COLLISION PROBABILITIES AND IMPACT VELOCITY DISTRIBUTIONS FOR VESTA AND CERES

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Overview: As main-belt asteroids, Vesta and Ceres experience collisions with other asteroids. Given the fairly large eccentricities and inclinations of asteroids in the main belt, these collisions tend to occur at high velocity (several km/s or more), and because of the large number of asteroids, these collisions occur relatively frequently, as compared to impacts on the terrestrial planets. Figure 1 shows the locations of Vesta and Ceres in the main belt. Here we calculate their collision probabilities and impact velocity distributions in the current main-belt environment, and discuss the implications for the current rate of impacts on their surfaces.

Model and Results: To perform these calculations, we use an algorithm based on [1], which determines the probability and impact velocity for all possible encounter geometries between a target and a population of impactors. Gravitational focusing is not taken into account in these calculations, but should only be an issue for the lowest-velocity impacts. For the main-belt impactors, we use the osculating orbital elements of all asteroids with absolute magnitude H>11 (roughly 30 km in diameter) from the astorb.dat catalog [2]. This sample of ∼1400 asteroids is reasonably observationally complete (although it's possible that the orbital distribution of much smaller bodies could vary from this). Proper orbital elements [3] are used for Vesta and Ceres, in order to average out the short term-variations in their orbital parameters. Note that all members of the Vesta family (except Vesta) are smaller than the H>11 threshold. We discuss the implications of Vesta's family membership in the final section.

Table 1 summarizes the intrinsic collision probability $\mathrm{P_i}$ and average collision velocities (mean, RMS, and median values) for Vesta, Ceres, and the entire main belt, where $\mathrm{P_i}$ is the collision frequency normalized by the number of impactors and the cross sectional area of the target body. The main belt values are for all main belt bodies interacting with one another. Figure 2 shows the full impact velocity distributions for Vesta and Ceres, compared to the main-belt average impact velocity distribution. It is important to note that while average impact velocities are often quoted and used (eg. the 'canonical' 5 km/s value for the main belt), asteroids in fact experience a significant fraction of impacts at velocities much smaller and larger than this. About 10% of all impacts in the main belt occur at velocities over 8 km/s.

Discussion and Implications: Ceres has a somewhat larger impact probability than Vesta due to its more central location, which allows it to cross the orbits of more potential impactors. Both asteroids have average impact velocities that are somewhat smaller than the main-belt average, due to the fact that their eccentricities and inclinations are not particularly large. A more significant difference is that impacts at velocities over ∼8-10 km/s are roughly half as likely on Vesta and Ceres than in the main belt in general. As impacts at these velocities may be in the range where significant melt is produced, the relative rarity of such impacts on Vesta and Ceres may hint at differences between the surfaces of these bodies and those of other asteroids with larger orbital eccentricities and inclinations.

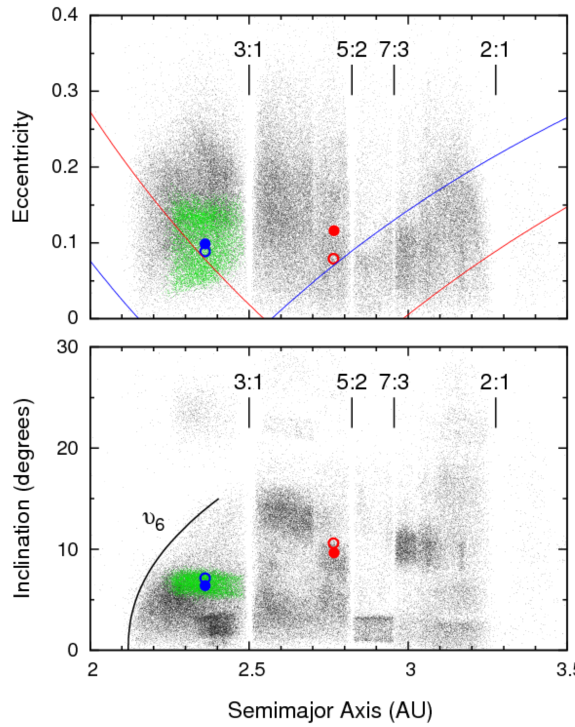

Figure 1: The location of Vesta (blue) and Ceres (red) in the asteroid belt. Open circles are their osculating (instantaneous) orbital elements [2], and solid points are their proper orbital elements [3]. Grey points are the osculating orbital elements of numbered asteroids. Green points are osculating elements of all numbered members of the Vesta family identified by [4]. Blue and red lines show the range of asteroids that currently cross the orbits of Vesta and Ceres. The main mean-motion and secular resonances are also shown.

