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Small crater populations on Vesta

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ABSTRACT

The NASA Dawn mission has extensively examined the surface of asteroid Vesta, the second most massive body in the main belt. The high quality of the gathered data provides us with a unique opportunity to determine the surface and internal properties of one of the most important and intriguing main belt asteroids (MBAs). In this paper, we focus on the size frequency distributions (SFDs) of sub-kilometer impact craters observed at high spatial resolution on several selected young terrains on Vesta. These small crater populations offer an excellent opportunity to determine the nature of their asteroidal precursors (namely MBAs) at sizes that are not directly observable from ground-based telescopes (i.e., below ~100 m diameter). Moreover, unlike many other MBA surfaces observed by spacecraft thus far, the young terrains examined had crater spatial densities that were far from empirical saturation. Overall, we find that the cumulative power-law index (slope) of small crater SFDs on Vesta is fairly consistent with predictions derived from current collisional and dynamical models down to a projectile size of ~10 m diameter (e.g., Bottke et al., 2005a, b). The shape of the impactor SFD for small projectile sizes does not appear to have changed over the last several billions of years, and an argument can be made that the absolute number of small MBAs has remained roughly constant (within a factor of 2) over the same time period. The apparent steady state nature of the main belt population potentially provides us with a set of intriguing constraints that can be used to glean insights into the physical evolution of individual MBAs as well as the main belt as an ensemble.

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1. Introduction

The NASA Dawn spacecraft was conceived to address key questions related to the dawn of our solar system, hence the name of the mission. The spacecraft was launched on 27 September 2007. Its main destinations were asteroids Vesta and Ceres, the two most massive bodies in the main belt of asteroids (Britt et al., 2002).

Vesta and Ceres were chosen because they are excellent targets for studying early solar system processes. They have also bore witness to 4.5 Gyr of main belt evolution, with cratered terrains that allow us to glean insights into how processes like collisional evolution have shaped the asteroid belt. In this paper, we focus our

attention on this aspect of main belt history, and in particular on the size-frequency distribution of small main belt asteroids (MBAs).

Small MBAs, defined here as bodies with diameters less than a few kilometers, are thought to be a steady-state population of fragments made by collisional and dynamical evolution processes (e.g., Dohnanyi, 1969; Davis et al., 1994; O'Brien and Greenberg, 2005; Bottke et al., 2005a,b). The main source of small MBAs is asteroid impacts, though a sizable fraction may come from mass shedding events caused by the YORP effect, a non-gravitational force that describes how the re-radiation of sunlight can spin some asteroids up to the fission limit (e.g., Pravec et al., 2010). The sinks for small MBAs are collisions, YORP, and thermal Yarkovsky drift forces, which drive many small MBAs to dynamical resonances where they can escape the main belt and reach planet-crossing orbits (e.g., Bottke et al., 2006). These mechanisms work incessantly to resupply the projectile populations that have struck the Moon and terrestrial planets over the last several Gyr.

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By understanding the MBAs size distribution and how it has varied over time, we can glean insights into main belt history, the physics of asteroid fragmentation, the importance of YORP-driven mass shedding events, and how much the near-Earth asteroid (NEA) population has changed over billions of years. A problem with this, however, is that the current and past nature of the MBA population is only partially (or indirectly) constrained.

For example, ground-based surveys have so far only been able to determine the MBA population down to objects a few hundreds of meters in diameter (e.g., Ivezic et al., 2001; Yoshida and Nakamura, 2007; Gladman et al., 2009). To deduce the nature of the MBA population at small sizes, collisional and dynamical models have tried to use a wide array of constraints, like the number and nature of the observed main belt asteroids and asteroid families, the known near-Earth asteroid population, small impact events detected in the Earth's upper atmosphere and the cratering history of the Moon and terrestrial planets (e.g., Morbidelli and Vokrouhlický, 2003; Bottke et al., 2005a,b; O'Brien and Greenberg, 2005). This has led to many intriguing solutions, but there has been no way to verify their work.

Ideally, a more direct way to infer the MBA population and how it has changed is to examine the crater populations on the surfaces of main belt asteroids. A number of asteroids have been visited by spacecraft (see Table 1). While this has led to an enormous reservoir of information on the collisional history of individual asteroids, interpreting the cratering record of these bodies is often difficult (e.g., O'Brien et al., 2006). Many of the larger worlds (e.g., Ida, Mathilde, Lutetia) have ancient surfaces, such that the spatial density of craters on their surfaces are arguably close to or perhaps in saturation, defined as a state where newly formed craters obliterate pre-existing ones (Gault, 1970; Hartmann, 1984; Chapman and McKinnon, 1986; Richardson, 2009; Marchi et al., 2012a). Craters on smaller asteroids, like Eros, Gaspra, or Steins, have possibly been affected by processes like impact-induced seismic shaking that can erase small craters (e.g., Greenberg et al., 1994; Richardson et al., 2004, 2005; O'Brien et al., 2006). For these and other reasons, previously visited asteroids, at first glance, do not provide a clear and consistent record of the MBA population.

