HYDROCODE SIMULATIONS OF BINARY ASTEROID IMPACTS.

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Introduction. Photometric and radar observational data show that about 15% of the Near Earth asteroids (NEAs) and small Main Belt asteroids (MBAs) are binary. The majority of observed binary asteroids (BAs) have primary components $D_p<10$km, a primary to secondary component size ratio, $D_s/D_p=0.2-0.5$ and a separation between the binary components, $A=1.5-3.5D_p$ [1,2]. The observed size and separation range is consistent with predictions of BA formation via the YORP effect [3,4].

In order for a clearly distinguishable doublet crater to form in a BA impact, the ground separation, L, between the components needs to be at least $8D_p$ [5], which is not a common separation in observed binaries. Such ground separations are achieved in highly oblique impacts, which are also not common. Unless there are mechanisms that increase the separation between the binary components upon approach to a planet (such as prominent tidal effects), the majority of BA impact craters are expected to form a single impact structure due to insufficient separation between the binary components at the point of impact. However, this single impact structure may exhibit morphological features that identify it as formed by a binary asteroid. Here we simulate a range BA impacts in a planetary environment to establish the change in crater morphology with increasing binary component separation (Fig. 1). We compare the predicted number of doublet craters with a list of suspected BA impact structures on Earth (Table 1) and Mars (Fig. 3).

Method. The iSALE-3D hydrocode [6] was used to simulate close BA impacts on Earth and Mars, for the following cases: $D_s/D_p=0.3$, 0.5 and 1.0 at L=2, 4, 6, 8 and $10D_p$ impacting vertically at 7 km/s. Weakened granite was used as Earth's surface analogue and basalt for Mars, both composed of Tillotson equation of state and constitutive model for rock [7]. Asteroids were modelled with the same meterials.

Results. The shape of a BA impact crater is a single structure if $L<8D_p$ (Fig. 1 and [5]). Crater shape is dependent on binary components L and D_s/D_p. If $L=2D_p$, a BA forms a single circular to slightly elliptical crater, as D_s/D_p value increases. If $L=4D_p$, the shape of the final crater is strongly dependant on the D_s/D_p value. For lower D_s/D_p values, such as 0.3, the final crater is circular as the primary crater ejecta buries the secondary; for higher values such is $D_s/D_p=0.5$, the final crater has a tear-drop shape with indications of an overlapping crater; and in extreme case of $D_s/D_p=1$, an elliptical crater forms. For $L=6D_p$ and lower D_s/D_p at $L=8D_p$ an overlapping crater forms. For high D_s/D_p values, an elliptical to peanut shape crater forms. A clearly distinguishable doublet crater forms at $L>8D_p$ depending on D_s. Well-separated craters produce two distinct craters (doublets) that are circular in shape, unless the incidence angle is highly oblique. In this case, both doublet craters should be elongated in the same direction, and have the same ejecta morphology.

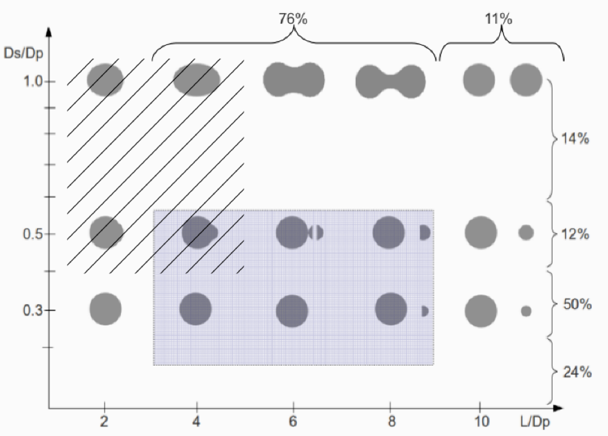

Fig. 1. Crater morphology formed in a close BA impact (at 7 km/s) as a function of D_s/D_p and L. Grey area indicates the crater morphology that has the highest probability of occurrence, based on the size and separation statistics in the observed BA dataset [1]. Cross-hatched lines emphasize the region of single elliptical craters.

About 24% of the observed BAs have $D_s/D_p\leq0.2$, 50% have $0.2<D_s/D_p\leq0.4$, 12% have $0.4<D_s/D_p\leq0.6$ and 14% have $D_s/D_p>0.6$ [1]. On average $A=3D_p$ [1] and there is 76% probability of an impact to occur at impact angles 20^o-70^o, and 11% at $>70^o$ [8]. Considering $L=A/\sin\Theta$, the majority of BAs are expected to form a circular to a tear-drop shaped crater. In some cases, a lip or overlapping crater features can be seen, especially in fresh craters.

Our results suggest that a significant fraction of BA impacts may form an elliptical or elongated crater that might be hard to distinguish from a crater formed by a highly oblique single asteroid impact. Crater ellipticity, e, is defined as a ratio of the crater's length over width. In a BA impact at $L=2,4D_p$, and larger D_s/D_p at $6D_p$ the crater becomes elliptical and $e\geq1.1$. For a small D_s/D_p ratio at $6D_p$, the secondary crater is more likely to be buried under the ejecta blanket from the primary crater, making the impact structure almost circular (Fig. 2).

According to the observed BA size and separation statistics 20% of all BA (3% of all asteroids [1]) have $D_s/D_p>0.4$ and $A\leq5D_p$ (indicated with cross-hatched lines in Fig. 1), which is a condition for an elliptical crater to form in a BA impact. Among 5-100 km craters 2% of fresh craters and 6% of all craters on

Mars are elliptical [9]. This indicates that some elliptical degraded craters could have been formed in a close BA impact rather than in a highly oblique single asteroid impact, assuming L≈A.

