal emission and geothermal heat flux, $F = \sigma T_s^4$, where σ is the Stefan–Boltzmann constant. Astrophysical radiation backgrounds (Mathis et al. 1983; Dole et al. 2006) are negligible.

Any gas present in the atmosphere at planetary ejection or outgassed subsequently by geological processes will tend to freeze into a low-thermal-conductivity blanket that could allow T_0 to exceed T_s. A blanket formed by freezing Earth's current atmosphere would only increase T_0 by about 4 K (Laughlin & Adams 2000). Isostatic adjustment (Fowler 1990), however, will tend to cause some continents or islands to rise above the layers of water and ice on an Earth-like Steppenwolf planet with an active mantle, allowing volcanoes to continuously emit gasses that can freeze onto the water-ice surface. Here, we will consider carbon dioxide because it is likely to be outgassed in significant quantities from an Earth-like planet and it supports a stable layer with relatively high base temperature relative to other common gases. To find an upper bound on the impact of a frozen gas layer, we will assume that the layer is Rayleigh–Taylor stable with respect to the underlying water ice, so it remains as a surface blanket.

To find the temperature at the carbon-dioxide layer base, we note that the thermal conductivity of carbon dioxide again scales as T^{-1} (here, in a more limited regime), but with constant of proportionality $A \approx 100$ W m^{-1} (Sumarokov et al. 2003). We find that the maximum temperature supported is robustly $\approx$220 K for Earth-like Steppenwolf planets and is determined by the weak temperature dependence of the melting curve (Giordano et al. 2006). Setting $T_0 = 220$ K reduces the required steady-state water-ice thickness by an order of magnitude.

At Earth mass, the temperature at the bottom of a layer of solid CO_2 reaches the melting temperature of CO_2 for a layer thickness of $\approx$2 km, or $\approx 3 \times 10^6$ kg m^{-2}. Venus' atmosphere has a partial pressure of CO_2 of $\approx$90 bar ($\approx 10^6$ kg m^{-2}), which is roughly the vapor pressure of carbonate rocks at Venus' surface temperature, implying that there may be more carbon locked in rock in equilibrium with the atmosphere (Pierrehumbert 2010). The store of carbon in carbonate rocks in Earth's interior is uncertain, but the continental crust is estimated to contain the equivalent of $\approx 7 \times 10^5$ kg m^{-2} CO_2 and the mantle may contain 2–4 times this amount (Zhang & Zindler 1993). Therefore, it appears reasonable to assume that a Steppenwolf planet could have a sufficient complement of CO_2 to significantly elevate T_0.

Since the viscosity of ice depends strongly on temperature (Barr & Showman 2009), if ice convection were to occur on a Steppenwolf planet, it would occur only in the lower, warmer ice regions and would be capped by a "stagnant" conducting lid (Solomatov 1995). We calculate the steady-state ice thickness when convection occurs following Hussmann et al. (2006), who assume a Newtonian rheology. We outline the solution here, but the reader should consult Hussmann et al. (2006) for more detail. We assume that convection occurs below temperature T_c (at higher temperature) and determine T_c by assuming that the viscosity is reduced by a factor $\gamma = 10$ over the convecting region, where the viscosity is given by the relation, $\eta(T) = \eta_0 \exp[l(T_m/T - 1)]$, where $\eta_0 = 10^{13}$ Pa s, T_m is the melting temperature, and $l = 25$. Assuming that $T_m = T_H$, we can solve for T_c. A Nusselt–Rayleigh number scaling (Nu $= a\mathrm{Ra}^\beta$) yields the thickness of the convecting region between temperature T_c and T_H,

$$H_{\mathrm{conv}}^{1-3\beta} = \frac{ak(T_H - T_c)}{F}\left[\frac{g\alpha\rho(T_H - T_c)}{\kappa\eta(\bar{T})}\right]^\beta, \tag{2}$$

where we evaluate the viscosity at the mean temperature of the convecting layer, $\bar{T} = \frac{1}{2}(T_c + T_H)$, $\kappa = 1.47 \times 10^{-6}$ m^2 s^{-1}, $\alpha = 1.56 \times 10^{-4}$ K^{-1}, $\rho = 917$ kg m^{-3}, $k = 3.3$ W m^{-1} K^{-1}, $a = 0.12$, and $\beta = 0.3$. Taking k to be constant in the convecting layer is a reasonable assumption given that the temperature is nearly constant within it. We add the thickness of the convective layer given by Equation (2) to the thickness of the stagnant lid, $H_{\mathrm{lid}} = \frac{A}{F}\log\left(\frac{T_c}{T_0}\right)$, to find the total ice thickness when there is convection. When the total thickness with convection exceeds the conductive thickness given by Equation (1), we use it for the ice thickness. This corresponds to a critical Rayleigh number of roughly 1000 within the convecting layer.