Vesta offers a unique opportunity to explore the small MBA population as a function of time, and offers several advantages over the previously mentioned asteroids explored by spacecraft. First, it is large enough that only the largest, closest impacts to the counting area are likely to produce episodes of extensive seismic shaking, unlike smaller asteroids where impacts anywhere on the surface may have global effects. Second, Vesta's large surface area allows for the existence of adjacent regions with very different ages, ranging from heavily cratered units in the northern hemisphere to mildly cratered units that mainly exist in the southern hemisphere. The latter regions appear to have been locally reset by

relatively recent large impact events. Accordingly, it is possible to study populations of craters made by small MBAs well before they can reach saturation.

2. Vesta's sub-kilometer crater populations

The Dawn spacecraft imaged the surface of Vesta at varying spatial resolutions during the orbiting phase of its mission. In this work, we concentrate on the Low Altitude Mapping Orbit (LAMO) phase which lasted for 141 days, from 12 December 2011 to 30 April 2012. The spacecraft operated at an altitude of about 210 km, resulting in an average Framing Camera spatial resolution of approximately 20 m/px. At this scale, the surface of Vesta appears peppered by numerous sub-kilometer craters, though only some are fresh; the rest appear to be partially buried by regolith. Most of these terrains are poorly suited to deduce the small MBA population, with many close to or in saturation. In addition, many craters on these surfaces have been erased, possibly as a consequence of redistributed ejecta and/or seismic shaking episodes via large impacts.

To overcome these concerns, we turn our attention to two of the youngest terrains on Vesta that appear to be relatively undisturbed by post-emplacement evolution. The first one is associated with the fresh 60-km diameter Marcia crater (Williams et al., this issue). Located near Vesta's equator, Marcia crater is characterized by the presence of pitted terrains in the proximal ejecta and crater floor possibly made by the outgassing of volatile-rich material (Denevi et al., 2012). Marcia's ejecta blanket is very ragged as a result of mantling and partial erosion of previous topography. These characteristics make it difficult to detect sub-kilometer craters on many Marcia-related units. To avoid these problems, we focused on a relatively small and smooth unit – possibly impact melt – within the rim of the Marcia crater shown in Fig. 1 (Williams et al., this issue). Our crater counts are shown on the figure. In defining the crater counting unit, we were careful to stay away from high-slope terrains

Table 1

Asteroids visited by spacecraft in the past. The column "Comment" contains a brief summary concerning the observations of sub-kilometer craters, which is the focus of this paper. The comments summarize results from the following papers: (Steins, Lutetia: Marchi and et al., 2010; 2012c; Gaspra, Ida, Mathilde: Chapman et al., 1996a,b; 1999; Eros: Richardson et al., 2004). The symbol † marks near-Earth objects.

Asteroid	Average size (km)	Spacecraft	Comment
Lutetia	100	Rosetta	Some data available
Mathilde	50	NEAR	Saturated, poor resolution
Eros†	17	NEAR	Small craters erased
Ida	16	Galileo	Saturated
Gaspra	6	Galileo	Some data available
Steins	5	Rosetta	Poor resolution, small craters erased
Itokawa†	0.3	Hayabusa	Too small object

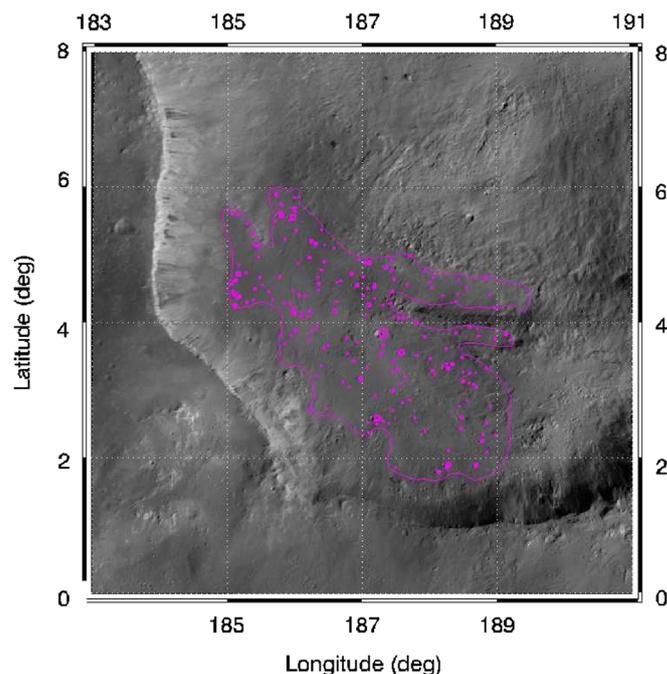


Fig. 1. Orthographic projection of a LAMO mosaic of the southwest portion of the 60-km Marcia crater. The contour line marks the region used for crater counts, whose area is 194.5 km². The map has a resolution of ~15 m/px. Circles indicate the 206 craters that have been measured, ranging from 50 m to 500 m in diameter.

