FORMATION OF IMPACT CRATERS ON COMETS AND ASTEROIDS: HOW LITTLE IS KNOWN.

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Impact phenomena shaped our solar system. From the accretion of planetesimals 4.6 billion years ago to the spallation of meteorites from their parent bodies, this process has left no bit of matter untouched. The study of impact craters on small bodies therefore provides a foundation for understanding accretion and the delivery of meteorites – topics central to the origin of planets. Moreover, geologic-scale impact craters forming in low gravity reveal details of the cratering process that are hidden on high-gravity worlds like the Earth and Moon.

The detailed study of small body cratering began with efforts by Housen et al. (1979), Veverka and Thomas (1979) and others, together with efforts related to catastrophic disruption of small bodies (Chapman and Davis 1975; Fujiwara et al. 1979; Farinella et al. 1982). But the discovery of Stickney (the ~10 km diameter crater on the ~20 km diameter Martian satellite Phobos) and comparably huge divots imaged by Voyager on satellites of Jupiter and Saturn made it clear that small bodies can sustain huge wallops despite the conclusion of scaling models, notably that the impactor responsible for Stickney would have catastrophically disrupted Phobos.

While large impact structures on bodies with significant gravity are much better understood today than they were originally, for small bodies this is not the case. We appear almost to be back-pedaling towards an earlier vision of the asteroid impact process, pioneered by Art Clokey (without much guidance from geologists) in his 1957 *Gumby* claymation adventure "The Small Planets". Although nobody today confesses to expect clear gravity signatures around ~10 m craters on ~100 m asteroids (we have yet to obtain clear images of anything much smaller than ten kilometers), few expected copious regolith on bodies the size of Eros (33×13 km) either. Surprise is the norm.

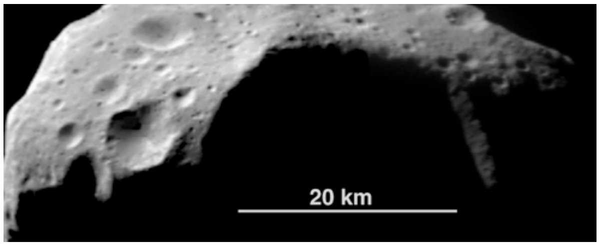
Fifteen years ago, bodies that size were widely believed to be capable of sustaining a few centimeters of regolith at best (e.g. Veverka et al. 1986). Instead, NEAR Shoemaker confirmed what had been hinted during less clearly resolved Galileo flybys of asteroids Gaspra and Ida: that Eros-sized asteroids can be awash in gravitationally bound debris (collisional or original is anybody's guess) ranging in size from ~100 m blocks (Chapman et al. 2001) to submicron grains accumulating in "ponds" (Robinson et al. 2002). Global regolith deposits on Eros range from 100's of m to undeterminable depth, and surface geophysics may even be dominated by quasi-aeolean processes such as electrostatic levitation (Lee 1996) and seismic shaking (Cheng et al. 2002; Asphaug et al. 2001).

Even on the smallest bodies yet observed, there is evidence for gravity dominance. Asteroid Ida's tiny (1.6 km) satellite Dactyl exhibits a spheroidal shape, as one would expected under self-gravitational control, and its major craters display rims and maybe central peaks[1].

But to contrast Dactyl, Phobos, Deimos and other gravity regime Lilliputians (e.g. Thomas 1998), one finds 60 km Mathilde, a body which trashes every established theory of impact cratering, and which is from impact cratering's point of view one of the most astonishing bodies. Here one sees huge craters devoid of any gravity signature, and devoid of any signature of overprinting, on a pitted spheroid lacking visible fractures or other strength-related de-

[1] Crater rims are not unique to the gravity regime, and can form by shear bulking during plastic deformation. Bulking requires weakly cohesive granular media on the smallest bodies since plastic deformation otherwise involves impact stresses that would result in material escape. In either case an asteroid is not monolithic if one sees rimmed craters.

formation. Nothing is here but the huge crater bowls themselves. Ejecta has either all entirely escaped (Asphaug et al. 2002) or was never ejected at all (Housen et al. 1999), evidently in a target sufficiently porous to not communicate each blow globally, yet sufficiently cohesive for its crater rims not to collapse into softer shapes.



Clues to impact geophysics are everywhere. Shown below is pathological example (NEAR Image 0136819148) where four ~100 m fragments of an ejecta block appear to rest in the ~700 m diameter secondary crater they created. If this is not a chance association (the odds are small), it is the record of an impact involving geologic masses at known speed (v_{orb}^{max} ~10 m/s) and mass (~2.e10 kg). Pi-group scaling predicts a crater about half as large, perhaps because low velocity coupling is more efficient than hypervelocity coupling.

While secondary craters on asteroids may seem oddities of cratering mechanics, they have potential significance for helping us understand accretion collisions in the solar nebula which took place at similar speeds and involved similar materials, and which are a problematic theoretical bottleneck (Benz 2000).

Another kind of comparative geology can be conducted by studying the largest craters on asteroids, which span the transition from the strength to gravity regimes and exhibit whole-body effects (e.g. Stickney on Phobos; Asphaug and Melosh 1993, Thomas 1998) or the lack thereof (Mathilde, as discussed above). From these, key impact aspects can be independently derived, and exhibit a unique geologic record of the planetary impact process masked in the enormous gravity of terrestrial planets. The mechanics of cratering is preserved like nowhere on Earth.

Conclusion: Two decades of experimental, theoretical, and numerical modeling (Holsapple et al. 2002; Asphaug et al. 2002) together with spacecraft reconnaissance of asteroids has forced us to revisit pretty much everything we think we know about how asteroids collisionally evolve. Geologists have had to get used to landscapes where sunlight may be as important a force as gravity, where cohesion less than that of dry snow can sustain cliff walls and monolithic structures, where puffballs can masquerade as rocks and vice-versa. Impact theorists have had to take a big step back in their view of the process, especially for oddities like Mathilde. But Mathilde is perhaps the norm, and we await an appropriate geophysical understanding of these objects, and how craters form when gravity and strength – the fundamental forces of geology – compete for dominance.

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