Given that the ice composition on a Steppenwolf planet is unknown and the ice material properties under appropriate conditions are poorly constrained, our convective calculation should be viewed as a rough estimate. For example, following Hussmann et al. (2006) and Fu et al. (2010), we have assumed Newtonian ice flow, which may or may not be realistic (Barr & Showman 2009). Creep mechanisms with stress-dependent viscosity, however, should yield results roughly similar to Newtonian flow (Kirk & Stevenson 1987). Another source of uncertainty is the appropriate ice grain size, the typical size of individual components of polycrystalline ice. In general, larger grain sizes correspond to higher viscosities, making convection

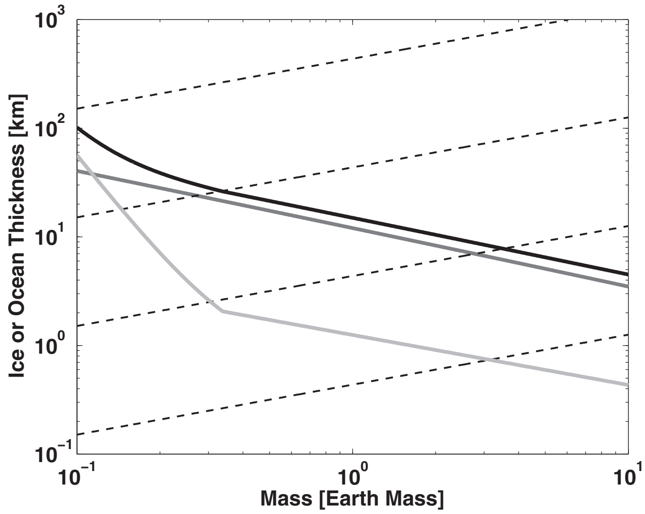

Figure 1. Ice thickness that is required to support liquid water at its base as a function of planetary mass, assuming: (1) solid black: a melting point of 260 K and surface temperature required to radiate the geothermal heat flux in steady state, (2) dark solid gray: a melting point of 176 K at the eutectic mixture of water ammonia (Grasset & Sotin 1996) and surface temperature required to radiate the geothermal heat flux in steady state, and (3) light solid gray: a melting point of 260 K and water-ice top temperature along the melt curve of carbon dioxide at ≈220 K (providing an upper bound on the possible impact of an insulating carbon-dioxide layer). The ice thickness is calculated using the conductive (Equation (1)) or stagnant-lid convective (Equation (2)) solution, as appropriate. Convection increases the required thickness at low mass, and follows the method in Hussmann et al. (2006). In the case where ammonia has suppressed the melting point by nearly 100 K, we find a modest change in the conductive regime, but that convection is suppressed (at fixed water-ice rheology). The dashed black lines show the adjusted ocean depth (ocean depth multiplied by the ratio of the density of water to that of ice) as a function of planetary mass using the simple scaling $M^{1-2\nu}$ for water complements that are 0.1 (lowest line), 1, 10, and 100 (highest line) times that of Earth, which is taken to be 4 km at $1M_\oplus$. A subglacial liquid ocean is possible when the adjusted ocean depth exceeds the ice thickness.

less likely. The value of, η_0 that we have used, 10^{13} Pa s corresponds to an ice grain size of ≈0.1 mm (Barr & Showman 2009). For reference, the typical ice grain size on terrestrial ice sheets is 0.1–10 mm (Barr & Showman 2009) and Fu et al. (2010) assume an ice grain size of 0.2 mm for their calculations of convection on icy extrasolar planets. Competing estimates of ice grain size on Europa, however, place it at either 0.02–0.06 mm or >40 mm (Barr & Showman 2009). Although the appropriate ice grain size on a Steppenwolf planet is a source of uncertainty, we have used a relatively small value, which is conservative in that it makes convection more likely to occur. Finally, the constant β can take different values between 0.25–0.33 depending on the geometry and boundary conditions (Hussmann et al. 2006). We have used a fairly high value of β, which leads to a conservatively strong scaling of H_{conv} with M.

