THERMAL CONSEQUENCES OF IMPACT BOMBARDMENTS TO THE SILICATE CRUSTS OF TERRESTRIAL-TYPE EXOPLANETS.

O. Abramov[1] and S. J. Mojzsis[2], [1]Planetary Science Institute, 1700 E Fort Lowell Rd # 106, Tucson, AZ 85719 (abramov@psi.edu), [2]Dept. of Geological Sciences, University of Colorado, UCB 399, Boulder, CO 80309.

Introduction: Post-accretionary impact bombardment is a natural consequence of the planet formation process. Consequently, such *late accretion* events modulate the initial physical and chemical states of terrestrial planets and their potential to host biospheres. Impact heating can lead to localized, regional [e.g., 1-3], or in extreme cases, wholesale global sterilization of the crust [e.g., 4]; less intense bombardment can also create hydrothermal oases favorable for life [e.g, 5]. Here, we generalize the effects of late accretion bombardments to extrasolar planets of several different masses (0.1-10M⊕). Thousands of extrasolar terrestrial planets have been discovered, some of which have bulk densities consistent with a rocky composition, and/or orbit within their star's so-called "habitable zone". One such planet is Proxima Centauri b, with an estimated mass approximately twice that of Earth [6]. We also model a "mini-Earth", with a mass 1/10th that of Earth, and a "super-Earth", with a mass 10 times that of Earth, at the approximate upper limit for transition to "mini-Neptune" [7]. We make predictions for lithospheric melting and subsurface habitable volumes.

Methods: The impact bombardment model [1,2] consists of (i) a stochastic cratering model which populates the surface with craters within specified constraints; (ii) analytical expressions that calculate a temperature field for each crater [e.g., 8,9]; and (iii) a