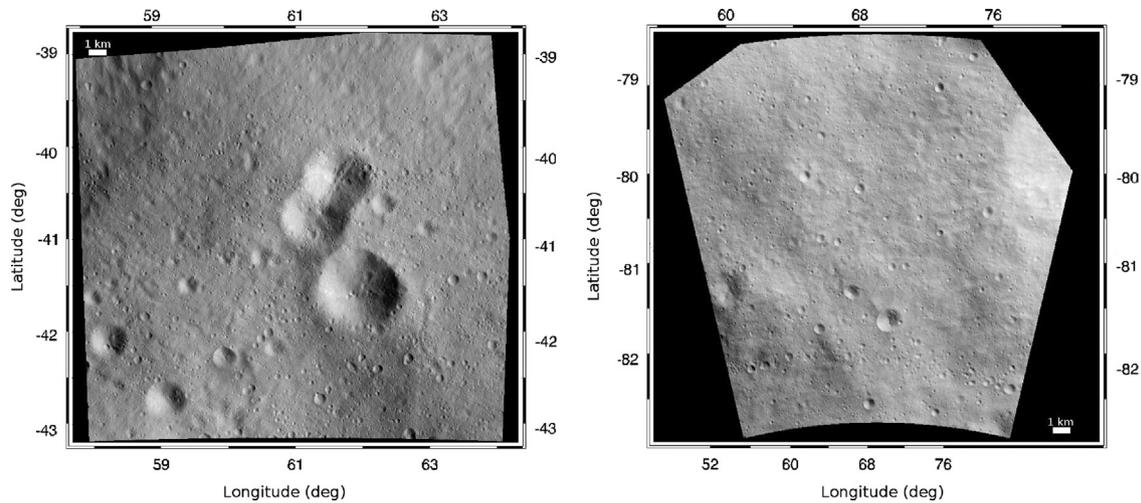


Fig. 2. Orthographic projections of two high resolution images (~ 22 m/px) acquired during the LAMO phase. Image ID: FC21B0014580_11353023506F1C (left panel: ejecta) FC21B0015216_11359132403F1D (right panel: floor).

(e.g., crater walls) because mass movements may affect the preservation of small craters.

The second terrain is associated with the Rheasilvia basin, a 500-km diameter impact basin that dominates the southern hemisphere of Vesta (e.g., Schenk et al., 2012). A preliminary analysis, based on the superposed crater SFD on its floor, showed that Rheasilvia's age is approximately 1 Gyr (Marchi et al., 2012b). Fig. 2 shows two LAMO images from Rheasilvia's floor and its proximal ejecta blanket. A comparison between the images shows that both terrains, at a first sight, appear to be well suited for counting fresh small craters. The Rheasilvia floor, however, is characterized by high slopes, while a large portion of the ejecta blanket near the rim known as Matronalia Rupes¹ is remarkably smooth and flat. This indicates that the emplacement of the ejected material created a layer that may be kilometers deep, thick enough to obliterate pre-existing topography (Schenk et al., 2012). For these reasons, we opted to measure small craters only on the ejecta blanket.

For comparison, Fig. 3 shows a representative LAMO image acquired in the heavily cratered northern hemisphere (Marchi et al., 2012b) that has a comparable resolution to those acquired in the southern hemisphere. Compared to the relatively fresh terrains shown in Fig. 2, here we see a highly complex topography, with numerous multi-kilometer depressions that could be ancient impact craters largely obliterated by subsequent evolution. Many of the sub-kilometer craters also look subdued or partially buried. In these terrains, we find it plausible that billions of years of cratering events have led to a quasi-steady state between crater formation and removal. The crater spatial densities determined here will be challenging to decipher, and we save them for future work.

Fig. 4 shows all of the craters that we have mapped on the smooth Rheasilvia ejecta unit. We concentrated our attention on a particular sub-region that was large enough (and contained enough craters) to be representative of the entire ejecta unit.

3. The model production function chronology

The crater size-frequency distributions (SFDs) of the units above can be compared to model size distributions of the MBAs in order to

¹ See IAU link <http://planetarynames.wr.usgs.gov/Page/VESTA/target> for a list of official names of Vestan surface features.

derive their crater retention ages. Here we use the chronology framework provided by the Model Production Function (MPF) (Marchi et al., 2009, 2011; Marchi et al., 2010). By modeling the MBA impactor flux and transforming the results using a crater scaling relationship, we can compare our crater production function to the data and solve for the surface age. This method is valid provided our MPF accurately estimates the MBA population over time.

In analogy with previous work, the impactor flux is characterized by its size-frequency distribution and impact velocity distribution. The impactor SFD is taken from the model of the main belt population of Bottke et al. (2005a). In this work, we will also consider a second MBA population derived by a recent survey of small main belt asteroids (Gladman et al., 2009). The latter distribution is valid down to absolute magnitudes of ~ 18 (corresponding to a diameter of about 0.8 km for an albedo of 0.2), therefore well above the range of interest for this work. We extended it towards smaller sizes (~ 10 m) by linearly extrapolating the cumulative slope of -1.5 measured in the range 0.8–3 km. We are aware that such distribution does not necessarily correspond to the real MBA SFD, however it provides a good term of comparison. Following the approach of Marchi et al. (2010), we derive the intrinsic collision probability between MBAs and Vesta $P_i = 2.85 \times 10^{-18} \text{ km}^{-2} \text{ yr}^{-1}$, as well as Vesta's impact velocity distribution (see Fig. 5).

