LARGE CRATERS ON MATHILDE

A. F. Cheng and O. S. Barnouin-Jha, Johns Hopkins Applied Physics Laboratory, Laurel, MD

Introduction. The Near Earth Asteroid Rendezvous (NEAR) flyby of the large, C-type main belt asteroid 253 Mathilde discovered 5 craters of diameter 19 to 33 km, comparable to the 26.5 km mean radius [1]. The NEAR flyby also yielded the first direct mass determination for an asteroid [2] and a density estimate of 1.3 ± 0.2 g cm^{-3} [1]. Comparison of this density with that of carbonaceous chondrites suggests a porosity of ~50% for Mathilde.

This paper will discuss evolutionary implications of the large craters on Mathilde whose diameters *D* are at least comparable to the mean radius *r*. We will use the term "giant craters" to denote craters of $D > 0.75\ r$, or $D > 19$ km on Mathilde. Giant impacts are of interest because they are close to the catastrophic disruption threshold, defined as an impact that leaves no target remnant larger than half the original diameter. Calculations by Asphaug *et al.*(1996) [3] exemplify how giant impacts form on an Ida-sized body by a vertical impact except when the free surface opposite to the point of impact is too close, causing disruption.

The present work uses available results from experiments and numerical simulations, including effects of oblique impacts into irregular bodies and considering energy losses from effects of porosity. In addition, important effects arise from the finite size and curvature of the target body [3, 5, 6]. We find it not surprising that Mathilde survived at least five giant impacts without being destroyed. Moreover, the observed bowl-shaped morphology is not unexpected for giant impacts, considering the expected occurrence of oblique impacts onto small, irregularly shaped bodies.

Angular distribution of impacts. The shape of the asteroid may play a role in the style of cratering that occurs on the surface. The most probable angle of impact is 45 degrees for the case of an isotropic population impacting a sphere [7, 8]. Asteroids, including Mathilde, are non-spherical. Figure 1 shows how the most probable impact angle can change when the dimensions of an elliptical spheroid are altered for an anisotropic impactor flux along one of the spheroid's axes. The most probable impact angle moves to more oblique impacts when the spheroid is stretched parallel, and to more normal impacts when the spheroid is stretched perpendicular, to the impactor flux relative to the spherical case. Similar changes are seen when an elliptical cylinder undergoes an isotropic impactor flux.

Oblique impact effects on Mathilde The above variations in angular distribution suggest that oblique impacts (θ < 30 degrees) possibly play an important role in the evolution of Mathilde. The effects of oblique impacts have been extensively documented in impact experiments [5, 6, 9, 10, 11, 12, 13]. These experiments reveal that both cratering efficiency (i.e. the mass displaced by an impact) and the peak pressures in the target and projectile decrease with impact angle. For a fixed crater diameter, the peak pressure generated in a target decreases with decreasing impact angle. Whether or not Mathilde disrupts depends on the peak tensile strain rate generated in the body [e.g. 14], which is comparable to the peak compressive strain rates achieved in Mathilde during the impact [15]. Compressive strain rates have been shown to be a function of peak impact stresses [16]. Hence, a decrease in peak pressure with impact angle, for fixed crater diameter, could give Mathilde a better chance of surviving during the formation of giant craters.

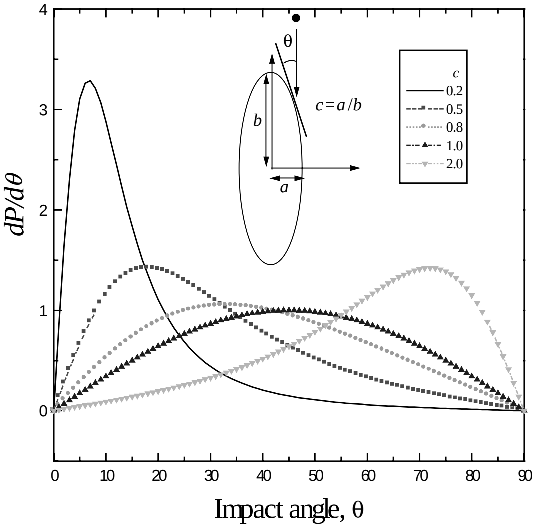

Figure 1: Probability *dP*/*d*θ of impact at a given impact angle θ for an elliptical spheroid undergoing an isotropic projectile flux along one of its axes.

Implications of target curvature. The existing laboratory database also describes the crater morphology resulting from oblique impacts into half space targets [5, 6]. Under most conditions, crater planforms are circular or nearly so. The most conspicuous observational signature of oblique impacts *in a half-space target* is the formation, at very low impact angles, of highly elongated craters that can be accompanied by one or more smaller downrange craters. These are due to relatively large fragments derived from the projectile that impact downrange from the initial contact either elongating the original crater or generating separate craters [10].

