THE LARGE CRATER ON ASTEROID STEINS: IS IT ABNORMALLY LARGE?
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Introduction: The Rosetta mission to comet 67/P Churyumov-Gerasimenko is also scheduled to do two asteroid fly bys. The first of these was on Sept. 5th, 2008, when the spacecraft flew within 800 km of asteroid 2867 Steins. The timing of the encounter meant that the surface of the asteroid (as seen from the spacecraft) was well illuminated, providing good imaging conditions. As well as providing an opportunity for checking out the instruments on the Rosetta spacecraft, the encounter also provided high quality data concerning this E type asteroid. Full publication of this data is eagerly awaited, but early reports noted a major crater like feature on the asteroid.

Asteroid Steins is a small, irregularly shaped object. Before the encounter, its size had been estimated as typically 4.6 km based on its light curve and albedo [1-3]. Estimates of the albedo vary somewhat, an initial 0.45±0.10 was determined by polarimetry [1] but was later lowered to 0.34±0.06 based on modeling of the spectrum over the range 5 – 38 µm [3]. Features in its spectra suggest an enstatite like composition and an E[II] type asteroid classification [4-5].

The asteroid is located at 2.36 AU, i.e., well within the main belt, and rotates with a period initially estimated as 6.052±0.007 hrs [6], and later refined as 6.04681±0.00002 hrs [3]. Based on 26 visible light curves, obtained from ground telescopes and the Rosetta spacecraft itself, a shape model of the asteroid was made in [3] which gave the 3 axis dimensions as 5.73±0.52, 4.95±0.45, and 4.58±0.41 km, where the ratios of the main axes were given as a/b = 1.17 and a/c = 1.25 and total volume as 64.3 km^3. One aspect taken from the shape model in [3] is shown in Fig. 1.

Observations: Shortly after the encounter the Rosetta team publicly showed images taken of the asteroid during the flyby. A typical montage (source the ESA web site accessed Dec 2008: http://www.esa.int/esa-mmg/mmg.pl?mission=Rosetta&type=I) is shown in Fig. 2. The agreement with the shape model developed pre-encounter is testament to the precision of that work. However, a major type of surface feature can now be observed which could not be previously modeled based on light curves, namely craters

Craters: Three types of craters were noted on the surface of asteroid Steins by the Rosetta team in their initial press announcements; small craters randomly distributed across the surface, a chain of (small) craters

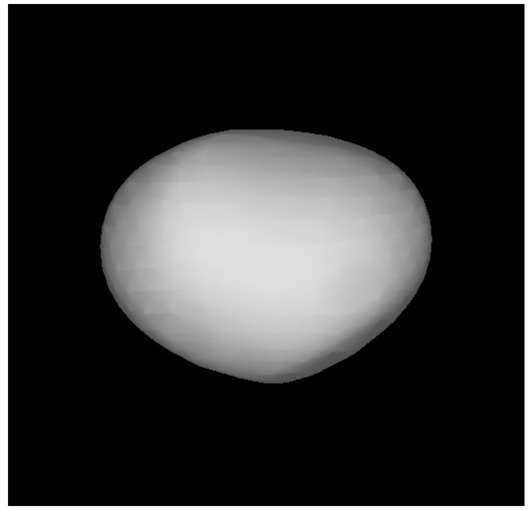

Fig. 1 One view of the pre-encounter 3 dimensional shape model of asteroid Steins. Taken from Fig. 12 in [3].

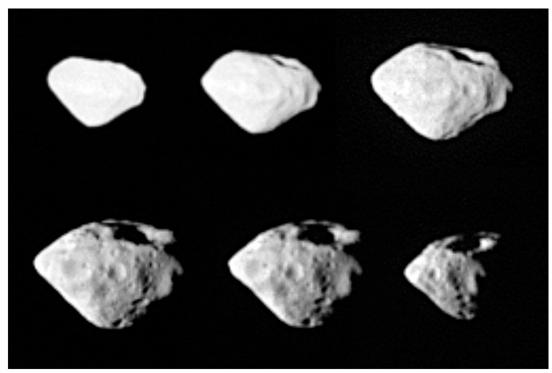

Fig. 2. Images of Asteroid Steins, taken from the Rosetta spacecraft by the OSIRIS imaging system. Image source: ESA web site (ESA ©2008 MPS for OSIRIS Team MPS/UPD/LAM/IAA/RSSD/INTA/UPM/DASP/IDA).

visible on the front of the lower 3 images in Fig. 2 (running vertically) and a single larger crater (located at the top of the images in Fig. 2). Here we consider the single larger crater. Note that implicit in such discussions is an impact origin of these crater like features.

The large crater was initially reported as some 2 km in diameter. Based upon the images in Fig. 2 we estimate it is some 43% of the length of the largest axis, i.e. has a diameter of some 2.5 km if we take the largest axis as 5.73 km [3]. The ratio of crater diameter (D) divided by target body radius (R) is often used in assessing critical crater size and here D/R ~ 0.86. The question that arises is: Is this an abnormally large crater? The problem is that a large impact will not just cause cratering, but, once a critical energy density is reached, will cause catastrophic disruption, i.e., the target body will split apart. The parts will then disperse if sufficient energy is present to overcome their self gravitation, or, at an intermediate energy they will mostly reassemble under their self gravity. In both these latter cases the original impact crater will be lost. We can thus already say that the impact associated with the large crater was sub-critical (i.e., did not cause disruption) and if Steins is a fragment of a larger primordial body this impact was not responsible.