For the crater scaling law, we adopted the Pi-group scaling relationships of Holsapple and Housen (2007). These scaling laws allow us to estimate the diameter of a crater given the velocity (v), diameter (d), and density (δ) of the impactor along with the density (ρ) and strength (Y) of the target. In addition to these quantities, two parameters (ν, μ) account for the nature of the terrains (hard-rock, cohesive soil, porous material). In this paper, we investigate both hard-rock and cohesive soils scaling laws, whose parameters are $\nu = 0.4, \mu = 0.55$ and $\nu = 0.4, \mu = 0.41$, respectively. We assume $\delta = 2.6 \text{ g/cm}^3$ and $Y = 2 \times 10^8 \text{ dyne/cm}^2$ for hard-rock (Marchi et al., 2010). The bulk silicate density of Vesta is $\rho \sim 3.1 \text{ g/cm}^3$ (Russell et al., 2012). An important aspect of crater formation concerns the transition from *transient* crater size to *final* crater size. During the formation of terrestrial and lunar simple craters, this transition occurs when excavation flow has ceased and material still lining the transient crater collapses under the influence of gravity to form a breccia lens. The collapse of that material effectively enlarges the diameter of the crater slightly (Dence et al., 1977; Grieve et al., 1977). The question is if this process occurs also on low-gravity asteroids. Measurements of the

depth to diameter (d/D) ratio and morphology of Vestan craters (Vincent et al., *this issue*) show that they exhibit signs of gravity-driven modifications comparable to lunar craters. This result suggests that Vestan craters undergo the transient to final modification, and therefore we applied this correction in our analysis, following the approach described by Marchi et al. (2011). We can also perform a simple natural experiment to estimate the crater scaling relationship between small craters and MBAs. Consider that the shape of the crater SFD on Rheasilvia terrains has an inflection point near $D \sim 1$ km. This feature corresponds to a similarly shaped inflection point in the near-Earth object SFD near ~ 0.1 km. At these sizes, the near-Earth object SFD closely resembles that of MBAs, which resupplies the NEO population (Bottke et al., 2006). Taking the ratio of these two values, we get a factor of ~ 10 , the same as that predicted by our crater scaling law relationship. Thus, we have increased confidence that the scaling laws used here are reasonable.

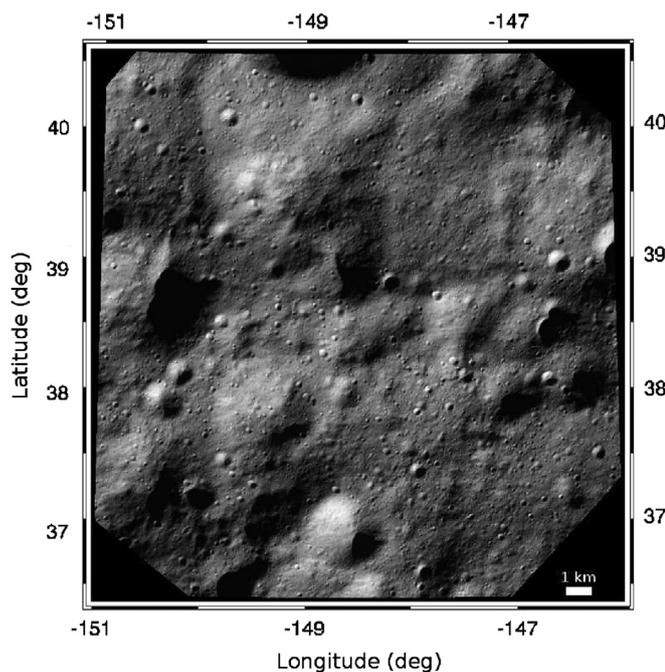


Fig. 3. Orthographic projection of a LAMO image acquired in the northern hemisphere (~ 21 m/px). Image ID: FC21B0023439_12085231933F1A.

