ON THE LIKELY PREVALENCE OF OCEAN-WORLDS IN M-DWARF SYSTEMS.

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Introduction: The habitability potential of planets in the circumstellar habitable zone (CHZ) of M-dwarf stars are of great interest because M-dwarf stars make up 75% of the population of stars in the galaxy, and >40% of M-dwarfs stars are expected to harbor Earth-sized planets (exo-Earths) in their CHZ [2, 3]. However, key differences between the stellar and planetary environments between M-dwarf stars and the more luminous Sun-like stars have led to a long-standing debate around the habitability of M-dwarf orbiting exo-Earths [4]. In particular, the relatively higher X-ray/UV luminosity, and more frequent flaring of M-dwarfs vs Sun-like stars have presented concerns about the surface habitability of planets orbiting these stars. Even if the harsh effects of the M-dwarf stellar environment were absent, a significant fraction of the M-dwarf orbiting exo-Earths would still require substantial greenhouse warming for liquid water to be stable on the surface, given their relatively low equilibrium temperature [1]. Another notable, common feature of these planets is tidal locking, possibly leading to an eyeball-like climate state, where most of the planet is frozen, with the exception of the substellar point, where liquid water may exist [5].

In such cold, icy, rocky planets, basal melting may provide an alternative means of forming liquid water in a subsurface environment shielded from high-energy radiation. Basal melting is responsible for the formation of subglacial liquid water lakes in various areas of Earth [6]. Similarly, basal melting of thick ice deposits during the Noachian era [>4 Ga] has been proposed as a potential solution to reconciling fluvial feature generation with the faint young sun paradox on Mars [7-10]. As such, basal melting may play an equally important role in the habitability of cold, icy exo-Earths. Furthermore, due to the billion-year half-lives of the heat-producing elements responsible for planetary geothermal heat, meltwater created by basal melting may be sustained on exo-Earths for a prolonged period.

In this work, we present a summary of results from ref [1], where we model thermophysical evolution of ice sheets of various thicknesses and demonstrate that basal melting is likely prevalent on M-dwarf orbiting exo-Earths, even with modest, Moon-like geothermal heat flow. We show that thick subglacial oceans of liquid water can form and persist at the base of and within the ice sheets on exo-Earths for a prolonged period. Our findings suggest that exo-Earths resembling the snowball Earth or the icy moons of Jupiter and Saturn may be common in the Milky-way galaxy.

Results: We take a conservative approach and assume that the surface temperature (T_s) equals the estimated equilibrium-temperature for all exo-Earths considered in this study. Depth-dependent initial profiles of ice phases, density, specific heat, thermal conductivity, and melting temperature are estimated self-consistently and coupled with the thermal evolution model to explore the feasibility of basal melting, while accounting for the time-varying ice phase evolution of the thick ice cap (see [1]). An example of a thermal profile and the time-dependent phase evolution of a 2-km thick ice sheet on Proxima Centauri b, assuming a T_s of 257 K and a basal heat flux of 30 mW m^{-2}, is shown in Figure 1. In this scenario, basal melting occurs within a few hundred thousand years post-deposition of the ice resulting in approximately 800 m thick liquid water ocean at the ice-crust interface.

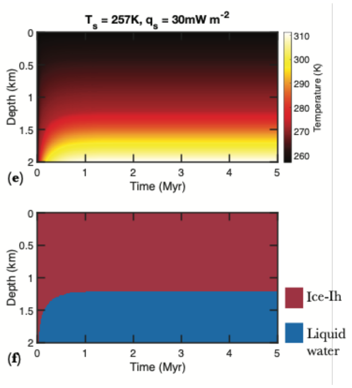

Figure 1. Temperature distribution and ice phase evolution as a function of depth and time on Proxima Centauri b assuming a 2 km thick ice sheet, T_s of 257 K, and heat flow of 30 mW m^{-2}.

The feasibility of basal melting is strongly dependent on T_s, with relatively low heat flow required for basal melting on planets with high T_s. Basal melting is also more likely to occur on planets with thicker ice sheets and higher surface gravity because the melting temperature of water-ice initially decreases with depth due to the pressure-reduced melting point of ice Ih. Figure 2 shows the heat flow required for basal melting as a function of T_s and surface gravity for ice sheets of various thickness. This figure demonstrate that basal melting is likely prevalent on M-dwarf orbiting exo-Earths, even with modest, Moon-like geothermal heat flow. While reasonable constraints on T_s of exo-Earths can be placed based on the estimated equilibrium-temperature, heat flow on exo-Earths is entirely