A Steppenwolf planet with mean ocean depth greater than the steady-state ice thickness, accounting for the ice-water density difference, will have an ocean under its ice layer. Figure 1 shows the required ice thickness to achieve liquid water in several scenarios. It is expected that the abundance of water on planetary surfaces varies greatly (Raymond et al. 2007), but we can consider a simple scaling to understand how the conditions for liquid water scale with planet mass and water complement. At fixed planetary water mass fraction and fraction of water at the surface (rather than in the mantle), the depth of the ocean scales approximately as the typical depth at Earth mass (D^*) times $(M/M_\oplus)^{1-2\nu}$. Figure 1 shows contours for planets with water complements that are 0.1, 1, 10, and 100 times that of Earth. Combining this scaling with Equations (1) and (2), we find that if a Steppenwolf planet is similar to Earth in water mass fraction ($D^* = D_\oplus \approx 4$ km), radionuclide composition, age, and has no frozen CO_2 layer, it must be ≈3.5 times more massive than Earth to sustain a subglacial liquid ocean. Contaminants which suppress the melting point have little effect on the conductive ice thickness, but significantly reduce the ability of the ice to convect. If a Steppenwolf planet has ten times more water ($D^* = 10D_\oplus$) than Earth or if it has a thick frozen CO_2 layer which reaches the maximum temperature of ≈220 K at its base, the planet must be only ≈0.3 times Earth's mass to have a liquid ocean.

3. OBSERVATIONAL PROSPECTS

We expect that detection of reflected sunlight in the optical wavebands and IR follow-up present the only viable observational choice in the near term. For a single-visit limiting magnitude $r \approx 24.7$ of LSST (Jones et al. 2009; and comparable $r = 24$ in the nearer-term Pan-STARRS; Jewitt 2003) and albedo of 0.5, the limiting distance out to which an object can be detected with reflected sunlight is $\approx 830(r/R_\oplus)^{1/2}$ AU. The Palomar survey of ∼12,000 $\deg^2$ to magnitude 21.3 (Schwamb et al. 2009) has discovered no such objects outside of the smaller trans-Neptunians such as Sedna.

The baseline requirement to identify a Steppenwolf planet is a detection of thermal emission in the far-IR. The flux at the Wien maximum is

$$S_{\max} = (108\,\text{mJy}) \cdot \left(\frac{T_s}{1\text{K}}\right)^3 \left(\frac{R}{R_\oplus}\right)^2 \left(\frac{d}{1\text{AU}}\right)^{-2}, \qquad (3)$$

where d is the Earth–object separation. At 10 $M_\oplus$, $T_s = 46$ K so that $\lambda_{\max} = 110\,\mu$m. Here, the *Herschel* PACS instrument reaches a 40 beams/source confusion limit at a flux of ≈2 mJy (Berta et al. (2010), suggesting a limiting distance of ≈4000 AU; PACS reaches 10 mJy at 5σ in 1 hr (Poglitsch et al. 2010)). Higher resolution is required to progress to lower flux limits. At 200 μm, the planned 25 m Cornell-Caltech Atacama Telescope (CCAT) would reach the source confusion limit[4] at 0.36 mJy.

Photometric microlensing has also been proposed as a method to detect rogue planets throughout the galaxy (Han et al. 2004). If each stellar system ejects one $M_\oplus$ planet, a survey like the Galactic Exoplanet Survey Telescope could anticipate ∼20 detections of rogue planets (Bennett & Rhie 2002; Bennett et al. 2010). Typical distances to these objects would exceed the capabilities of follow-up that could elucidate their nature. Free-floating super-Jupiters have been discovered (Bihain et al. 2009), but these represent a different class of objects.

4. DISCUSSION AND CONCLUSION

A Steppenwolf planet's lifetime will be limited by the decay of the geothermal heat flux, which is determined by the half-life of its stock of radioisotopes (^{40}K, ^{238}U, ^{232}Th) and by the decay of its heat of formation. As these decay times are ∼1–5 Gyr, its lifetime is comparable to planets in the traditional habitable zone of main-sequence stars (Kasting et al. 1993).

If a Steppenwolf planet harbors life, it could have originated in a more benign era before ejection from the host star. Alternatively, after ejection, life could originate around hydrothermal vents, which are a proposed location for the origin of life on

[4] http://www.submm.org/doc/2006-01-ccat-feasibility.pdf, at 30 beams/source.

Earth (Baross & Hoffman 1985). If life can originate and survive on a Steppenwolf planet, it must be truly ubiquitous in the universe.

We have shown that an Earth-like rogue planet drifting through interstellar space could harbor a subglacial liquid ocean despite its low emission temperature, and so might be considered habitable. Such an object could be detected and followed up using current technology if it passed within $\mathcal{O}(1000\ \mathrm{AU})$ of Earth.

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