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Triggering Comet-Like Activity of Main Belt Comets

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Abstract. Main Belt Comets (MBCs) have attracted a great deal of interest since their identification as a new class of bodies by Hsieh and Jewitt in 2006. Much of this interest is due to the implication that MBC activity is driven by the sublimation of volatile material (presumed to be water-ice) presenting these bodies as probable candidates for the delivery of a significant fraction of Earth's water. Results of the studies of the dynamics of MBCs suggest that these objects might have formed in-situ as the remnants of the break-up of large icy asteroids. Simulations also show that collisions among MBCs and small objects could have played an important role in triggering the cometary activity of these bodies. Such collisions might have exposed sub-surface water-ice which sublimated and created thin atmospheres and tails around MBCs. In order to drive the effort of understanding the nature of the activation of MBCs, we have investigated these collision processes by simulating the impacts in detail using a smooth particle hydrodynamics (SPH) approach that includes material strength and fracture models. We have carried out simulations for a range of impact velocities and angles, allowing m-sized impactors to erode enough of an MBC's surface to expose volatiles and trigger its activation. Impact velocities were varied between 0.5 km/s and 5.3 km/s, and the projectile radius was chosen to be 1 m. As expected, we observe significantly different crater depths depending on the impact energy, impact angle, and MBC's material strength. Results show that for all values of impact velocity and angle, crater depths are only a few meters, implying that if the activity of MBCs is due to the sublimation of water-ice, ice has to exist in no deeper than a few meters from the surface. We present details of our simulations and discuss the implications of their results.

Keywords. asteroids, methods: numerical

1. Introduction

The detection of comet-like activities in several icy asteroids has generated much interest in the origin of these objects and the mechanism of their activation. Known as Main Belt Comets (MBCs), these bodies show dynamical behaviors characteristic of main belt asteroids whereas unlike most asteroids, they carry tails similar to those of comets. Much of interest in these objects is due to the implication that their comet-like tails and activity are driven by the sublimation of volatile material, presumably water-ice. The latter suggests that MBCs might have contributed to the delivery of water to the accretion zone of Earth. At the time of this writing, 8 unambiguous MBCs† were known. Table 1 shows these objects along with some of their physical and orbital characteristics.

† We call an MBC unambiguous if its activation can only be explained by the sublimation of volatiles that have been surfaced as a result of its collision with a small impactor.

Table 1. Physical properties of the currently known MBCs. The quantity D_e represents the effective diameter of the MBC, a, e and i are its semimajor axis, eccentricity and orbital inclination, respectively, T_J is its Tisserand number with respect to Jupiter, and v_{esc} is the value of its escape velocity. Values adopted from Jewitt *et al.* (2015).

Object	D_e [km]	a [AU]	e	i[deg]	T_J	v_{esc} [m/s]
133P/(7968) Elst-Pizarro	3.8 ± 0.6	3.157	0.165	1.39	3.184	2.13
176P/(118401)LINEAR	4.0 ± 0.4	3.196	0.192	0.24	3.167	1.95
238P/Read (P/2005 U1)	0.8	3.165	0.253	1.27	3.152	....
259P/Garradd (P/2008 R1)	0.3 ± 0.02	2.726	0.342	15.90	3.216	0.62
P/2010 R2 (La Sagra)	1.1	3.099	0.154	21.39	3.098	0.49
288P/(300163) 2006 VW_{139}	3	3.050	0.200	3.24	3.203	...
P/2012 T1 (PANSTARRS)	2.4	3.154	0.236	11.06	3.134	...
313P/Gibbs (P/2014 S4)	1.0	3.156	0.242	10.97	3.132	0.86

Studies of the dynamical evolution of 7968 Elst-Pizarro, 118401, and 238P/Read indicated that while the orbits of 7968 Elst-Pizarro and 118401 are stable for 1 Gyr, 238P/Read becomes unstable in about 20 Myr (Haghighipour 2009). Given the association of 7968 Elst-Pizarro with the Beagle family, and the proximity of 118401 and 238P/Read to the Themis family, these results suggested that 7968 Elst-Pizarro, 118401, and 238P/Read are most likely natives to the asteroid belt and formed in-situ through the breakage of larger asteroidal bodies (Haghighipour 2009, 2010).

