MODELING OF IMPACT EJECTA TEMPERATURES ON THE EARTH AND THE MOON.

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Introduction: Impact bombardment(s) defined several key aspects physical and chemical aspects of the young terrestrial planets and their surfaces. Effects of bombardments include, but are not limited to: radical changes in surface morphology, principally expressed as cratered terrains; chemical composition changes via delivery of materials, melt mixing and induced differentiation; modification to and sometimes wholesale removal of primordial atmospheres; and perhaps the overall thermal structures of terrestrial planets. Heating due to impacts probably had important consequences for an emerging biosphere. Hence, it makes sense to advance our understanding of the durations and intensities of bombardment events in the early solar system.

In particular, a cataclysmic spike in the number of impacts, termed the Late Heavy Bombardment (LHB), has been inferred from lunar rocks and impact melts, lunar and asteroidal meteorites, and an ancient Martian meteorite; all record thermal metamorphic events with ages that group around and/or do not exceed 3.9 Ga [1-3]. The LHB is of particular interest and importance because it may coincide with the establishment of life on Earth. However, the duration, intensity, and even the very existence of the LHB continue to be debated.

A robust way to test the LHB hypothesis is to first model how the daughter-parent ratios of various radioisotopic systems, in both whole rocks and mineral grains such as zircons and apatites, can be reset by impact-induced heating of heating by a broad range of projectiles. We have previously developed a global-scale model of the thermal effects of impact bombardments on the subsurface [4]. Here we examine the thermal state of ejecta deposited on the surface to further understand the mechanism(s) behind impact-induced modifications of radiogenic systems. The ultimate aim of this work will be to inversely model the results of laboratory analyses of ancient lunar and terrestrial rocks and minerals to constrain bombardment conditions to the crust in the earliest times.

Methods: Mass delivered to the Earth during the LHB has been estimated at 1.8×10^{23} g based on dynamical modeling [5], and 2.2×10^{23} g based on the lunar cratering record [6,7]. For the purposes of this work, we adopted the average value of 2.0×10^{23} g. The mass delivered to the Moon is ~20 times smaller [5]. Impactors that bombarded the Earth and Moon were likely dominated by main belt asteroids [8], and the size/frequency distribution of the asteroid belt is unlikely to have changed significantly since that time [9]. Thus, we used the size/frequency distribution of the current asteroid belt.

Ejecta deposition model: Post-impact temperature distributions due to shock heating were calculated using the Murnaghan equation of state [10], using parameters for granite and basalt. The most statistically common impact angle of 45° was assumed. Other input parameters for calculating post-impact temperature distributions include rock parameters heat capacity, latent heat, melting temperature, vaporization temperature, with appropriate values used for granite and basalt, planetary gravity, impact velocity (20 km s^{-1}), surface temperature (20 °C for Earth, -50 °C for Moon), and geothermal gradient (12 °C/km for both).

The diameter and depth of the transient crater formed by a given impact was calculated using the Pi-scaling laws [11]. The temperature of the ejecta associated with a given impact crater was calculated by volumetrically averaging the temperatures to which non-vaporized material (below 3350 °C for basalt [12], and below 3327 °C for granite [13]) within the transient crater was heated. It was also recognized that condensed rock vapor would deliver a significant thermal component for large craters, and volumes of vaporized material were calculated as well.

The final rim-to-rim crater diameter was calculated from the transient crater diameter using the relationship of [14].

Results: Combining the predicted mass delivered during the LHB with the size-frequency distribution, the largest impactor predicted to have hit the Earth is 310 km in diameter, forming a final crater 3270 km in diameter. The largest LHB impactor to hit the Moon is predicted to have been 155 km in diameter, forming a final crater 2002 km in diameter, close to the diameter of the South Pole - Aitken basin (~2500 km).

This method allows for the calculation of mean global ejecta thickness produced by a given impact by dividing the volume of ejecta by the surface area of the planet. This method yields 26 m of ejecta and 185 m of condensed rock vapor for largest projectile expected to strike the Earth (310 km), assuming a granitic target, which agrees well with the results of [15].

Figure 1 illustrates the predicted mean temperature of ejecta associated with craters of various diameters. It is worth noting that this model does not yet account for in-flight cooling, and thus the deposition temperature of ejecta is expected to be lower. On the Earth, ejecta temperatures for granitic and basaltic lithologies are fairly similar: for smaller craters, ejecta temperatures of basaltic targets are moderately higher than for granitic targets, but become lower for large craters due to the higher latent heat of basalt. On the Moon, however, ejecta temperatures for a given crater are significantly lower than those on Earth. This is due to the fact that it requires less energy to form a crater of a given diameter on the Moon because of lower gravity, as well as due to the lower initial temperatures on the Moon. Thus, material ejected from the transient crater tends to be cooler. To take a specific example, ejecta from the Imbrium basin (D ~1100 km) is expected to have experienced a mean temperature of ~1300 °C, which is just above a typical lunar liquidus of 1280 °C. This suggests that the ejecta was a mixture of melt and solid clasts, which is in agreement with observations.

