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Morphology and population of binary asteroid impact craters

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ABSTRACT

Observational data show that in the Near Earth Asteroid (NEA) region 15% of asteroids are binary. However, the observed number of plausible doublet craters is 2–4% on Earth and 2–3% on Mars. This discrepancy between the percentage of binary asteroids and doublets on Earth and Mars may imply that not all binary systems form a clearly distinguishable doublet crater owing to insufficient separation between the binary components at the point of impact. We simulate the crater morphology formed in close binary asteroid impacts in a planetary environment and the range of possible crater morphologies includes: single (circular or elliptical) craters, overlapping (tear-drop or peanut shaped) craters, as well as clearly distinct, doublet craters. While the majority of binary asteroids impacting Earth or Mars should form a single, circular crater, about one in four are expected to form elongated or overlapping impact craters and one in six are expected to be doublets. This implies that doublets are formed in approximately 2% of all asteroid impacts on Earth and that elongated or overlapping binary impact craters are under-represented in the terrestrial crater record. The classification of a complete range of binary asteroid impact crater structures provides a template for binary asteroid impact crater morphologies, which can help in identifying planetary surface features observed by remote sensing.

1. Introduction

The low probability of two craters forming close together in space and time suggests that such "doublets" were formed by the simultaneous impact of a binary asteroid: two asteroids that revolve around a common centre of mass. The existence of binary asteroids was suggested by the occasional observation of doublet craters on planetary bodies such as the Earth (Melosh and Stansberry, 1991), Moon (Trego, 1989), Venus (Cook et al., 2003) and Mars (Melosh et al., 1996). For example, early analysis of the surface of Mars using Mariner 6 and 7 photographs suggested that a non-random distribution of Martian craters could be attributed to simultaneous impacts of gravitationally coupled asteroids and gravitationally induced asteroid break-ups (Oberbeck and Aoyagi, 1972). Investigation of a lightly cratered terrain on Mars (Vastitas Borealis) has since showed that 3 out of 133 (2–3%) crater doublets larger than 5 km are likely to have been formed in a binary asteroid impact (Melosh et al., 1996).

Before binary asteroids were observed Melosh and Stansberry (1991) predicted that between 10% and 20% of Near Earth Asteroids (NEAs) must be binaries with orbital separations, A, of approximately four times the primary impactor diameter D_p to explain the three doublets they identified on Earth (out of 28 craters with primary diameter >20 km). The three doublet craters on Earth they sought to explain were: Clearwater East and Clearwater West, Gusev and Kamensk, and Ries and Steinheim, which are separated by approximately 28 km, 9.5 km and 46 km, respectively. As a first order estimate, applying crater scaling laws (e.g., Schmidt and Housen, 1987) using terrestrial gravity and average impact velocity, suggest that the ground separation, L, between the centres of each doublet crater pair is $>7D_p$ (Table 1). Such large separations cannot be produced by atmospheric breakup (Passey and Melosh, 1980), breakup at the Roche limit (Aggarwal and Oberbeck, 1974; Nor̈dlinger, 1980) nor the tidal disruption of contact binaries during final approach prior to impact (Melosh and Stansberry, 1991; Bottke and Melosh, 1996). Moreover, low angle impact is not a plausible explanation as none of the crater pairs show evidence of extreme obliquity. Melosh and Stansberry (1991) concluded that a significant fraction of NEAs must be well-separated binaries and that the components separation was not changed substantially during their final encounter with Earth.

Since the 1990s, photometric surveys via light curve observations and more recently radar have been used to detect binary asteroids. These two mutually different and independent techniques made significant progress in identifying binary asteroids with parameters similar to those first hypothesised by Melosh and Stansberry (1991). Photometric survey by Pravec et al. (2006) showed that 15% of the observed NEAs (with $D_p = 0.3-10$ km and $D_s/D_p \geq 0.2$) are binary. Radar observations, able to detect individual asteroids with 10 m resolution in the NEA region (Margot et al., 2002), also showed 16% of the NEAs larger than 200 m are binary, regardless of D_s/D_p ratio. Smaller asteroids are likely to be monolithic and therefore less prone to tidal forces (Pravec and Šarounová, 2000).

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Table 1
List of possible doublet craters on Earth. D_{cp} and D_{cs} are the doublet crater diameter and L is the ground separation between the craters. This data were compiled from a list of 130 impact craters from the Spray and Elliot (2010). First three for Earth were also suggested by Melosh and Stansberry (1991). Using impact scaling laws (Collins et al., 2005), we calculate the expected binary asteroid size (D_p and D_s) that formed these craters. All craters are complex, except Gusev. $T \pm \Delta T$ is the estimated crater age (Grieve, 1991; Spray and Elliot, 2010). Based on a combination of age uncertainty and separation $L < 10D_p$ a crater pair is considered very likely to be a doublet, at $L < 20D_p$ a likely doublet and $L < 120D_p$ a possible doublet.