As shown by Haghighipour (2009), interactions with mean-motion resonances could have affected the dynamics of other MBCs as well, causing them to be scattered into orbits away from their birth places. As suggested by this author, the latter implies that, while asteroid families and associations in the outer part of the asteroid belt present promising regions to search for MBCs, stand-alone MBCs can also exist and may be found throughout the asteroid belt. Among the currently known MBCs, 5 are of this kind.

An interesting characteristic of MBCs is their small sizes. As shown in Table 1, these objects are smaller than 5 km in size. These small sizes of MBCs have strong implications for the history and mechanism of the activation of these objects. Hsieh *et al.* (2004) and Hsieh & Jewitt (2006) studied the mass loss and activation of 7968 Elst-Pizarro, and showed that, considering an albedo of 0.05 and temperature of 150 K, this MBC reduces size at a rate of 1 m/yr. Given that the diameter of 7968 Elst-Pizarro is slightly smaller than 4 km, such a rapid rate of size-reduction strongly suggests that the activation of this MBC has been recent. Hsieh *et al.* (2004) and Hsieh & Jewitt (2006) suggested that 7968 Elst-Pizarro was impacted by a 1-10 m-sized body which excavated its sub-surface volatiles, presumably water-ice, causing ice to sublimate and create a thin atmosphere and a tail when the orbit of this MBC brings it close to the Sun.

The degree to which the impact of a meter-sized body with a km-sized MBC can excavate sub-surface ice and trigger MBC activity depends on whether the resulted impact crater will be deep enough to reach the underlying water-ice. The depth of the crater, itself, depends on the impact velocity of the m-sized impactor and the material strength of the MBC. The purpose of our study is to examine the viability of the above-mentioned scenario by identifying ranges of these parameters for which sub-surface ice may be exposed.

2. SPH simulations and initial set up

We use the 3D SPH code developed by Schäfer *et al.* (2007) and Maindl *et al.* (2013) to simulate an impact between two bodies. Our code includes material strength and