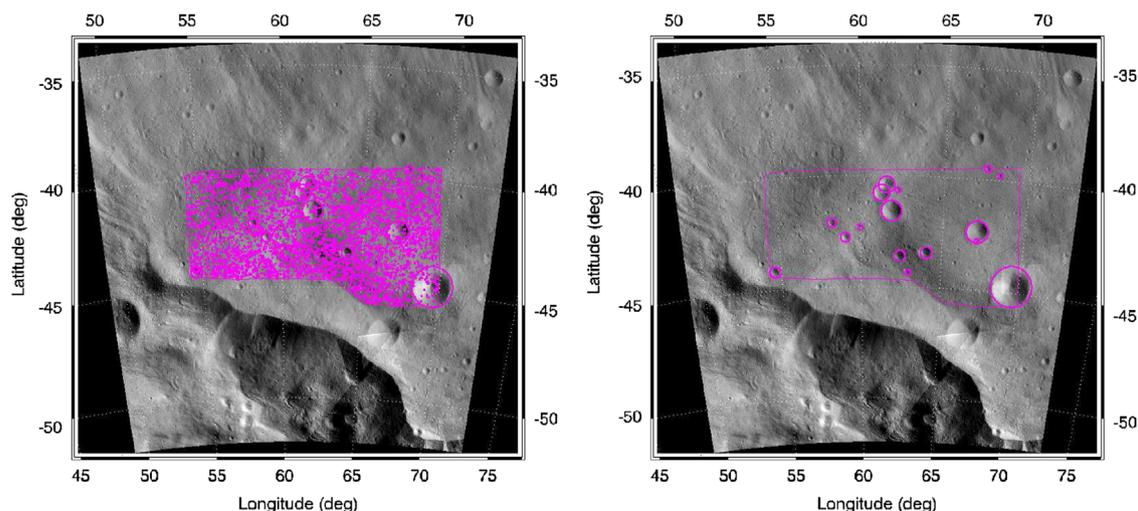


Fig. 4. Orthographic projection of a LAMO mosaic showing the boundaries of the counting region (1200.1 km^2) and the craters that have been mapped on the Rheasilvia smooth ejecta unit. Left panel: 3708 craters larger than 80 m. Right panel: Craters larger than 1 km.

Using the impactor SFD, the intrinsic collisional probability and the crater scaling law described above, we derive the Model Production Function for 1 year, $\text{MPF}(1 \text{ yr})$. Then, we can compute absolute surface ages provided we understand both the time dependence of the impactor flux in the past and how the SFD has varied over the same time. While neither component is known a priori, modeling work suggests the MBA impact rate and their SFD has been fairly constant, say within a factor of ~ 2 , for the last 3–3.5 Gyrs (Bottke et al., 2005a,b). The production rate of kilometer-sized and smaller craters on the Moon, which were caused by impactors derived from the MBA population, also appears to have been constant over this time range (Neukum and Ivanov, 1994). Also, the match between the crater SFDs on ancient lunar terrains and the current MBA SFD, suggests the latter

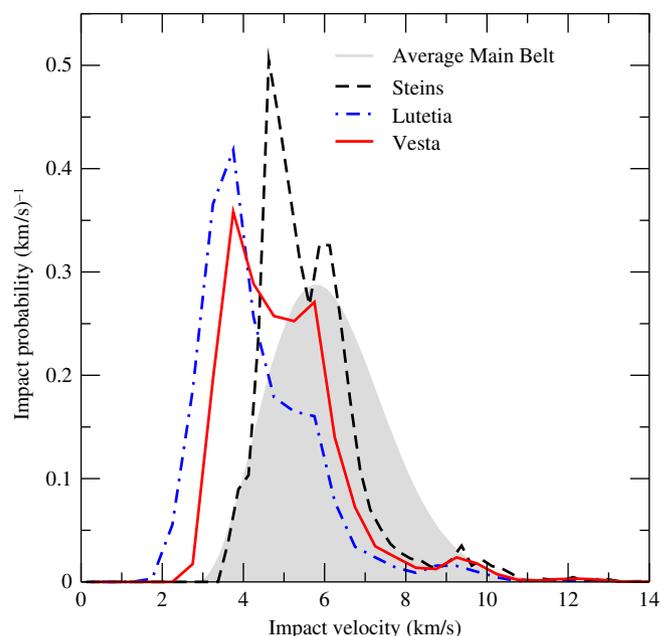


Fig. 5. Impact velocity distribution for Vesta. For comparison, asteroids Steins and Lutetia are also shown, as well as the average impact velocity distribution for the main belt. The computed average impact velocity for Vesta is 5.0 km/s. The impact velocities are derived using Farinella and Davis (1992) algorithm, which computes the average impact velocity between asteroids with absolute magnitude < 13 and Vesta.

has remained unchanged over the past ~4 Gyr (Strom et al., 2005), although this conclusion applies to larger impactors (> 0.5 km).

Assuming all craters that formed on Vesta's surface are retained (i.e., crater obliteration processes are negligible), the crater MPF for Vesta at a time t is given by

$$\text{MPF}(t) = \text{MPF}(1 \text{ yr}) \cdot t \quad (1)$$

where t is the age ($t=0$ is the present). Note that Eq. (1) assumes a constant flux, which is a valid assumption for the young terrains under study in this work. The MPF(t) is used to derive the model cratering age via a best fit to the observed crater SFD that minimizes the reduced chi squared value, χ_r^2 . Data points are weighted according to their Poisson statistics errors. The formal errors on the best age correspond to a 50% increase of the χ_r^2 around the minimum value. Other sources of uncertainties are neglected (see Marchi et al., 2011, for more details).

4. MPF fitting of the crater SFDs

Fig. 6 (left panel) shows the crater SFDs from Figs. 1 and 4, as well as those from the Rheasilvia floor (Marchi et al., 2012b). We find that Marcia's smooth terrains have ten times fewer craters per square kilometer than Rheasilvia's ejecta terrains, implying a significantly older age of the latter. We also find an apparent mismatch in crater spatial density between $D > 1.5$ km craters on the Rheasilvia's ejecta terrains and those on its floor. This may seem odd, given that surfaces with the same age should have the same spatial density. The likely explanation is small number statistics. Indeed, Fig. 4 (right panel) shows that the counting area has an excess of large craters compared to surrounding areas, which would imply we lack statistically significant results for larger craters.