The $\mathrm{P_i}$ values from Table 1 can be used to estimate the rate of impacts on Vesta and Ceres. Given the mean cross-sectional radius $\bar{\mathrm{r}} = \bar{\mathrm{r}}_\mathrm{t} + \bar{\mathrm{r}}_\mathrm{p}$ (sum of the mean target and projectile radii) and the number of projectiles $\mathrm{N_p}$ (which could be, for example, the number of bodies of a given size in the main belt), $\mathrm{P_i}$ can be converted to impact frequency $\mathrm{f} = \mathrm{P_i}\,\bar{\mathrm{r}}^2\,\mathrm{N_p}$. Vesta has a mean radius of 258 km [5], and for an intrinsic colli-

Asteroid	P_i (10^{-18} km^{-2} yr)	V_{mean} (km/s)	V_{RMS} (km/s)	V_{median} (km/s)
Vesta	2.72 (2.97)	4.75 (4.74)	5.18 (5.17)	4.41 (4.40)
Ceres	3.43 (3.70)	4.79 (4.79)	5.19 (5.20)	4.54 (4.54)
Main Belt	2.79 (3.11)	5.14 (5.17)	5.64 (5.67)	4.79 (4.81)

Table 1: Collision velocities and probabilities for impacts on Vesta, Ceres, and the entire main belt. Values in parentheses include only those asteroids interior to the 2:1 mean-motion resonance with Jupiter (approximately 3.3 AU).

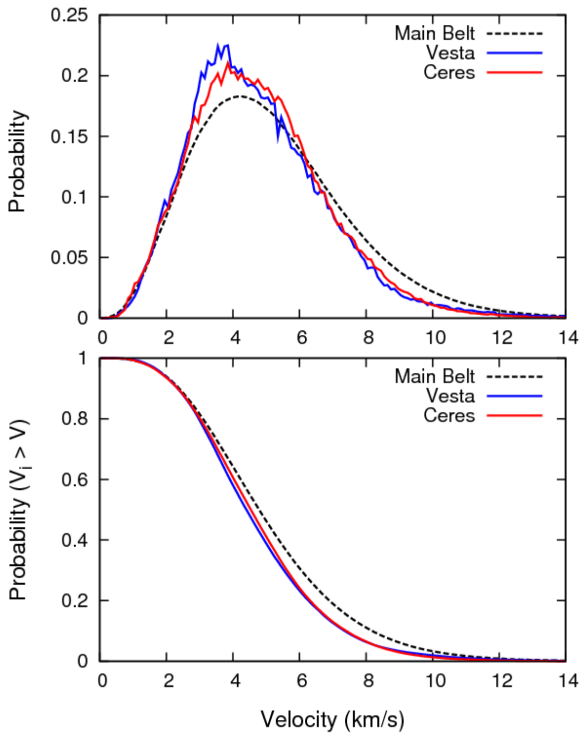

Figure 2: Collision velocity distributions for Vesta, Ceres, and the entire main belt. The lower figure is a cumulative version of the upper figure, showing the fraction of impacts larger than a given impact velocity V_i.

sion probability P_i of 2.72×10^{-18} km^{-2} yr^{-1}, this implies that a randomly-selected main-belt asteroid has a 1.81×10^{-13} yr^{-1} chance of hitting Vesta. The main belt contains roughly 1.3 million bodies larger than 1 km in diameter [6, 7], suggesting that an asteroid >1 km in diameter should impact Vesta every ∼4.2 Myr. A similar calculation for Ceres, with a mean radius of 476 km [8], suggests that it should be hit by a >1 km asteroid every ∼1.0 Myr.

Vesta is a member of a collisional family (the green points in Fig. 1), whose members (‘Vestoids’) are fragments from a large impact on Vesta in the past. Because they are clustered, Vesta will have different P_i and V_{mean} with the Vestoids compared to general main-belt impactors. Using the osculating elements [2] of the 1000 largest Vesta family members identified by [4], we find $P_i = 14.2 \times 10^{-18}$ km^{-2} yr^{-1} and V_{mean} = 3.37 km/s for impacts by Vestoids. While the family members only make up about 5% of all asteroids, they will result in about 25% more impacts on Vesta than would be estimated by considering the H>11 background objects alone, although these impacts will occur at a somewhat lower velocity that those by background main-belt objects. In the past, when the Vesta family was likely more tightly clustered, and its size distribution was likely steeper, impacts with Vestoids would have been even more common, but at an even lower velocity. Understanding how the impact rate from Vesta family members has evolved with time will be the focus of future study.

At the mean impact velocities from Table 1 and typical densities inferred for asteroidal material, scaling laws [eg. 9] predict that a 1 km diameter impactor should create a crater on the order of 10 km in diameter. Vesta and Ceres should both have several such craters less than ∼10 Myr old, and these may expose fresh material that is relatively unaltered by space weathering effects.

The cratering records on planetary surfaces provide an important means of determining the relative ages of different surfaces and units, and with suitable constraints can be used to estimate absolute ages as well. Impact probabilities and velocities as calculated here, combined with more detailed calculations of the crater-impactor scaling relationship and estimates of the main-belt size distribution, can provide a means for assigning absolute ages to surfaces on Vesta and Ceres that are studied using crater counting techniques, and can help connect the cratering records on those bodies to the better-constrained Lunar Reference System [eg. 10].

Acknowledgments: This work was supported by NASA’s Dawn at Vesta Participating Scientist Program.

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