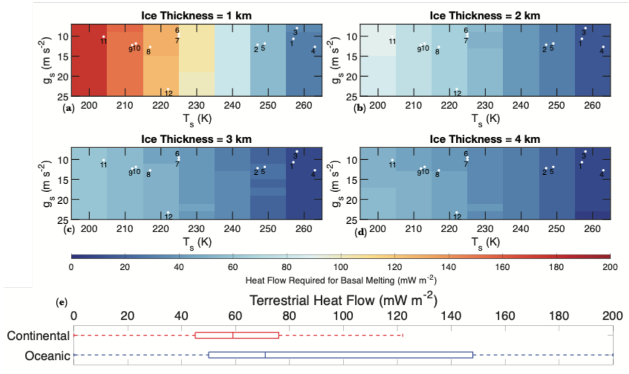

Figure 2. Heat flow required for basal melting as a function of surface gravity and temperature for ice sheets 1 – 4 km in thickness. The white dots (the numbers correspond to the index number of planets in ref [1]) show the approximate surface gravity and surface temperature of various exo-Earths with high similarity to Earth. **(e)** A box and whisker diagram showing the heat flow distribution in the continental and the oceanic regions of the Earth. The box's lower and upper extent corresponds to the 25th and 75th percentile of the heat flow values, and the center corresponds to the median heat flow values.

unconstrained. The main source of long-term heat in a planet after the initial stage of accretion and differentiation is the radiogenic decay of isotopes of heat-producing elements with billion-year half-lives such as ^{40}K, ^{232}Th, ^{235}U, and ^{238}U (i.e., geothermal heat). Radiogenic heat production as a function of age for cosmochemically Earth-like exoplanets suggests that exo-Earths similar in age to Earth should have a comparable heat production rate (H) [11]. However, there is a considerable degree of variations and uncertainties associated with the age of the M-dwarf systems considered in this study. A comparison of the H values required for basal melting on the various exo-Earths to the age-dependent heat production values of cosmochemically Earth-like exoplanets [11] demonstrates that despite the old age of some of the M-dwarf systems, the heat production rates on these exo-Earths may be sufficient for basal melting if they are cosmochemically Earth-like [1]. The notable exceptions are TRAPPIST-1 f and TRAPPIST-1 g, where basal melting of thin ice sheets by geothermal heat alone may not be feasible given their old age (hence lower radiogenic heat production) and their relatively low T_s.

Discussion: The primary goal of this work is to demonstrate the relative ease by which basal melting may be attainable on M-dwarf orbiting exo-Earths. While there are notable uncertainties about the presence and the volume of hydrospheres on these bodies, if even a handful of potentially habitable exo-Earths discovered so far (or in the future) were to contain thick (> few km) hydrospheres, then liquid water via basal melting may be present on those bodies with relatively modest heat flow. Our heat flow constraint required for basal melting, under the assumption that the estimated T_{eq} is equal to the T_s, is an overestimate. The presence of greenhouse gases on any of these exo-Earths will raise the T_s, and therefore the heat flow required for basal melting would be notably lower than the estimates presented here. The interaction of planetary hydrospheres with silicate bedrock will also inevitably result in the incorporation of other soluble minerals/chemicals that have the potential for significantly lowering the freezing point of pure water and nutrients essential for sustaining habitable conditions[12, 13]. The results presented here are based on pure water thermodynamics and thus represent a conservative scenario that allows liquid water to form and be stable in the hydrospheres of ice-rich exoplanets.

The subsurface world of these exo-Earths might resemble the subsurface conditions found on Europa. The ensuing water-rock interactions at the crustal interface may provide a variety of chemicals and energy that could play a role in the origin and sustenance of putative life forms at the ocean floor, akin to those found at hydrothermal vents on Earth. Despite the high pressures present at the base of the ice sheets on super-Earths, it may not be a limiting habitability agent as life on Earth has been observed at subduction forearc with pressure exceeding 340 MPa[14]. An isolated ocean between layers of low density, low pressure ice and high density, high pressure ice may also form, without chemical exchange (i.e. nutrient flux) with the rocky core, which may not be adequate for habitability[13]. These bodies would classify as class IV habitat with liquid water layers between two ice layer, such as the internal models of Ganymede and Callisto. Still, the absorptive properties of the frozen surface ice layer would shield basal melt environments from X-ray, extreme, and far UV radiation. Thus, basal melting provides a potentially habitable environment for cool, terrestrial planets orbiting M-dwarfs. It may also provide an environment isolated from the active and variable radioactive properties of M-dwarfs, which have long been a concern for the habitability of these planets.

References: **[1]** Ojha et al. *Nat Comms*, 2022. 13(1): p. 7521.**[2]** Kopparapu, R.K., ApJ, 2013. 767(1): p. L8. **[3]** Dressing et al. ApJ, 2015. 807(1): p. 45. **[4]** Shields et al. (2016). Phys Reports, 2016. 663: p. 1-38. **[5]** Yang et al. (2020). Nat Astro, 2020. 4(1): p. 58-66. **[6]** Livingstone et al. Nature Reviews, 2022. 3(2): p. 106-124. **[7]** Ojha et al., Science Advances, 2020. 6(49): p. eabb1669. **[8]** Carr and Head. GRL, 2003. 30(24). **[9]** Goldspiel and Squyres. Icarus, 2000. 148(1): p. 176-192. **[10]** Buffo et al. EPSL, 2022. 594: p. 117699. **[11]** Frank et al. Icarus, 2014. 243: p. 274-286. **[12]** Journaux et al. SSR, 2020. 216(1): p. 1-36. **[13]** Journaux, B., Nat Comms, 2022. 13(1): p. 1-4. **[14]** Plümper et al. PNAS, 2017. 114(17): p. 4324-4329. 249.