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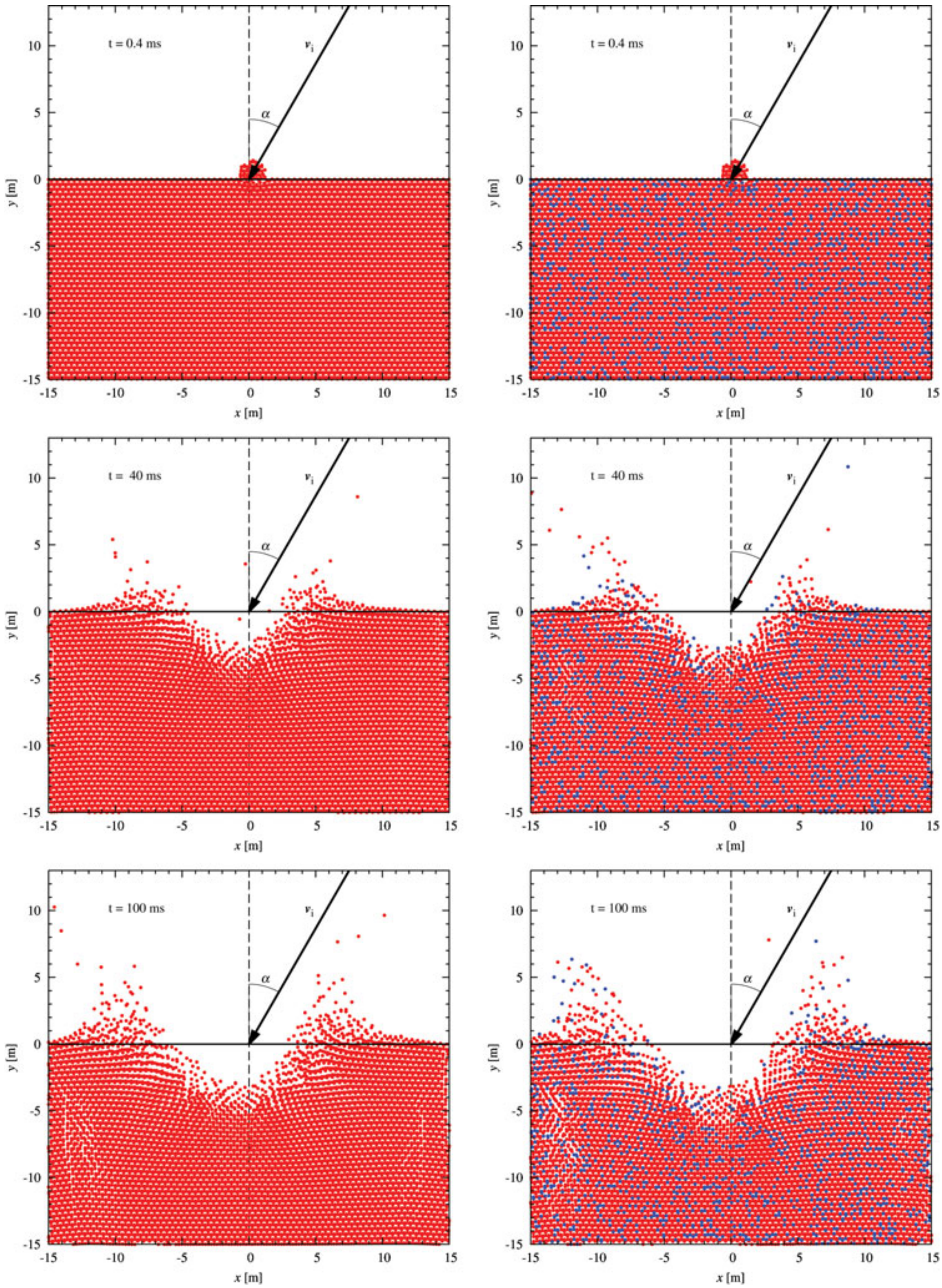

Figure 1. Snap shots of the impact of a meter-sized rocky impactor with a km-size target. The target on the left is pure rock and that on the right has a water-mass fraction of 5%. The impact velocity is 4.4 km/s and the impact angle is 30°.

implements a full elasto-plastic continuum mechanics model (see e.g., Maindl *et al.* 2013 and 2014). To treat fracture and brittle failure, we use the Grady-Kipp fragmentation prescription (Grady & Kipp 1993, Benz & Asphaug 1994). This prescription is based on flaws that are distributed in the material following a Weibull distribution with

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material-dependent parameters. We consider rock to be basalt (density of 2.7 g/cm^{-3}) and use the values given by Maindl *et al.* (2013) (based on measurements by Nakamura *et al.* 2007, see their Table 1) for rock and ice parameters in the equation of state and the Weibull distribution. Basaltic rock, represented by the parameters of the basalt equation of state, as given by Melosh (1996), is widely used as the material of rocky bodies from cm-sized up to the mantles of large asteroids such as Vesta or Ceres (Agnor & Asphaug 2004, Nakamura *et al.* 2009, Michel *et al.* 2009). We use slightly modified parameters similar to those used by Benz & Asphaug (1999) and apply a tensorial correction as suggested by Schäfer *et al.* (2007) to ensure first-order consistency.

To simulate collisions, we resolve the combined system of the impactor and target into approximately 500,000 SPH particles. Following Maindl *et al.* (2015) and because the impact timescales are very short compared to the time of the influence of the gravitational force of the target body (the collision velocities are in the order of km/s whereas the MBCs' surface escape velocities are less than a few m/s, see Table 1), we simulate collisions without self gravity. To analyze the evolution of the system during each impact, we take 250–500 snapshots every 0.4 ms. In between the snapshots, time integration is continued with an adaptive step-size.

