HABITABLE ICE-COVERED EXOPLANETS. R. Barnes[1,2], S. Vance[2,3], P.E. Driscoll[4], B. Guyer[1], C. Sotin[2,3,], J. M. Brown[2,5]. [1]Astronomy Dept. and Astrobiology Program, U. of Washington, Box 351580, Seattle, WA 98195 (rory@astro.washington.edu). [2]NAI Icy Words Team. [3]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr, Pasadena, CA 91109. [4]Dept. of Terrestrial Magnetism, Carnegie Institute of Washington, 5241 Broad Branch Road, NW, Washington, DC 20015. [5]Dept. of Earth and Space Sciences, U. of Washington, Box 351310, Seattle, WA, 98195.

Introduction: The discovery of an inhabited exoplanet is a major goal in astrobiology, with most research focused on planets in the habitable zone (HZ), the shell around a star in which an Earth-like exoplanet can support liquid surface water [1]. However, in our solar system some large satellites are likely to possess liquid water mantles that may be habitats for life [2,3], suggesting a less restrictive approach to exoplanets may be appropriate. If exoplanets beyond the HZ possess similar relative abundances of refractory and volatile material, they may have similar structures as Europa, Ganymede, Callisto, or Titan, and hence may be habitable. We call such worlds "Habitable Ice-Covered ExoPlanets" or HICEPs. NASA's *Kepler* mission may already have discovered such worlds, see Fig. 1, and similar worlds probably orbit stars closer to Earth, and may be discovered by the *TESS* mission, or by future direct imaging campaigns.

Here we perform numerical calculations of HICEPs to identify conditions that permit water layers, direct rock-water interfaces, and the presence of high pressure ices. We consider planets with a 1 Earth-mass solid interior and Earth-like composition, except for variations in radiogenic species. We model heat fluxes at the base of the volatile layer for different assumptions using a thermal interior model calibrated to Earth [4]. The structure of the volatile layer is computed using the formalism in [5], in which the locations of liquid water and its solid phases are determined based on the seafloor heat flux, icy surface temperature, the H_2O liquidus, and updated empirical relationships between the chemical potential and the phases of water ice as function of temperature, pressure and salinity.

As with the icy worlds in the solar system, water layers can persist in HICEPs over a wide range of seafloor heat fluxes and salt concentrations. The structure of the volatile layer depends on these parameters and includes worlds with direct rock-water interfaces as well as HICEPs with high-pressure ice phases between the liquid water and solid components. Moreover, the structure can change significantly over time, and some exoplanets may develop these high pressure ice layers after billions of years, potentially altering the liquid water layer's habitability.

These results suggest that terrestrial exoplanets beyond the HZ should not be discarded as potential habitats for life. Unlike the icy satellites of our Solar System except Titan, HICEPs have sufficient gravity to retain an atmosphere, and hence biologically-generated molecules in the subsurface liqud water layer may accumulate in the atmosphere and be amenable to remote sensing. Future direct imaging missions, such as the *LUVOIR* mission concept, should consider HICEPs as targets for biosignature searches. One potentially enticing aspect of such an investigation is the fact that HICEPs are more distant from their host star than those in the HZ, and so may be easier to observe with direct imaging techniques.

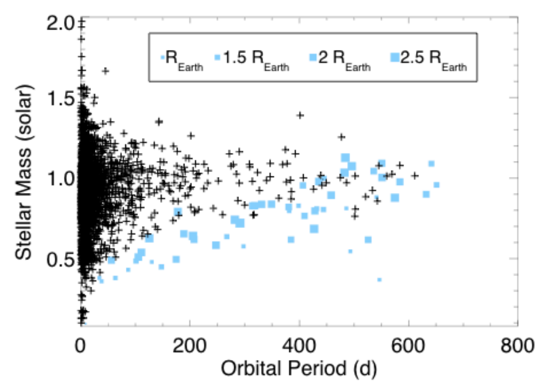

Figure 1: Potential HICEPs discovered by NASA's *Kepler* mission. The blue points are planets with incident stellar radiation fluxes below 90% of Earth's, with point size corresponding to planet radius as shown. Some of these worlds are beyond the classic habitable zone, but the internal energy of these planets may be large enough to support subsurface liquid water layers.

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