Large Craters on Mathilde: A.F. Cheng and O.S. Barnouin-Jha

The formation of highly elongated and downrange craters is suppressed in the case of impacts into highly curved targets, or equivalently, in the case of giant craters. This is because curvature of the target surface can cause projectile fragments to miss the surface entirely, so they do not participate in the later stages of crater growth . Nearly circular planforms result [5, 6].

Hence, giant craters in small bodies are expected to have a bowl-shaped morphology, even considering oblique incidence. The observed morphology of giant craters on Mathilde is not surprising.

Relative likelihood of giant cratering vs. disruption. Mathilde has sustained impacts that created at least five giant craters without causing disruption. In these impacts, Mathilde was most likely the larger of the colliding bodies; even the present-day Mathilde remnant is a relatively large asteroid. With established scaling relations extended by using the normal component of the incident velocity [6], we estimated the size of the projectiles required to create a crater of fixed diameter, for varying impact angles. Because of Mathilde's measured porosity, we used Schmidt and Housen [18] coupling parameters for "dry soil" and "wet soil", the latter representing a less porous and more cohesive (but not necessarily water-rich) target. We calculate the projectile diameters $a_{19}(\theta)$ and $a_{33}(\theta)$ predicted to create craters of fixed 19 km and 33 km diameters, respectively. In both cases, a larger projectile is required for more oblique impacts. Owing mainly to the effects of porosity on reducing energy coupling, larger projectiles are required for "dry soil" than for "wet soil". We did not account for effects of ricochet at very low incidence angles.

We assume a projectile size distribution of the conventional form derived for Gaspra and Ida [7]

$$dn = 2.7 \times 10^{12} a^{-2.95} da, \quad \mathrm{a} > 100\,\mathrm{m}$$

where dn is the number of projectiles in the diameter range a, $a+da$. Then projectiles in the diameter range from $a_{19}(\theta)$ to $a_{33}(\theta)$ will make giant craters as observed on Mathilde, whereas projectiles larger than $a_{33}(\theta)$ are assumed to cause catastrophic disruption. Since a 33 km crater is observed on Mathilde, the actual catastrophic disruption threshold must be at least that large, but it may be somewhat larger. Hence our procedure overestimates the number of projectiles that cause catastrophic disruption.

To obtain the relative probability of giant crater formation versus catastrophic disruption, we must average over the distribution of impact angles. It turns out that the ratio $[a_{19}(\theta) / a_{33}(\theta)]$ is very nearly independent of impact angle, so the resulting relative probability (giant craters/disruption) is nearly independent of the impact angle distribution. We find that the relative probability of giant crater formation versus disruption is 2.64 for "dry soil" parameters and 2.25 for "wet soil," so giant crater formation is significantly more likely than disruption in either case. Hence the occurrence of five giant craters on one face of Mathilde may not be extremely unlikely. This conclusion is robust against our uncertainty regarding the actual catastrophic disruption threshold, because we have overestimated the probability of disruption by putting the threshold at a 33 km diameter crater

Acknowledgement. This work was made possible by NASA grant NAGW-4979.

References: [1] Veverka et al. (1998) Science, 2109-2113; [2] Yeomans et al. (1998) Science, 2106-2109; [3] Asphaug et al. (1996) *Icarus 120*, 158-184; [4] Housen et al. (1983), *JGR 88*, 2465-2499; [5] Schultz, P. H. (1997a), *LPSC XXVIII* (abstract); [6] Schultz, P.H. (1997b), *BAAS 29* (abstract), n.3; [7] Gilbert, G.K., (1893), *Bull. Phil. Soc. Wash. 12*, 241-292; [8] Shoemaker, E. (1962*) Physics and astronomy of the Moon*, A. Kopal (editor), Academic Press, 283-571; [9] Gault, D.E. and J. Wedekind (1977) *PLPSC VIII*, 3843-3875; [10] Schultz, P. H. and D.E. Gault, (1990), *GSA Spec Pap. 246*, 239-261; [11] Schultz, P. H. and D.E. Gault, (1995), *LPSC XXVI*, 1251-1252; [12] Schultz, P.H. and R.R. Anderson (1996), *GSA Spec Pap. 302*, 397-417; [13] Schultz, P. H. and S. D'Hondt (1996) *Geology 24*, 963-967. [14] Grady, D.E. (1982), *J. Appl. Phys. 55*, 322, [15] Melosh. et al. (1992*) JGR 97*, 14735-14759; [16] Swegle, J.W. and D.E. Grady (1986), Shock waves in condensed matter-1985, Y.M. Gupta (editor), Plenum, 353; [17] Meyers, A. (1994) *Dynamical behavior of Materials*, 668pp; [18] Schmidt R.A. and K.R. Housen (1987) *Int. J. Impact Engin.* 5, 543-560; [19] Greenberg et al. (1996) Icarus 120, 106-119.