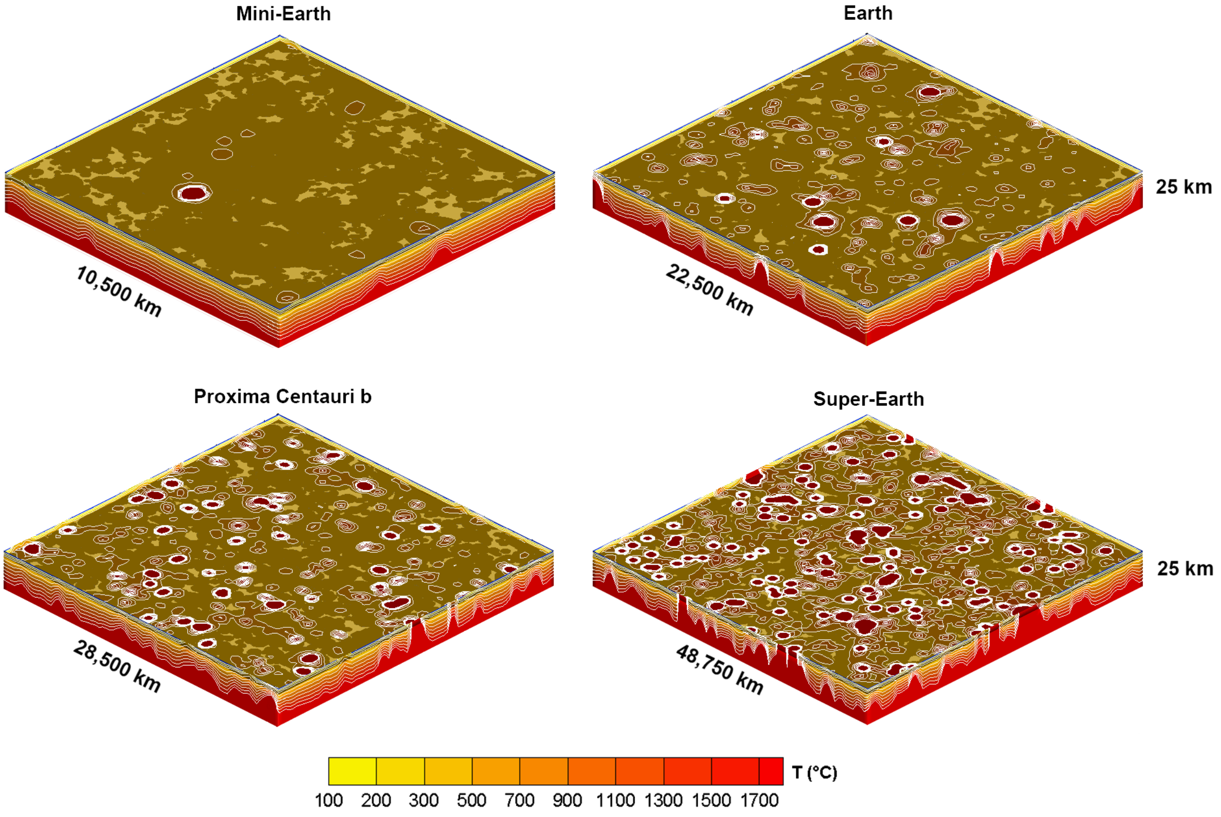

Figure 1. A three-dimensional thermal model showing the upper lithosphere of a planet 100 Myr after the start of the impact bombardment. The planet's entire surface area is represented with periodic boundary conditions (wrap-around). Dark circles indicate crater locations, and white lines are temperature contours. The upper boundary shows temperatures at a depth of 4 km. Clockwise from upper left: Mini-Earth, Earth, Proxima Centauri b, Super-Earth.

three-dimensional thermal model of the planetary lithosphere, where craters are allowed to cool by conduction and radiation (Fig. 1).

We present modeling results for the first 500 Myr of impact bombardment based on our solar system's mass production functions for that time [10]. Surface temperatures and geothermal gradients are set to 20 °C and 70 °C/km [2]. Total delivered mass for the Earth was estimated at 7.8×10^{21} kg, and scaled to other planets based on cross-sectional areas, with 1.7×10^{21} kg for mini-Earth, 1.2×10^{22} kg for Proxima Centauri b, and 3.6×10^{22} kg for super-Earth. The size-frequency distributions of the impacts is based on our main asteroid belt [11]. Impactor and target densities are set to 3000 kg m^{-3} and planetary bulk densities are assumed to be that of Earth (5510 kg m^{-3}), omitting likely gravitational compression [7]. Impactor velocity was estimated at 1.5 times the escape velocity for each planet, with 7.8 km s^{-1} for mini-Earth, 16.8 km s^{-1} for the Earth, 21.1 km s^{-1} for Proxima Centauri b, and 36.1 km s^{-1} for super-Earth.

Results: Figure 2 shows a percent of the thermal lithosphere melted by impacts as a function of time in the four planets under study. The planets are modeled as undergoing bombardment with fully formed crusts, so the amount of melt immediately increases due to impacts. Super-Earth reaches a maximum of ~45% of the lithosphere in molten state, whereas mini-Earth reaches a maximum of only ~5%. This is due to much higher impact velocities and cratering densities on the super-Earth compared to mini-Earth.

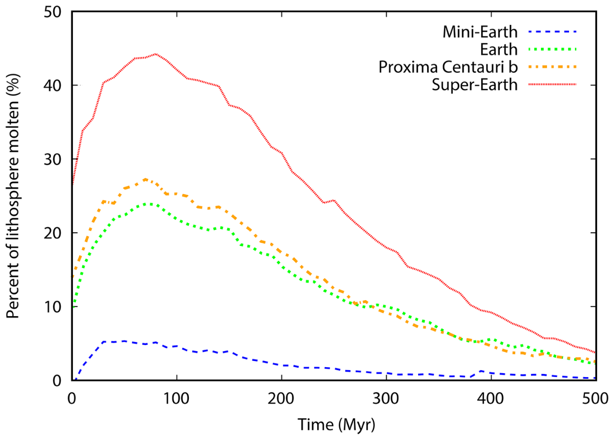

Figure 2. Percent of a planet's thermal lithosphere in a molten state as the bombardment progresses. Derived from a three-dimensional transient thermal model (Fig. 1). Melt deposited in ejecta blankets is not included.

Figure 3 shows the geophysical habitable volumes within the upper 4 km of a planet's crust as the bombardment progresses. Impacts sterilize the majority of the habitable volume on super-Earth; however, due to its large total volume, the total habitable volume is still higher than on other planets despite the more intense bombardment in terms of energy delivered per unit area.

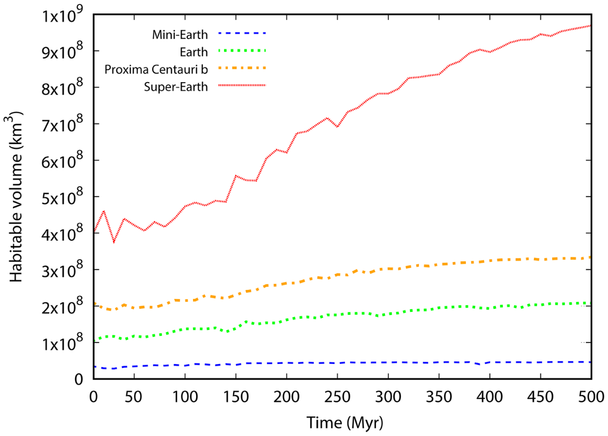

Figure 3. Habitable volumes based on temperatures between 20 and 50 °C (appropriate for mesophiles) in a planet's near-subsurface during impact bombardment.

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