3. Impact simulations and calculation of crater depth

The fact that the activation of MBCs is recent indicates that irrespective of the origin of these objects, collisions between impactors and MBCs must have happened when the projectile and target were both in the asteroid belt. As shown by Bottke *et al.* (1994), the mean impact velocity of bodies in the asteroid belt is ~ 5.3 km/s with the most probable value being around 4.4 km/s for bodies larger than 50 km. We, therefore, considered impact velocities in the range of 0.5 km/s to 5.3 km/s and added a tail to our velocity distribution towards smaller values to account for small objects. We also chose the impact angle (α) to vary in the range of 0 (head-on collision) to 60°.

We considered the target to be a mix of ice and rock, and carried out simulations for different values of its ice-to-rock ratio. We followed the conventional consideration of the water-mass fraction of asteroids in models of terrestrial planet formation (Raymond *et al.* 2004, 2009, Izidoro *et al.* 2013, 2014, Haghighipour & Winter 2016) and considered a target with a water-mass fraction of 0 % (solid rock) or 5 % corresponding to objects in the outer part of the asteroid belt. In all our simulations, the impactor was considered to be pure rock. We distributed ice uniformly throughout the target, and did not consider porosity.

We would like to mention that results presented here are only a small sample of the results of a large project in which simulations have been carried out for a more expansive range of parameters (water content, water-ice distribution, MBC material strength). Those results are presented in Haghighipour *et al.* (2016). Here, we only show a sample of results and focus our analysis on the depths of impact craters to differentiate between two models of ice-longevity in asteroids.

Figure 1 shows snapshots of a sample of our simulations for the nominal impact velocity of 4.4 km/s and an impact angle of 30°. To reduce the amount of unnecessary computations, we limited the region of simulation in the target to a volume of 30 m × 30 m × 30 m in size.

We measure the depth of a crater through the following steps. First, we fit a spheroid to the crater. We then cut the impact scenario and the fitted spheroid along the impact's plane of symmetry in the direction of the vertical component of the impact velocity. In the resulting 2D section (see the left column of figure 2), we determine the location of the

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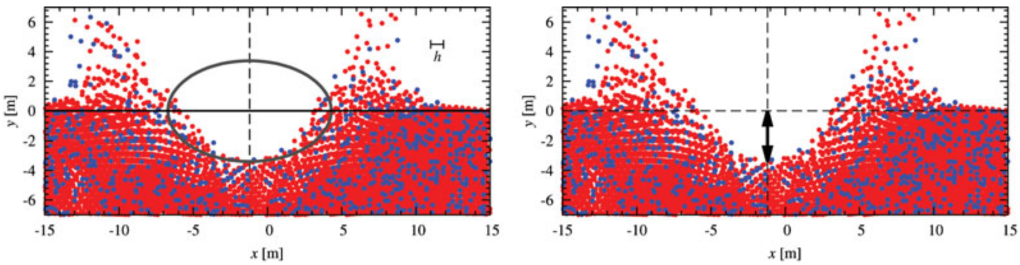

Figure 2. 2D cross section of a crater along the vertical component of the impact velocity of 4.4 km/s at a 30° angle. The target has 5% water-ice content. The ellipse represents the fitted spheroid. The crater depth is 3.39 m and its diameter is 11 m.

bottom of the spheroid corresponding to the deepest penetration into the target while ignoring single, scattered SPH particles. We define the crater depth to be the distance between this deepest point to the surface of the target (right column of figure 2). Figure 2 shows the fitted spheroid and depth of the crater for an impact scenario of figure 1. As shown here, the final depth of the crater for a target with 5% ice to rock ratio is approximately 4 m.

