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 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 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 O(10^3) 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 steppes.

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 ~10^8 years, much shorter than the timescale of decay of the geothermal heat flux. Geothermal
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 \( T_s \) (at higher temperature) and determine \( T_s \) by assuming that the viscosity is reduced by a factor \( \gamma = 10 \) over the convecting region, where the viscosity is given by the relation, \( \eta(T) = \eta_0 \exp[(T_m/T - 1)] \), where \( \eta_0 = 10^{13} \) Pa s, \( T_m \) is the melting temperature, and \( j = 25 \). Assuming that \( T_m = T_H \), we can solve for \( T_s \). A Nusselt–Rayleigh number scaling (\( Nu = a Ra^{\frac{1}{5}} \)) yields the thickness of the convecting region between temperature \( T_s \) and \( T_H \),

\[
H_{\text{conv}}^{1 - 3\beta} = \frac{a k (T_H - T_s)}{F} \left[ \frac{\rho g \alpha \rho (T_H - T_s)}{\kappa \eta(T)} \right]^{\gamma},
\]

where we evaluate the viscosity at the mean temperature of the convecting layer, \( T = \frac{1}{2}(T_s + T_H) \), \( \kappa = 1.47 \times 10^{-6} \) 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,

\[
H_{\text{lid}} = \frac{a}{F} \log \left( \frac{T_s}{T_H} \right),
\]

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
Combining this scaling with Equations (1) and (2), we find that if a Steppenwolf planet is similar to Earth in water mass fraction ($D^* = D_0 \approx 4$ km), radionuclide composition, age, and has no frozen CO$_2$ layer, it must be 3.5 times more massive than Earth to sustain a glacial 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 ($D^* = 10D_0$) 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 $7800(r/R_0)^{1/2}$ AU. The Palomar survey of $\sim 12,000$ 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

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

where $d$ is the Earth–object separation. At 10 $M_\oplus$, $T_s = 46$ K so that $S_{\text{max}} = 110$ mJy. 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 5$\sigma$ in 1 hr (Poglitsch et al. 2010). Higher resolution is required to progress to lower flux limits. At 200 $\mu$m, the planned 25 m Cornell-Caltech Atacama Telescope (CCAT) would reach the source confusion limit 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 (40K, 238U, 232Th) 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
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 $O(1000 \text{ AU})$ of Earth.

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REFERENCES

Baross, J. A., & Hoffman, S. E. 1985, Orig. Life Evol. Biosph., 15, 327
Barc, A. C., & Showman, A. P. 2009, in Europa, Heat Transfer in Europa’s Icy Shell, ed. R. T. Pappalardo, W. B. McKinnon, & K. Khurana (Tucson, AZ: Univ. Arizona Press), 405
Bennett, D. P., & Rhie, S. H. 2002, ApJ, 574, 985
Bennett, D. P., et al. 2010, arXiv:1012.4486
Berta, S., et al. 2010, A&A, 518, L30
Bihain, G., et al. 2009, A&A, 506, 1169
Choukroun, M., & Grasset, O. 2007, J. Chem. Phys., 127, 124506
Debes, J. H., & Sigurdsson, S. 2007, ApJ, 668, L167
Dole, H., et al. 2006, A&A, 451, 417
Durand-Manterola, H. J. 2010, arXiv:1010.2735
Ehrenreich, D., Lecavelier des Etangs, A., Beaulieu, J., & Grasset, O. 2006, ApJ, 651, 535
Fortes, A. D., & Choukroun, M. 2010, Space Sci. Rev., 153, 185
Fowler, C. M. R. 1990, The Solid Earth: An Introduction to Global Geophysics (Cambridge: Cambridge Univ. Press)
Fu, R., O’Connell, R. J., & Sasselov, D. D. 2010, ApJ, 708, 1326
Giordano, V. M., Datchi, F., & Dewaele, A. 2006, J. Chem. Phys., 125, 054504
Grasset, O., & Sotin, C. 1996, Icarus, 123, 101
Han, C., Chung, S., Kim, D., Park, B., Ryu, Y., Kang, S., & Lee, D. W. 2004, ApJ, 604, 372
Hussmann, H., Sohl, F., & Spohn, T. 2006, Icarus, 185, 258
Jewitt, D. 2003, Earth Moon Planets, 92, 465
Jones, R. L., et al. 2009, Earth Moon Planets, 105, 101
Kapitsa, A., Ridley, J., Robin, G., Siegert, M., & Zotikov, I. 1996, Nature, 381, 684
Kargel, J. 1991, Icarus, 94, 368
Kargel, J. 1992, Icarus, 100, 556
Kasting, J. F., Whitmire, D. P., & Reynolds, R. T. 1993, Icarus, 101, 108
Kirk, R., & Stevenson, D. 1987, Icarus, 69, 91
Laughlin, G., & Adams, F. 2000, Icarus, 145, 614
Lissauer, J. 1987, Icarus, 69, 249
Mathis, J., Mezger, P., & Panagia, N. 1983, A&A, 128, 212
Petenko, V. F., & Whitworth, R. W. 2002, Physics of Ice (Oxford: Oxford Univ. Press)
Pierrehumbert, R. T. 2010, Principles of Planetary Climate (Cambridge: Cambridge Univ. Press)
Poglitsch, A., et al. 2010, A&A, 518, L30
Pollack, H., Hurter, S., & Johnson, J. 1993, Rev. Geophys., 31, 267
Raymond, S. N., Scalzo, J., & Meadows, V. S. 2007, ApJ, 669, 606
Schwamb, M. E., Brown, M. E., & Rabinowitz, D. L. 2009, ApJ, 694, L45
Solomatov, V. 1995, Phys. Fluids, 7, 266
Stevenson, D. J. 1999, Nature, 400, 32
Sumarokov, V. V., Stachowiak, P., & Ježowski, A. 2003, Low Temp. Phys., 29, 449
Turcotte, D. 1980, Earth Planet. Sci. Lett., 48, 53
Valencia, D., O’Connell, R., & Sasselov, D. 2006, Icarus, 181, 545
Zhang, Y., & Zindler, A. 1993, Earth Planet. Sci. Lett., 117, 331