Fig. 6 (right panel) shows how these new data compare with previous measurements on asteroids Gaspra, Ida, and Lutetia (see Section 1). Gaspra's sub-kilometer crater SFD has a cumulative slope which is roughly compatible with that observed on Vesta over the same size range. This is consistent with previous suggestions that Gaspra's craters are not saturated and are representative of the production population (Chapman et al., 1996a). It would also

argue against the idea that its observed small craters have been strongly affected by seismic shaking given that this effect, if present, should affect smaller bodies to a larger degree than on Vesta (e.g., Greenberg et al., 1994). Moreover, the spatial density of Gaspra's craters is higher than those on Rheasilvia. This translates into an age of ~1.6 Gyr, assuming the same crater scaling law used for Vesta applies to Gaspra. Note that for Vesta we applied a correction that transforms the transient crater size into a larger final crater size. It is not clear if such a correction should apply to Gaspra given its much smaller gravity. On the other hand, crater d/D ratios on Gaspra (Carr et al., 1994) are close to those found for lunar craters. It is also possible that other processes, like seismic shaking, may be more effective in producing shallow craters than gravitational collapse. If we neglect this correction, the age of Gaspra would become ~3 Gyr. Gaspra is often assumed to be a representative member of the Flora family, which is thought to produce many NEAs (Vernazza et al., 2008). Accordingly, this result may have key implications for the age and evolution of the Flora family.

Interestingly, our age estimate for Gaspra is significantly older than previous estimates: ~50 Myr by Greenberg et al. (1994), ~200 Myr by Chapman et al. (1996a), and 65–100 Myr by O'Brien et al. (2006). This difference can be understood in the light of our different assumptions. Age estimates of Gaspra require one to determine (i) the collision probability of background MBAs with Gaspra, (ii) the MBA SFD, and (iii) the crater scaling relationship that can transform projectiles slamming into Gaspra into craters. While the methods to achieve (i) have been known for some time (e.g., Opik, 1951; Wetherill, 1967; Farinella and Davis, 1992; Bottke et al., 1994), the assumptions used for (ii) and particularly (iii) by previous works differ from those made here. For example, Greenberg et al. and O'Brien et al. both used a crater scaling law based on early hydrocode simulations (Nolan et al., 1996) that, in some cases, assumed that the ratio between crater to projectile diameters was 20–30, as large or larger than the expected value for asteroids making craters on the Moon at ~20 km/s. More modern estimates, like those used in this paper (Holsapple and Housen 2007; see discussion in Marchi et al., 2010), however, suggest this value may only be ~10. This lower value is also consistent with an interpretation of crater SFDs from Ida and Eros (Bottke and

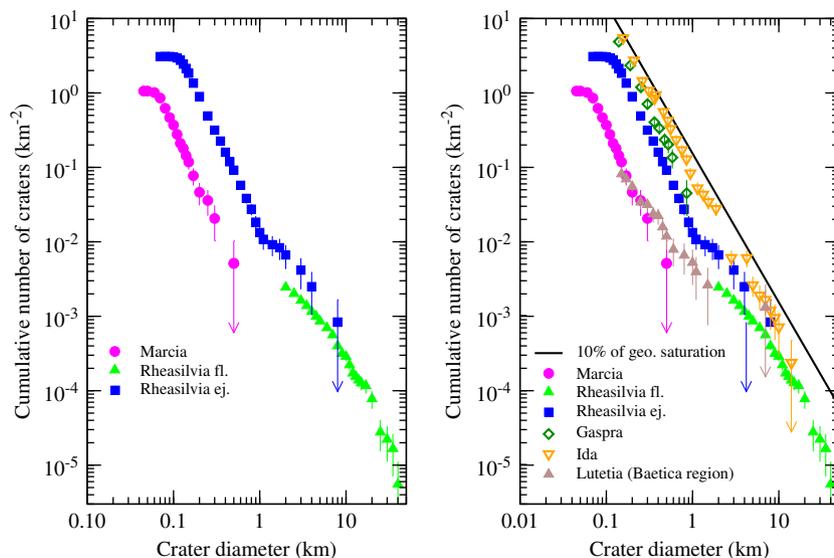


Fig. 6. Left panel: Crater size-frequency distributions measured on Marcia smooth units and Rheasilvia ejecta blanket. Right panel: Comparison with Gaspra and Lutetia. Green triangles are counts from the floor of Rheasilvia (Marchi et al., 2012b).

Chapman, 2006), as well as our natural experiment described above. When our code adopts the O'Brien et al. scaling law, we get an age of ~ 80 Myr for Gaspra, very close to their estimates.