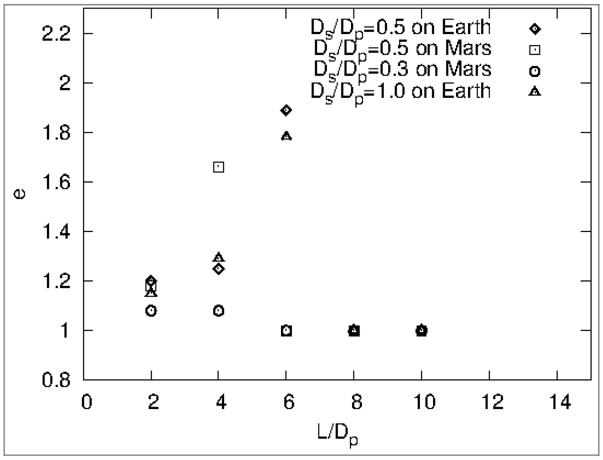

Fig. 2. Crater ellipticity changes with L/D_p for different D_s/D_p ratios.

Most observed BAs have separations that are more likely to create a single crater, than a distinguishable doublet. Assuming no change in separation in planetary approach, about 11% of BA impacts might be expected to form two separate craters. Considering that 15% of NEA asteroids are binary, this implies that only about 2% of asteroid impacts on Earth and Mars make distinguishable doublets, which is in reasonable agreement doublet crater statistics on Earth and Mars: 1.7-5.1% of all craters on Earth larger than 6 km are plausible doublets [10; Table 1] and 2-3% on Mars [11].

Crater pair	D_{c1}; D_{c2}	L	D_s/D_p
West & East Clearwater	36; 26	28	0.64
Kamensk & Gusev	25; 3	9.5	0.07
Ries & Steinheim	24; 3.8	46	0.67
Flaxman & Crawford	10; 8.5	11.7	0.81

Table 1. List of possible doublet craters on Earth. D_{c1} and D_{c2} are the doublet crater diameter and L is the ground separation between the craters, in km. The first three were also suggested in [6]. Using impact scaling laws [3], we calculate the expected BA size (D_p and D_s) that formed these craters.

Simulation results agree with the ejecta pattern seen in Fig. 3. The long transverse ejecta tails are created by the collision of ejecta from the impacts of the primary and secondary asteroids. These represent a unique feature by which fresh close BA impact structures can be recognized.

Conclusions. Numerical modelling has given us unique insight into the processes and parameters that lead to single, overlapping and doublet craters as a result of BA impacts in different materials and gravities. For $L \leq 8D_p$, the crater is a single structure that can be: circular, elliptical, tear-drop or overlapping in shape, with a variable ellipticity (Figs. 1, 2). For $L > 8D_p$ doublet craters are expected to form. Binary asteroid impact structures may create an additional bias in calculating: crater ages, frequency of elliptical craters and the incidence angle threshold for creating an elliptical crater.

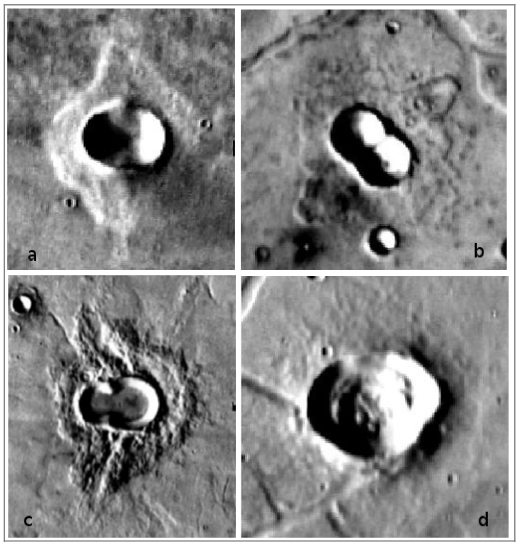

Fig. 3. Example of complex craters most likely created in close BA impacts:(a) elliptical (b) elliptical (c) tear-drop shaped (d) elliptical with a lip, identified using THEMIS database [12].

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References: [1] P. Pravec and A. W. Harris (2010) http://www.asu.cas.cz/asteroid/binast_20100408.zip; [2] K. J. Walsh (2009) *Earth Moon Planet*, 105:193–199; [3] M. Ćuk (2007) *AJ*, 659, L57-L60; [4] K. J. Walsh et al. (2008) *Nature*, 45:188-191; [5] W. F. Bottke and H. J. Melosh (1996) *Icarus*, 124:372–391; [6] D. Elbeshausen et al. 2009 *Icarus* 204: 716-731; [7] G. S. Collins et al. (2004) *Meteorit. Planet. Sci.*, 39(2): 217-231; [8] E. Pierazzo and H. J. Melosh (2000) *Ann. Rev. Earth Planet. Sci.*, 28:141–167; [9] G. S. Collins et al. (2011) *Earth Planet. Sci. Lett.*, 310:1–8; [13] P. R. Christensen et al. (2010) http://themis-data.asu.edu; [10] J. Spray and E. Beverley (2010) www.passc.net/EarthImpactDatabase/index.html; [11] H. J. Melosh et al. (1996) *LPSC*, 27:863–864; [12] H. J. Melosh and J. A. Stansberry (1991) *Icarus*, 94:171–179.