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The large crater on the small Asteroid (2867) Steins

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A R T I C L E I N F O

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The maximum size of impact craters on finite bodies marks the largest impact that can occur short of impact induced disruption of the body. Recently attention has started to focus on large craters on small bodies such as asteroids and rocky and icy satellites. Here the large crater on the recently imaged Asteroid (2867) Steins (with crater diameter to mean asteroid radius ratio of 0.79) is shown to follow a limit set by other similar sized bodies with moderate macroporosity (i.e. fractured asteroids). Thus whilst large, the crater size is not novel, nor does it require Steins to possess an extremely large porosity. In one of the components of the binary Asteroid (90) Antiope there is the recently reported presence of an extremely large depression, possibly a crater, with depression diameter to mean asteroid radius ratio of ~(1.4–1.62). This is consistent with the maximum size of a crater expected from previous observations of very porous rocky bodies (i.e. rubble-pile asteroids). Finally, a relationship between crater diameter (normalised to body radius) is proposed as a function of body porosity which suggests that the doubling of porosity between fractured asteroids and rubble-pile asteroids, nearly doubles the size (D/R value) of the largest crater sustainable on a rocky body.

1. Introduction

The fate of small Solar System bodies under impact is either cratering or disruption. At a critical transition between the two, the largest possible crater will form on the body. The size of such a crater will be a function of several key properties of the body, including its composition and structure. Previous work has looked at impacts on mid-sized icy satellites (diameter 400–1600 km) for example (Moore et al., 2004), and impacts on smaller rocky bodies (with diameters of order 10–500 km, e.g. see Thomas, 1999). Recently, the data for large impact craters on small rocky and icy bodies (size range 1–500 km) was updated by Leliwa-Kopystynski et al. (2008). At these smaller sizes, a range of bodies have been imaged, i.e., asteroids, comets and satellites. These bodies have a variety of compositions; not just rocky and icy, but also of varying porosity. They are also not necessarily spherical, being below the size where gravity will draw the bodies into spherical forms. Nevertheless, Leliwa-Kopystynski et al. (2008) showed that in the size (diameter) range 1–500 km the ratio largest crater diameter (D)/body equivalent mean radius (R) was a near constant value (mean $D/R = 0.90 \pm 0.05$ averaged over rocky and icy bodies or $D/R = 0.84 \pm 0.04$ for just rocky bodies). There is some scatter about these mean values (and the maximum observed values are somewhat larger with $(D/R)_{max} = 1.2$ and 1.6 for icy and rocky bodies respectively), but the data generally lie along a single trend independent of size.

Data from 21 bodies (rocky and icy) were used in the study of Leliwa-Kopystynski et al. (2008), but more data are becoming available. In particular, there are two new recent reports of large craters on asteroids. One is that of a crater on Asteroid (2867) Steins, observed during the fly-by of the Rosetta spacecraft in 2008 (Keller et al., 2010). The initial reports emphasised the presence of a large deep crater on the asteroid (e.g. see Besse et al., 2009; Burchell and Leliwa-Kopystynski, 2009; Michel et al., 2009). There is also the recent report of a newly detected large depression on (90) Antiope (a binary asteroid with components of 86 and 91 km diameter) found by observing its light curves. The structure in the light curves has been interpreted as arising due to a bowl shaped depression on the surface of one component and it has been suggested that this may be a crater (Descamps et al., 2009).

Here we consider the observed crater on Steins and compare the crater size to those from other small bodies. We also consider the size of the depression on Antiope and consider what we can learn if we take it as a crater.

2. Steins

Asteroid (2878) Steins has been observed for many years by telescope. It was a target of opportunity for a close fly-by by the

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Rosetta spacecraft whose main science goal is a rendezvous with Comet 67/P Churyumov–Gerasimenko. The Rosetta spacecraft's closest approach to Steins was on September 5th, 2008 (Schulz, 2009; Keller et al., 2010). The timing of the encounter meant that the asteroid surface was well lit, permitting extensive optical imaging of the surface (Fig. 1). Prior to the encounter an extensive set of telescope observations had been made of the asteroid, which had permitted a well defined 3D model of the body to be made based upon the light curve data (e.g., see Fornasier et al., 2006, 2008; Lamy et al., 2008). The results of this work are summarised in Table 1 along with the results of the observations made from the spacecraft during the encounter (Keller et al., 2010). Given its reflectance spectra (Barucci et al., 2005, 2008), the asteroid was held to possess an enstatite like composition and was identified as an E(II) asteroid.

The images taken during the encounter (Fig. 1 and see Keller et al., 2010), show that Steins has a classical multi-faceted shape, similar to that often found in cut glass. There is a large "hole" in the "top" most facet, and this is interpreted as an impact crater. The dimensions of Steins and its crater can be obtained from the preliminary shape model presented by Besse et al. (2009), and it has a mean radius of 2.7 ± 0.3 km. An updated model is given by Keller et al. (2010) with mean radius 2.65 km. Since the shape model is not equi-radial on all three axes, the individual radii were given as 2.2 km along its spin axis and 3.1 km in the perpendicular direction (Keller et al., 2010). These values are equivalent to diameters of 4.4 and 6.2 km, comparable with those estimated pre-encounter (Table 1). The crater was given as having a diameter of 2 km by Besse et al. (2009) and 2.1 km by Keller et al. (2010). Based on our analysis of the Rosetta images, it has a maximum diameter of 43% of the length of the longest axis.