The Vesta and Gaspra distributions both have a lower crater density than that observed on Ida, which appears to be near saturation. This would explain why its crater SFD has a shallower slope than the others. A lower limit on the age of Ida would be ~ 3 Gyr (obtained without considering crater obliteration processes, thus the real age is probably older). This age is consistent with dynamical studies, which suggest the approximate time needed for Ida and other comparable-sized Koronis family members to obtain their so-called Slivan state spin vectors via the YORP effect is 2–3 Gyr (Vokrouhlický et al., 2003).

Curiously, the crater SFD measured on Lutetia's young Baetica region is not near saturation, yet it shows a shallower slope than that observed on Rheasilvia ejecta terrains. Marchi et al. (2011) suggested this could be because downslope movement of small debris may have buried some small craters; there is observational evidence for landslides in the Baetica region, and its surface has an average gravitational slope of roughly 25° .

Fig. 7 shows the MPF-based best fit to both Rheasilvia ejecta and Marcia smooth unit crater SFDs. The red dashed line indicates the best fit of Rheasilvia floor crater SFD published in Marchi et al. (2012b), which was calculated using the hard rock scaling law (Holsapple and Housen, 2007) and a model MBA SFD from Bottke et al. (2005a,b). Intriguingly, the model provides a very good fit to both sets of crater data. This implies that the MBA SFD used to derive the MPF (namely, Bottke et al., 2005a,b) works fairly well down to crater sizes of about 100 m and projectile sizes of about 10 m. It is also consistent with the shape of the MBA SFD remaining roughly constant over timescales of the order of 0.1 Gyr, 1 Gyr, and 2 Gyr, which agrees with model predictions from Bottke et al. (2005a,b) and lunar data (Strom et al., 2005). We also examined how our results were affected by the adopted crater scaling law. We found that computing an MPF using the crater scaling law for sand produced essentially the same results, in terms of quality of the fit. However, the actual value of the material strength has important implications for the age determination (see below).

Another interesting result is that we find most of the Rheasilvia floor and ejecta crater SFDs fit on the same MPF, which strongly

suggests they were created at the same time that the Rheasilvia basin-formation event took place. Interestingly, both Rheasilvia floor and ejecta contain crater clusters, which, given the lack of nearby large craters, could be due to self-secondary cratering. Our results, however, rule out a significant contribution of self-secondary craters to the populations of craters > 100 m.

Similar conclusions can be drawn for the Marcia crater. First of all, our MPF does a good job in fitting the observed crater SFD. If we apply the same crater scaling law used for Rheasilvia (i.e., hard rock), we derive an age of ~ 60 Myr. For a comparison, using the cohesive soil scaling law (and leaving the other parameters unchanged), the age becomes ~ 170 Myr. This is certainly an upper limit because it is derived using hard rock strength of 2×10^8 dyne/cm². Indeed, in the case of cohesive soils, a reduced strength should be considered. Interestingly, using a more realistic strength of about a factor of 10 lower would give an age of ~ 50 Myr, which is in agreement with the first estimate. Therefore it is likely, on the basis of our current data, that Marcia crater formed about 60 Myr ago.

5. Discussions and conclusions

Our results have interesting implications for main belt evolution. First, the crater SFDs on the Marcia and Rheasilvia regions, as well as the asteroid Gaspra, have approximately the same shape between $0.1 < D < 1$ km. Given that their crater spatial densities have a wide range of values, this implies the main belt SFD for asteroid diameters between $0.01 < D < 0.1$ km has had approximately the same shape for the last few Gyr. This is consistent with observations of larger impactors from lunar cratering (Strom et al., 2005).

This outcome matches predictions made by main belt collisional evolution models (e.g., Bottke et al., 2005a,b; O'Brien et al., 2006). In these models, asteroid populations beat up on themselves, with catastrophic disruption events continually demolishing older asteroids and creating new fragments. In these codes, model objects can also be delivered into the terrestrial planet region by algorithms that try to account for the fact that small MBAs have their orbits modified by Yarkovsky thermal drift forces