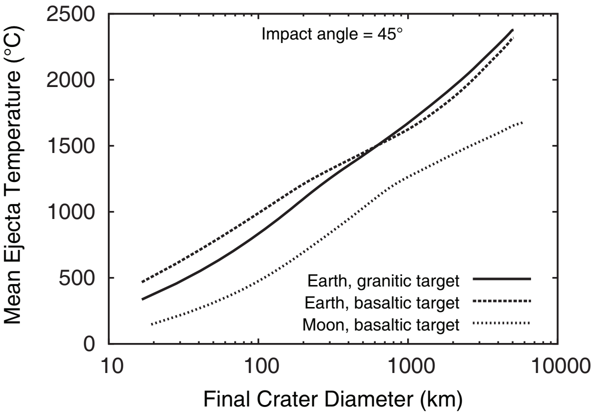

Figure 1. Mean ejecta temperature as a function of crater diameter on the Earth and Moon.

Figure 2 shows the mean cumulative global thickness of impact ejecta (Fig. 2a) and condensed rock vapor (Fig. 2b) expected during the LHB. It was calculated by multiplying the mean global ejecta thickness produced by impactors within a given bin size by the number of impactors expected within that bin. On the Earth, the global thickness of ejecta produced by impactors of various diameters during the LHB is relatively constant, while the volume of condensed rock vapor increases as a function of impactor (and crater) diameter. On the Moon, however, there is a noted increase in global cumulative thickness for both ejecta and vapor as a function of crater diameter for large impacts. This appears to be due to both the nature of the size-frequency distribution used and the fact that it requires less energy to form craters of a given size on the Moon.

Overall, this method predicts that the LHB would have deposited ~3.5 km of ejecta on the surface of the Moon, with a mean temperature of 1075 °C, as well as ~2.1 km of condensed rock vapor. However, it should be noted that escape of ejecta into space is not yet included in the model, and these values should be treated as upper limits. If only Imbrium-size impacts and smaller are considered, these numbers reduce to ~1.8 km of ejecta with a mean temperature of 754 °C, and ~0.3 km of rock vapor. For granitic lithologies on the Earth, ~0.9 km of ejecta and ~1.2 km of condensed rock vapor are predicted to have been deposited by the LHB. The mean temperature of the ejecta is 1267 °C, and 66% of ejecta is below 1000 °C. The results for basaltic lithologies on the Earth are similar.

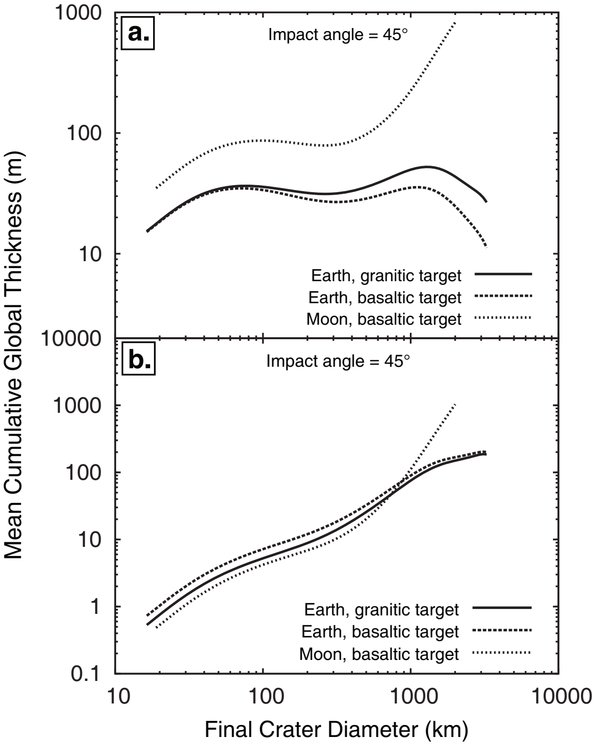

Figure 2. (a) Mean cumulative global thickness expected during the LHB of (a) impact ejecta and (b) condensed rock vapor as a function of binned final rim-to-rim crater diameters. The bin width increases by a factor of 1.25.

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