To many people, this seems like a large crater for a small body. The ratio commonly used to characterise relatively large craters on relatively small bodies is the ratio: crater diameter (*D*)/body radius (*R*) i.e. *D*/*R*. Taking 2.1 km as the crater diameter and a mean radius for Steins of 2.65 km (as given by Keller et al. (2010)), gives a *D*/*R* ratio of 0.79. Since Steins is somewhat oblate, rather than purely spherical, *D*/*R* = 0.68 if the mean equatorial radius is used, or *D*/*R* = 0.95 if the mean polar radius is taken for *R* (Keller et al., 2010). Alternatively, *D*/*R* = 0.86 if taken directly from the images as suggested above. The possibility that this ratio is relatively large for a small body has prompted attempts to explain it, such as modelling of potential impacts in terms of possible macro or micro porosity of the body (e.g. Michel et al., 2009; Jutzi et al., 2010). However, without quantifying what should be considered as a large crater on a small body, this may be somewhat misleading.

In Leliwa-Kopystynski et al. (2008) as well as finding the mean behaviour of *D*/*R*, a relationship was established for the maximum (limiting) value of the ratio *D*/*R*, which was 1.2 for an icy body and 1.6 for a rocky body. For example, Deimos (satellite of Mars) has a radius of 6.2 km, a crater diameter of 10 km and hence *D*/*R* = 1.61. Clearly, Steins is well below the limit found by Leliwa-Kopystynski et al. (2008). Indeed it is more akin to the cases of (433) Eros, (951) Gaspra, (5535) Annefrank and Dactyl, with radii of 8.68, 6.2, 3 and 0.7 km and *D*/*R* = 0.576, 0.48, 0.5, and 0.857 respectively (Fig. 2). Note that these bodies are similar in size to Steins and cover a similar range of values for *D*/*R*. That the bodies are of similar size to Steins is important. For small rocky bodies the growth of craters and the interaction of the craters with the bulk bodies themselves on a global scale may well depend on the overall size of the body. Some effects, such as global resurfacing after a large impact, are indeed thought to depend on the size of the body (e.g. see Asphaug (2008) for a discussion).

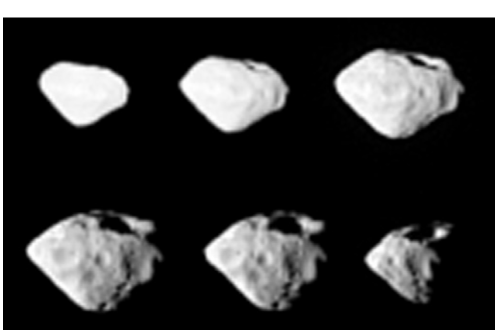

Fig. 1. Images of Asteroid Steins, taken from the Rosetta spacecraft by the OSIRIS imaging system. Image source: ESA web site (ESA©2008 MPS for OSIRIS Team MPS/UPD/LAM/IAA/RSSD/INTA/UPM/DASP/IDA).

We can immediately observe that the crater on Steins is not abnormal in terms of its diameter relative to parent body size. Indeed, although there are only a limited number of small rocky bodies which have been observed in sufficient detail to resolve craters, several of these have similar sized craters or larger. Further, the value of *D*/*R* for Steins is well away (by a factor of 2) from the rule for limiting behaviour set by Leliwa-Kopystynski et al. (2008).

3. Antiope

(90) Antiope is a binary asteroid, located in the main Asteroid Belt. It is considered a member of the Themis family of asteroids, identified by Zappalà et al. (1995) with ∼550 members (completeness size limit ∼20 km) and more recently reported by Leliwa-Kopystynski et al. (2009) as having over 9000 members (completeness size ∼7 km and based on analysis of a data set of 205,770 asteroids, compared to 12,487 in Zappalà et al. (1995)). Antiope was identified as a synchronous pair by direct imaging (Merline et al., 2000) and was later subject to an extended programme of ground based observations to accurately determine its light curve (Descamps et al., 2007). Based on this campaign the components were identified as having diameters of 91 and 68 km, and orbit the combined centre of mass with a period of 16.505 h. However, some fine details of the light curves in that work were not fully explained and another extended observing campaign was carried out by Descamps et al. (2009). In this more recent work, the shapes of the components have been corrected to fully explain the data. The new data more fully constrain the tri-axial sizes of the two bodies (Table 2) and reveal a large geological feature, diameter 68 km on one of them. This was described by Descamps et al. (2009), as an impact crater, although given that it has not been directly imaged this is contentious. Further, given the nature of the observations and analysis method it is not possible to determine which of the pair contains the crater. However, here we consider what we learn if we were to take it as a crater. Expressed as a fraction of the mean radii of the two components, this putative crater has *D*/*R* between 1.54 and 1.62 (in Descamps et al. (2009) the putative crater diameter was given with respect to the mean diameter as ∼0.7, which is equivalent to *D*/*R* ∼ 1.4).

Clearly, whichever of the values of *D*/*R* (1.4, 1.54 or 1.62) is taken, this would one of the largest known craters on a small rocky body (Fig. 2). In terms of *D*/*R* this is most comparable with that for Deimos (*D*/*R* = 1.61), i.e. right on the maximum limit previously observed. It is also larger than the value of *D*/*R* = 1.26 obtained for (253) Mathilde.

4. Discussion

When considering the issue of disruption of asteroids, much attention has previously focused on the critical energy density just