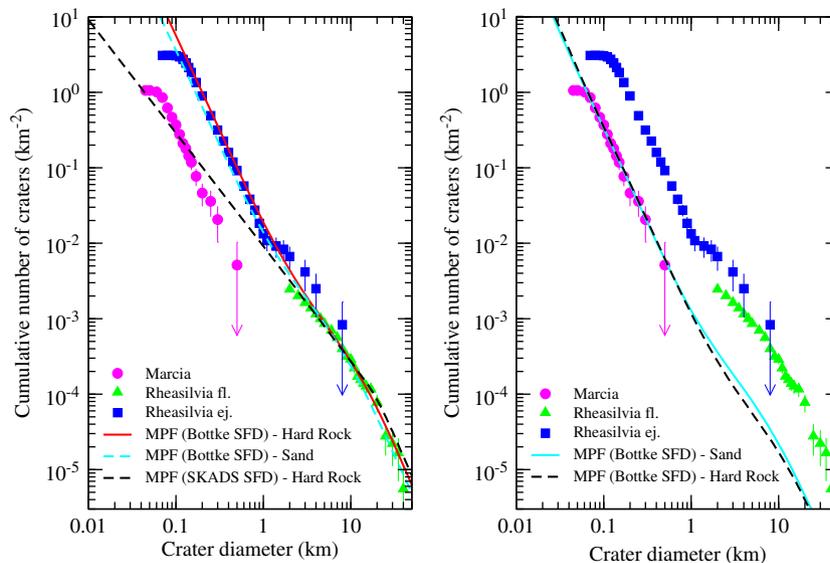


Fig. 7. MPF-based best fits of the crater SFDs of Rheasilvia (left panel) and Marcia (right panel). The MPFs are derived using Bottke et al. (2005a, b) MBA SFD and crater scaling laws as indicated (see main text for further details). The left-hand panel also reports a MPF derived extrapolating Gladman et al. (2009) MBA SFD (valid down to ~ 0.8 km projectile size or ~ 5 km crater size). The latter is clearly extrapolated beyond the range of validity and it is shown only as a comparison (see text).

and resonances. Overall, the model runs of Bottke et al. and O'Brien et al. show that the MBA SFD quickly develops a wavy shape and maintains this shape for billions of years. The pattern only deviates from this in runs for the occasional case where a very large main belt object is disrupted (i.e., something hundreds of kilometers in diameter). Even then, the characteristic SFD quickly returns to the original equilibrium shape.

An interesting question is whether the absolute number of small MBAs has also remained more or less constant over billions of years. This would imply MBAs were in a quasi-steady state over the same time period. Note that such behavior is a common feature of the best fit runs of Bottke et al. (2005a,b). Although the absolute ages of cratered terrains on Vesta and Gaspra are unknown, we can glean insights into this issue by examining the impact history of the Moon.

Dynamical studies and interpretations of the cratered SFDs on lunar terrains suggest the main asteroid belt has been the dominant source of lunar impactors for the last ~4 Gyr (Bottke et al., 2002; Ivanov et al., 2002; Kring and Cohen, 2002; Morbidelli and Vokrouhlický, 2003; Strom et al., 2005). Several terrains on the lunar nearside have absolute ages that were determined directly (and indirectly) using samples returned by the Apollo and Luna missions. Combining these values with measurements of the spatial density of small craters on these surfaces, it is possible to estimate the average lunar impact flux at several moments in time between the present day and ~3.5 Gyr ago (see Stöffler and Ryder, 2001, for a recent review of these issues, as well as Neukum and Ivanov, 1994). The most straightforward interpretation of these values is that the average lunar impact flux for MBA-derived projectiles has remained approximately constant (i.e., within a factor of 2) over the last few Gyr (Hartmann, 1981; McEwen et al., 1997; Stöffler and Ryder, 2001; Marchi et al., 2009; Hiesinger et al., 2012).

Accordingly, if the lunar impact flux has not changed very much over a ~3 Gyr interval, and nothing else important has changed regarding the delivery of small MBAs to the terrestrial planet region, it is logical to think that the small MBA population has remained more or less constant over this time period as well. Accordingly, we predict the small MBA population, on average has been near or in steady state for several Gyr.

Note that the match obtained between model results and observations probably means the assumptions made by the collision codes are broadly reasonable (e.g., collision probabilities, disruption scaling laws, nature of their fragment SFDs, dynamical depletion rates, etc.). With this said, one must be careful in how this interpretation is used; while the results of the best fit collision models indeed match numerous constraints, they may not yet provide unique solutions.

For instance, small asteroids can also lose material via the non-gravitational YORP spin-up mechanism (e.g., Pravec et al., 2010). Interestingly, the older collisional codes discussed above do not include this effect, yet they appear to reproduce the small MBA SFD and many other constraints. This could suggest that YORP mass shedding, as a process, is secondary to other mass loss mechanisms, and that it is reasonable to neglect it when modeling the collisional evolution of the small MBA SFD. It is also possible, however, that other aspects of the modeling are incorrect and are in effect compensating for the absence of YORP mass shedding. If so, a closer analysis of this mass shedding process, combined with our new crater constraints, may yield new insights into the main belt evolution (Rossi et al., 2012). We consider this an interesting issue for future work.

The apparent stability of the small MBA SFD in terms of both shape and population over time is perhaps surprising. It indicates that the sources of small MBAs, such as asteroid family forming events, are well balanced by the various sink mechanisms.

Modeling work suggests that large asteroid disruption events are capable of supplying a sizeable fraction of the total MBA population for hundreds of Myr to Gyr timescales via a collisional cascade (Bottke et al., 2005a,b). Thus, at any given time, the small MBA population may be dominated by fragments from several tens of large breakup events. This likely explains why the samples in our meteorite collections only appear to represent about 30 parent bodies (Meibom and Clark, 1999; Keil, 2000, 2002; Burbine et al., 2002; Bottke et al., 2005c).

In summary, we have presented in the paper the sub-kilometer crater SFDs of two young terrains on Vesta. We found that these crater SFDs match the estimated crater production function derived from model main belt SFDs. We used the modeled crater production function to estimate the ages of our two young regions. We find an age of ~ 1 Gyr for Rheasilvia basin and ~60 Myr for Marcia crater.

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