Several methods are available for determining the critical crater diameter for impacts on small bodies which lead to disruption. At laboratory scales, impacts can be undertaken using two stage light gas guns which can reach the 5 – 6 km s^{-1} impact speeds typical of impacts in the asteroid main belt. However, projectile sizes are limited to the mm and cm scale, so results are not directly relevant (unless some size dependent weakening is introduced when extrapolating to larger, km sized bodies). The other two methods are modeling (which requires not only appropriate equations of state etc., but also a detailed knowledge of a particular target body properties) or compilation of observed features on other small bodies. In the latter case, by observing many bodies a limit on crater size can be found which approaches the critical upper limit of crater size on a finite small body. Conveniently, such a compilation has recently been published [7] and the target body radii cover the range 0.7 to 265 km, i.e. Steins is within the size range. The data concern a total of 21 bodies (13 satellites and 8 asteroids) and include rocky and icy bodies. For the rocky bodies, Dactyl is smaller than Steins, and 5535 Annefrank is similar in size.

The ratio of largest observed crater diameter to target body radius is plotted for the bodies in [7] in Fig. 3. It can be seen that Steins fits the general trend for rocky bodies, indeed it is not even the limiting case (i.e., is not proportionally the largest crater known on a small rocky body). For the smaller Dactyl, D/R ~ 0.86 [7], the same value as here for Steins. And for the slightly larger Deimos D/R ~ 1.6, significantly greater than for Steins.

Discussion: It has been suggested [8] that Steins and NEA (3103) Eger are fragments of a larger body, disrupted in the asteroid belt some 2 bya. This is based on their similar spectral properties and differences with the other known E[II] group members: 434 Hungaria, 2035 Stearns, 2048 Dwornik, 4660 Nereus, and 6911 Nancygreen have shallower bands at 0.49 µm and 64 Angelina has a spectral slope different to Steins and Eger. In [8], modelling of the orbits suggests a common origin for Steins and Eger at least 2 bya. Such a long period since its formation would permit significant subsequent cratering of the surface of Steins, consistent with the observations. If Steins is a disrupted fragment of a larger primordial body, it is difficult to estimate the original total mass of the parent with only 2 putative family members. If we make a shape analysis based on the assumption that the pointed base of Steins (the bottom in Fig. 2) was at the centre of the parent body, and the flat upper facet (where the large crater is) was on the original surface, then we have a parent with radius ~5 km. This can be treated as a minimum size estimate. If spherical, the parent thus had volume ≥524 km^3, i.e. Steins is ≤12% of the original parent volume.

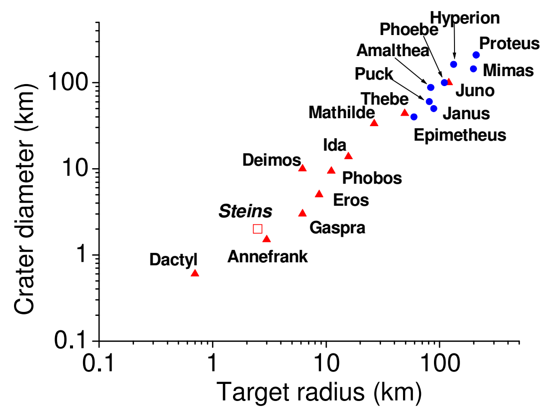

Fig. 3. Diameter of largest crater observed on small bodies tabulated in [7]. Red triangles are for rocky bodies, blue circles are icy bodies. Steins is shown as a red (open) square.

Conclusions: The results of the analysis by the Rosetta team of the observations of asteroid 2867 Steins by the Rosetta spacecraft are eagerly awaited. However, by comparison with other similar sized bodies, we can already say that the early claims that, based on the visual images of the surface, Steins has an abnormally large impact crater can be seen to be incorrect. The crater is indeed large, but not abnormally so and it well fits the known trend for large craters on small rocky bodies.

References: [1] Fornasier S. et al. (2006) *Astron. & Astrophys.*, *449*, L9–L12. [2] Fornasier S. et al. (2008) *Icarus*, *196*, 119-134. [3] Lamy P.L. et al. (2008) *Astron. & Astrophys.*, *487*, 1179–1185. [4] Barucci M.A. et al. (2005) *Astron. & Astrophys.*, *430*, 313-317. [5] Barucci M.A. et al. (2008) *Astron. & Astrophys.*, *477*, 665-670. [6] Kuppers M. et al. (2007) *Astron. & Astrophys.*, *462*, 13-16. [7] Leliwa-Kopystyński J. et al. (2008) *Icarus, 195*, 817-826. [8] Fornasier S. et al. (2007) *Astron. & Astrophys.*, *474*, L29–L32.