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Impact-induced compositional variations on Mercury

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ABSTRACT

Remote sensing data suggest Mercury's surface has compositional variations spatially associated with crater and basin ejecta, the so-called "Low-Reflectance Material" (LRM), which has been suggested to be enriched in a subsurface native darkening agent that is excavated and redeposited onto the surface. This unit may record the evidence of impact-induced mixing of Mercury's outer layers during its early history. Here, we develop a fully three-dimensional Monte Carlo model of impact cratering, excavation, and ejecta blanket deposition on a global scale for Mercury.

New dynamical simulations of the early evolution of the asteroid belt hint at the presence of additional asteroids in a region interior to the present-day belt, known as the "E-belt". We use Monte Carlo methods to show that the predicted bombardment from this population matches the observed spatial crater densities on Mercury. Impacts large enough to pierce through the crust create surface ejecta deposits rich in mantle material. Later impacts onto enriched ejecta deposits redistribute mantle material away from the basins. For the suggested average mercurian crustal thickness of 50 km, the surface has, on average, ∼0.4% mantle material by volume; the most enriched areas have ∼30% mantle by volume.

The regional coverage of impact-induced compositional changes is strongly dependent on the thickness to the subsurface source. Because observations indicate LRM covers ∼15% of Mercury's surface, our model suggests the darkening agent is ∼30 km deep. Considering the current estimated average mercurian crustal thickness of 50 km, this implies the darkening agent is likely located within a chemically distinct lower crust.

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1. Introduction

The MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) Gamma-Ray Spectrometer (GRS) and X-Ray Spectrometer (XRS) have been used to map the chemical heterogeneity of Mercury's surface and, by correlating with landforms, infer subsurface composition and primordial conditions (Nittler et al., 2011; Evans et al., 2012; Peplowski et al., 2012; Weider et al., 2012). Though much of Mercury's surface has been altered by smooth plains, the majority of which probably have a volcanic origin (Denevi et al., 2013), the chemical heterogeneity of the heavily cratered terrains will likely show signs of impact-induced compositional variations. In particular, there seem to be chemically distinct units primarily associated with cratering features, such as ejecta blankets.

The Low-Reflectance Material (LRM), which covers ∼15% of the surface, is primarily found within crater and basin ejecta (Murchie et al., 2008; Robinson et al., 2008; Denevi et al., 2009). Because immature impact ejecta on Mercury have lower reflectance than their lunar counterparts, there may be a native darkening agent located at depth (Denevi and Robinson, 2008). Thus, LRM, which can reach reflectance values 30% below the global mean (Denevi et al., 2009), is suggested to be caused by an enrichment in a native darkening agent that is excavated during impacts and redistributed within ejecta blankets (Denevi and Robinson, 2008). Although LRM is generally associated with crater ejecta, it is not found within the continuous ejecta blankets of many impact craters, perhaps suggesting the subsurface darkening agent is not uniformly distributed (Denevi et al., 2009).

For planets with thin crusts, such as Mercury, with an estimated crustal thickness ranging between 20 and 80 km (Smith et al., 2012), impact mixing of mantle and crustal materials may be an efficient process in producing surface compositional heterogeneities. The distribution and magnitude of the heterogeneity will be dependent on the number and size of impactors and the crustal thickness. The number and clustering of ages of lunar impact basins suggest the terrestrial planets experienced a period of frequent impacts ∼700 million years after the endpoint of planet formation dubbed the "Late Heavy Bombardment" (LHB) (Tera et al., 1974; Hartmann et al., 2000). Recent work seeking to clarify

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the number of lunar basins and relatively young terrestrial impact spherule beds suggests this bombardment lasted from the endpoint of planet formation to 2 Gya, longer than previously thought (Bottke et al., 2012). In this scenario, the planets are hit by asteroids from the main belt and E-belt, an extinct asteroid population located interior to the present-day belt. The lunar cratering production function closely matches an E-belt dominated bombardment (Bottke et al., 2012). Because Mercury is an airless inner Solar System body, the evidence of an E-belt dominated bombardment should be recorded on Mercury's ancient, heavily cratered terrain.

Here, we show that this bombardment may be the cause for the suggested impact-induced compositional variations on Mercury. We construct a 3-D Monte Carlo model of impact cratering and ejecta deposition to investigate the effect of an E-belt dominated bombardment on the composition of Mercury's heavily cratered terrains. Additionally, we use mercurian cratering statistics (Fassett et al., 2011, 2012) to show that this new dynamical model of the early sculpting of the asteroid belt is supported by Mercury's cratering record.

2. Mercury's impactor population

The source for the LHB impactors is likely the primordial main asteroid belt, but early works had difficulty explaining why so many asteroids would hit the terrestrial planets a few hundred million years after the endpoint of planet formation (Strom et al., 2005). The *Nice* Model for early Solar System evolution suggests the increase in impact rate associated with the LHB occurred when Jupiter and Saturn cross a 1:2 mean motion resonance, scattering cometary and asteroidal material onto the planets (Gomes et al., 2005; Tsiganis et al., 2005).