Crater pair	D_{cp} and D_{cs} (km)	L (km)	D_p and D_s (km)	D_s/D_p	L/D_p	$T \pm \Delta T$ (Ma)	Doublet?
West Clearwater lake East Clearwater lake	32 22	28.5	2.5 1.6	0.64	11.4	290 ± 20 290 ± 20	Very Likely
Kamensk Gusev	25 3	15	1.9 0.15	0.08	7.9	65 ± 2 65	Very Likely
Ries Steinheim	24 3.4	46	1.8 0.2	0.1	25.6	14.8 ± 0.7	Likely
Flaxman Crawford	10? 8.5?	11.7	0.7 0.6	0.85	16.7	> 35 > 35	Possible
Serra da Cangalha Riachao Ring	12 4.5	46	0.8 0.3	0.37	57.5	< 250 260–251	Possible

From the latest available NEA, MBA (Main Belt asteroids) and MC (Mars crossing) population observational data we identify the trends between binary asteroid parameters (separation, A, primary D_p and secondary D_s component size) and use these in iSALE-3D hydrocode simulations to investigate the crater morphology in such binary asteroid impacts. This paper provides a unique way of classifying impact craters made by binary asteroids and estimates the expected population of such craters. In addition, this crater morphology classification can help identify unknown planetary surface features observed by remote sensing.

The only previous experimental study of binary impact morphology was carried out by Oberbeck (1973) using cylindrical projectiles fired into fine grained quartz sand target. The iSALE-3D hydrocode simulates larger scale impacts illustrative of planetary-scale scenarios, thereby extending the experimental study to larger scales.

We show that a binary asteroid impact can result in one of the three separate outcomes: (i) a doublet crater, (ii) an overlapping crater or (iii) a single crater. A doublet crater is where binary asteroid impact forms two separate craters with little influence on each other even though they formed at the same time. A single crater has a morphology akin to craters formed in a single asteroid impact, but may be elongated. An overlapping crater forms when two recognisable craters are formed but are not sufficiently separated to form a doublet. In this case, the crater rims and ejecta blankets mutually disturb the crater sites, resulting in a multi-component impact structure. Our iSALE-3D hydrocode simulations show the planform of these craters and proximal ejecta deposits, which is crucial for making a distinction between close binary asteroid impact sites and regular single asteroid impacts. Finally, using the outcomes from our numerical simulations and the observed binary population, we estimate the proportion of binary impacts that result in these outcomes.

2. Properties and statistics of binary asteroids and possible binary asteroid impact craters on Earth and Mars

2.1. Binary asteroid population among Earth-crossing, Mars-crossing and small Main Belt asteroids

Photometric and radar observations show that about 15% of the NEAs and MBAs smaller than 10 km are binary (Pravec et al., 2006; Pravec and Harris, 2010; Walsh, 2009). The observed binary asteroids in Fig. 1 are taken from the PDS archive and Pravec and

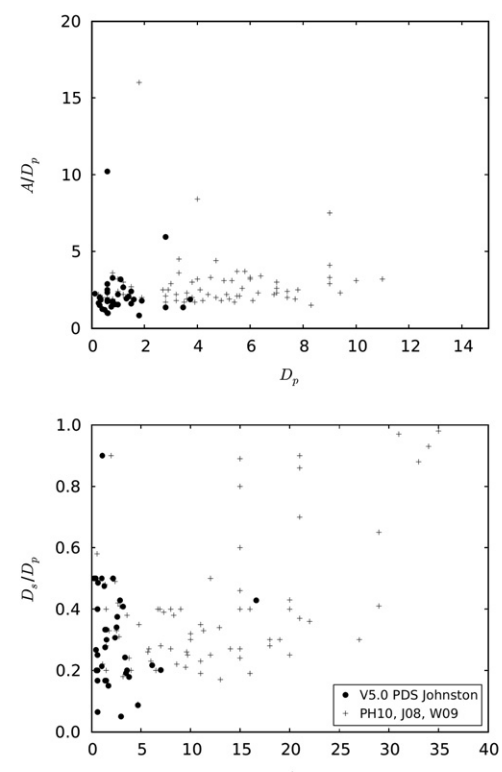

Fig. 1. The collection of Earth-crossing (EC), Mars-crossing (MC) and the rest of observed binary asteroids (BAs) up to the Main Belt asteroids (MBAs) data taken from Pravec and Harris (2010), Johnson (2008) and Walsh (2009) show the average $D_s/D_p \approx 0.3$ and $A/D_p \approx 3$. PH10, J08, W09 data is shown in crosses. V5.0 PDS Johnston archive data is shown in full circles. PDS data shows the most confident selection of binary asteroids in the NEA region and it is used here to confirm and emphasise the near Earth binary asteroid population.

Harris (2010). PDS data shows the NEAs and additional data from Pravec and Harris (2010) extends towards Mars-crossing (MC) and observed binary asteroids up to the Main Belt. All observed Earth-crossing (EC) binary asteroids have primary components, D_p, in the size range smaller than 10 km, mostly $D_p \leq 2$ km. The separations between the binary components, A, are between $1.5D_p$ and $3.5D_p$ and the size ratio of primary and secondary components, D_s/D_p, for the majority of binaries is between 0.2 and 0.5. MC binary asteroids are larger than EC binaries,