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Thermal consequences of impact bombardments to silicate crusts of terrestrial-type exoplanets

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Introduction. Post-accretionary impact bombardment is part of planet formation and leads to localized, regional [e.g., 1-3], or even wholesale global melting of silicate 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 different masses (0.1-10$M_{\oplus}$). One example is Proxima Centauri b, estimated at ~2× $M_{\oplus}$ [6]. We model a 0.1$M_{\oplus}$ "mini-Earth"and "super-Earth" at 10$M_{\oplus}$, the approximate upper limit for a "mini-Neptune" [7]. Output predicts lithospheric melting and subsurface habitable volumes.

Methods. The model [1,2] consists of (i) stochastic cratering; (ii) analytical thermal expressions for each crater [e.g., 8,9]; and (iii) a 3-D thermal model of the lithosphere, where craters cool by conduction and radiation.

We analyze impact bombardments using our solar system's mass production functions for the first 500 Myr [10]. Surface temperatures and geothermal gradients are set to 20 °C and 70 °C/km [2]. Total delivered mass for Earth is 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 impactors' SFD 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 5510 kg m^{-3}, omitting gravitational compression [7]. Impactor velocity was estimated at $1.5 \times v_{esc}$ 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. We assume fully formed crusts, so melt volume 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. We also show 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.

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