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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.

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., Ivezić 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.

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

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., 2014). 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., 2014). Our crater counts are shown on the figure. In defining the crater counting unit, we were careful to stay away from high-slope terrains (e.g., crater walls)

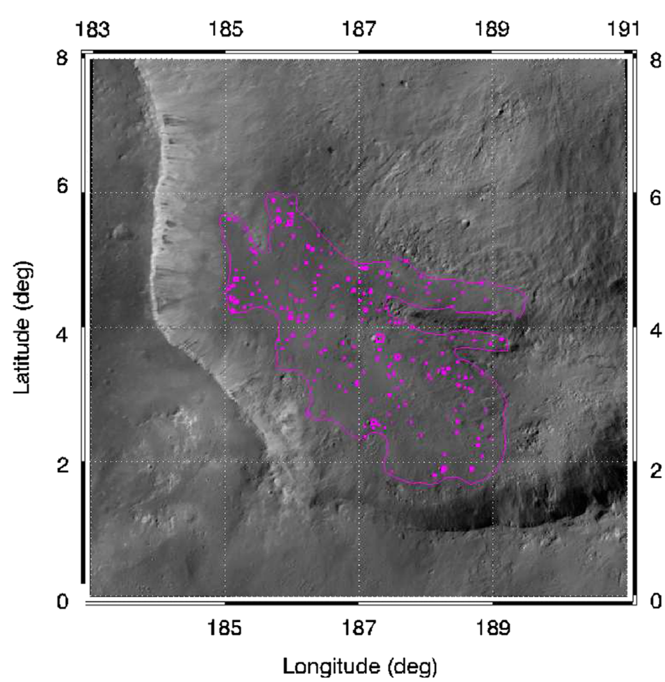

Fig. 1. Orthographic projection of a LAMO mosaic of the southwest portion of the 60-km Marcia crater. The contour line marks the region used for crater counts, whose area is 194.5 km^2. The map has a resolution of ~15 m/px. Circles indicate the 206 craters that have been measured, ranging from 50 m to 500 m in diameter.