4. Implications for models of ice-longevity in asteroids

In order for the activity of MBCs to be ignited and continue by the sublimation of exposed water-ice, the impact crater has to be deep enough to reach the buried ice. The two current models of ice-longevity in asteroidal bodies, namely, Schorghofer (2008) and Prialnik & Rosenberg (2009), make different predictions of the depth where the ice in an MBC could be buried. As suggested by Schorghofer (2008), in asteroids with mean surface temperatures smaller than 145 K (e.g., the MBC 7968 Elst-Pizarro), a layer of dust of only a few tens of centimeter in thickness would be sufficient to allow ice to survive in the top few meters of an MBC for the age of the solar system. According to this model, an impact crater of only a few meters in depth would be sufficient to expose sub-surface water-ice. The model by Prialnik & Rosenberg (2009), however, makes drastically different predictions. These authors suggest that an MBC such as 7968 Elst-Pizarro can maintain only crystalline water-ice and only in depths ranging from 50 m to 150 m.

We use the results of our impact simulations to differentiate between these two models. Figure 3 shows crater depths in all our simulations in terms of the impact energy and the vertical component of the impact velocity. As expected, crater depth shows a clear dependence on the material strength. For a given value of the vertical impact velocity, as the water-mass fraction of the target increases, the crater depth increases as well.

An interesting result shown in figure 3 is that for the MBC material considered here, the crater depth does not exceed a few meters. For the conventional case of 5% water-mass fraction, the depth of the crater stays below 6 m in all simulations (in simulations with larger water contents, crater depth increases by only a few meters). Our results suggest that if the activation of MBCs is due to the sublimation of water-ice, consistent with the model by Schorghofer (2008), the ice must be buried in the top few meters from the surface.

5. Summary and Concluding Remarks

It has been suggested that the activation of MBCs is due to the sublimation of water-ice that has been surfaced as a result of the impact of these bodies with m-sized objects. To

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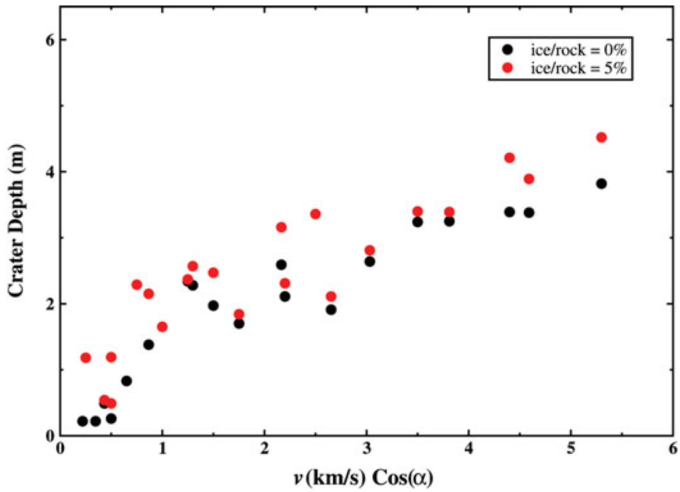

Figure 3. Variations of crater depth in terms of the vertical component of the impact velocity.

determine the viability of this scenario, we simulated collisions between a m-sized body and a km-sized asteroid. The latter was taken as a proxy for an MBC. Previous studies of the dynamical evolution of the currently known MBCs have indicated that these objects were most probably formed in-situ at the outer part of the asteroid belt (where ice can survive for a long time). That, combined with the small sizes of MBCs, and the high rate of their mass loss implies that the activation-triggering collisions of these objects must have been recent. We, therefore, carried out our simulations for a range of impact velocities corresponding to the current impact velocities of asteroids in the asteroid belt. We also considered water-mass fractions that would correspond to water-mass fractions of planetary embryos in the current models of terrestrial planet formation. Results of our simulations indicated that for all values of impact velocity, the depth of the impact crater does not exceed 6 m implying that if the activation of MBCs is due to the sublimation of sub-surface water-ice, this ice cannot be buried deeper than a few meters from the surface.

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