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Spin-Orbit Variations, Greenhouse Gases, and Superhabitable Conditions on Terrestrial Worlds in Multi-Planet Systems

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Heller and Armstrong (*Astrobiology*, 2014) describe a number of ways in which an Earth-like world ("Earth twins" with a tidal heat flux F_t less than 0.04 W/m^2, and within their star's habitable zone) might be "superhabitable," with surface environments that are more amenable to life than the common benchmark of modern Earth. Over Earth history, several time periods are known from the geologic record that could meet these criteria, providing multiple opportunities to explore known superhabitable and inhabited planetary conditions from an astrophysical perspective.

Earth during the Mid-Cretaceous Period circa 100 million years ago satisfies several Heller and Armstrong (*Astrobiology*, 2014) superhabitability criteria, as applicable to Earth twins: 1) elevated CO_2 levels (Foster et al., *Nature Commun*. 2017; Huber et al., *Global Planet. Change* 2018; Lenton et al., *Earth-Sci. Rev.* 2018) providing enhanced climate warming that more than offset a slightly reduced solar insolation (Gough, *Solar Phys.* 1981); 2) extensive coastal regions and interior seaways covered by shallow marine waters (Frisch et al., 2011); 3) reduced equator-to-pole temperature gradients (Upchurch et al., *Phil. Trans. Royal. Soc. Lond. B* 1998; Hunter et al., *Palaeogeogr. Palaeoclim. Palaeoecol.* 2013); and 4) atmospheric O_2 levels slightly greater than modern Earth (Lenton et al., *Earth-Sci. Rev.* 2018).

The Mid-Cretaceous is the archetypal stable planetary greenhouse environment, and was among the warmest, most extensively inhabited times on Earth since continents became emergent. Geologic evidence suggests that the warm temperatures were mainly a product of higher greenhouse gas levels compared to modern, with atmospheric CO2 estimates ranging from 750 to 3000 ppmv. Carbon dioxide was elevated in part due to increased volcanic activity and higher spreading rates at the Earth's mid-ocean ridge plate boundaries. The Cretaceous climate was one in which high latitudes were free of major ice sheets, and probably had a cryosphere that was seasonally limited, with some faunal evidence suggesting high latitude temperatures that were above freezing year-round.

A common problem with simulating superhabitable greenhouse states is that, although elevated CO_2 increases the global mean surface temperature, coupled GCMs do not generate meridional temperature gradients that are as shallow as geologic evidence suggests. There is irrefutable evidence that polar regions were extremely warm in the Cretaceous, while some paleoclimate proxies suggest that the tropics remained relatively cool. However, dynamic coupled models do not move sufficient heat poleward to both warm high latitudes and limit tropical temperatures to levels that don’t exceed the tolerances of known complex life forms. If our GCM simulations are underestimating heat redistribution, then we are probably underestimating the amount of available habitat space on warmer worlds.

One climate forcing not yet explored in detail with GCMs for greenhouse worlds is high-frequency, low-amplitude spin-orbit variability (“Milankovitch cyclicity”). We know from Earth history that these relatively subtle variations, the product of Earth’s orbital interactions with other planets of the Solar System, have proven sufficient to contribute to modulation of relatively warmer and colder climates during the most recent ice age (2.5 million years ago to present). We also know from the deep-time geologic record that this variability has left detectable signals in sedimentary and stable isotopic successions, implying a spin-orbit climatic influence beyond simply pushing the planet in and out of glacial states (Meyers and Malinverno, *PNAS* 2018; Olsen et al., *PNAS* 2019). Teasing out the contributions of spin-orbit variability to greenhouse climates may help round out our understanding of exogenous climate forcings, and close the gap between modeled and reconstructed climates. We may also be in a better position to ask similar questions about spin-orbit interactions and climate variability in other multi-planet systems.

We have used ROCKE-3D to explore the Cretaceous superhabitable climate states by varying levels of atmospheric CO_2 from modern pre-industrial Earth levels (285 ppm = 1X) to 16X CO_2 and have successfully produced a range of warm climates that match aspects of the Cretaceous geologic record. With these simulations all exhibiting some climate features that are not supported by the geologic record (either cold poles or overheating tropics) the addition of reasonable spin-orbit states may resolve some mismatches, and will help us produce the most accurate simulations possible. Using Laskar et al. (*A&A* 2004, 2010) as a guide, we have reviewed the range of possible spin-orbit configurations for the interval between 105-95 million years ago, and used the estimated minimum and maximum values for obliquity (22.04 to 24.13 degrees) and eccentricity (0.00035 to 0.06453) to drive an additional series of simulations that combine both elevated CO_2 and spin-orbit variability. The results of these simulations will be presented at this meeting.