A recent re-evaluation of the number and ages of lunar basins and the number and ages of terrestrial impact spherule beds, which are a product of the vaporized rock during an impact, suggests that objects may have hit the planets over a longer period of time than previously thought (Simonson and Glass, 2004; Hassler et al., 2011; Bottke et al., 2012). The additional impactors are thought to come from the so-called "E-belt", which is an extension of the asteroid belt that was located interior to the present-day belt. This extended belt is now extinct, but the Hungaria asteroid family is thought to harbor its few survivors (Warner et al., 2009; Bottke et al., 2012; Morbidelli et al., 2012). Orbital integrations seeking to study the effect of giant planet migration on the evolution of an extended asteroid belt (Gomes et al., 2005; Tsiganis et al., 2005; Bottke et al., 2012) show the terrestrial planets' bombardment occurred primarily in two stages: (i) a pre-LHB consisting of remnant planetesimals in the inner Solar System and E-belt projectiles sent into planet-crossing trajectories via gravitational interactions with Mars, and (ii) the LHB, triggered by giant planet migration during which the main belt and E-belt are excited to higher impact velocities when resonances with the giant planets sweep across the primordial asteroid belt. These simulations indicate the E-belt is the principal source of LHB impactors (Bottke et al., 2007, 2012; Morbidelli et al., 2012). Using a similar approach to Bottke et al. (2012) and our own Monte Carlo methods, we show that Mercury's cratering record supports this new model.

2.1. Methods

The Size–Frequency Distribution (SFD) of the E-belt is equivalent to the main belt because it was merely its extension (Bottke et al., 2012); therefore, we use the present-day asteroid belt SFD, which is derived from absolute magnitude data (Ivezić et al., 2001; Jedicke et al., 2002) and converted to projectile diameter D (km) $= 1329\rho_v^{-\frac{1}{2}}10^{-H/5}$, where $\rho_v = 0.092$ is the visual geometric albedo, and H is the absolute magnitude (Bottke et al., 2005b; Fowler and Chillemi, 1992). The present-day asteroid belt SFD is used because dynamical simulations suggest the asteroid belt quickly evolves to its present-day structure (Bottke et al., 2005a). The distribution has two major slope breaks: one near projectile diameter $D \sim 3$ to 4 km and another for $D \sim 100$ km (Bottke et al., 2005b). Owing to the resolution of our 3-D model (see Section 3), we consider projectiles with $D \geqslant 5$ km. Thus, our SFD contains only one major inflection point following a differential power law in mass (m) of the form $dN/dm \propto m^{-1.7}$ for $D \leqslant 100$ km and $dN/dm \propto m^{-2.2}$ for $D \geqslant 100$ km (Jedicke et al., 2002; Bottke et al., 2005b), assuming an impactor density $\rho_i = 2.7\ \mathrm{g/cm^3}$ (Ivanov et al., 2002; Bottke et al., 2005b, 2012; Le Feuvre and Wieczorek, 2011), which is similar to CM meteorites (Britt et al., 2002).

Impactor masses are randomly selected to create a distribution consistent with the primordial main belt SFD. We constrain the total mass of objects impacting Mercury by the mass hitting the Moon and the relative impact probabilities between the two bodies. The total mass accreted by the Moon during its bombardment history, which is derived from isotopic studies of lunar mantle melts (Walker et al., 2004; Day et al., 2007, 2010), has been estimated to be $\sim 3.5 \times 10^{22}$ g (Morbidelli et al., 2012). Crater densities in the Nectaris basin suggest a total mass of $\sim 2 \times 10^{21}$ g has bombarded the Moon since 4.1 Gya (Morbidelli et al., 2012); thus, $\sim 3.3 \times 10^{22}$ g of asteroidal material impacts the Moon during the pre-LHB. Dynamical studies indicate mean pre-LHB and LHB lunar impact velocities of 11.9 km/s and 20.7 km/s respectively (Bottke et al., 2012). Le Feuvre and Wieczorek (2011) estimate the ratio between the impact probabilities on the Moon and Mercury to be 1.82, and suggest that mean impact velocities on Mercury should be a factor of 2.16 higher than the Moon. These ratios along with the approximations to the total lunar bombarding mass suggest Mercury has accreted $\sim 6.4 \times 10^{22}$ g during its bombardment history; 6×10^{22} g in the pre-LHB and 4×10^{21} g in the LHB. The mean impact velocity in the pre-LHB is 25.7 km/s and in the LHB is 44.7 km/s.

Assuming the density of Mercury's outer layer is $\rho_m = 3.7\ \mathrm{g/cm^3}$ (Smith et al., 2012), Pi scaling laws suggest a projectile of diameter D impacting at velocity v_i produces a transient crater of diameter (Ivanov et al., 2002)

$$D_{tc} = 1.16\left(\frac{\rho_i}{\rho_m}\right)^{\frac{1}{3}} D^{0.78}(v_i \sin\Omega)^{0.43} g^{-0.22}, \tag{1}$$

where $g = 3.7\ \mathrm{m/s^2}$ is Mercury's gravity, and Ω is the impact angle, the distribution of which follows $d\Omega = \sin(2\Omega)$ such that 45° is the most common value. To account for the effect of impact angle on D_{tc}, we use the equivalent vertical projectile scaling, $D_{eq} = 1.07D(\sin\Omega)^{1/2}$ for $\Omega < 60°$ and $D_{eq} = 1$ for $\Omega > 60°$ (Pierazzo and Melosh, 2000; Barr and Canup, 2010). Both phases of the bombardment history are simulated assuming impact velocities follow a Rayleigh distribution about the mean values for the pre-LHB and LHB. The synthetic transient crater population is converted to their final crater diameter following

$$D_{fc} = 1.17\left(\frac{D_{tc}^{1.13}}{D_x^{0.13}}\right), \tag{2}$$

where D_x is the crater diameter at which cratering shifts from the simple to complex regime (McKinnon and Schenk, 1985; Collins et al., 2005), which for Mercury has been found to range from 10–16 km (Pike, 1980, 1988), with current measurements indicating 12 km (Barnouin et al., 2012).

2.2. Results

The Monte Carlo bombardment model creates five hundred synthetic impactor populations and the average number and sizes

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