Triggering the Activation of Main-belt Comets: The Effect of Porosity

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Abstract

It has been suggested that the comet-like activity of Main-belt comets (MBCs) is due to the sublimation of sub-surface water-ice that is exposed when these objects are impacted by meter-sized bodies. We recently examined this scenario and showed that such impacts can, in fact, excavate ice and present a plausible mechanism for triggering the activation of MBCs. However, because the purpose of that study was to prove the concept and identify the most viable ice-longevity model, the porosity of the object and the loss of ice due to the heat of impact were ignored. In this paper, we extend our impact simulations to porous materials and account for the loss of ice due to an impact. We show that for a porous MBC, impact craters are deeper, reaching to ∼15 m, implying that if the activation of MBCs is due to the sublimation of sub-surface ice, this ice has to be within the top 15 m of the object. Results also indicate that the loss of ice due to the heat of impact is negligible, and the re-accretion of ejected ice is small. The latter suggests that the activities of current MBCs are most probably from multiple impact sites. Our study also indicates that for sublimation from multiple sites to account for the observed activity of the currently known MBCs, the water content of MBCs (and their parent asteroids) needs to be larger than the values traditionally considered in models of terrestrial planet formation.

Key words: methods: numerical – minor planets, asteroids: general

Supporting material: animations

1. Introduction

With orbital and dynamical properties characteristic of asteroids, and tails similar to those of comets, Main-belt comets (MBCs) have attracted a great deal of interest since their identification as activated asteroids by Hsieh & Jewitt in 2006. Most of the interest in these objects is due to the implication that their comet-like activity is the result of the sublimation of sub-surface volatiles, presumably water-ice. This, combined with results of dynamical studies that suggest MBCs are native to the asteroid belt (see below), argues strongly in support of the idea that water-carrying planetesimals and planetary embryos from the outer part of the asteroid belt provided the majority of Earth’s water during its formation.

At the time of this writing, eight unambiguous MBCs were known.4 Table I and Figure 1 show these objects along with some of their physical and orbital properties. As shown here, MBCs are km-sized bodies with orbits that are mainly in the outer part of the asteroid belt. Dynamical studies by Haghighipour (2009, 2010) and Hsieh & Haghighipour (2016) strongly suggest that these objects are most probably fragments of larger asteroids, and were scattered to their current orbits through interactions with giant planets. This scenario is also supported by the fact that three of these objects, namely, 133P/Elst–Pizarro, 313P/Gibbs, and P/2012 T1 (PANSTARRS) are members of two asteroid families (Nesvorný et al. 2008; Hsieh et al. 2013, 2015). We refer the reader to Haghighipour et al. (2016, hereafter Paper I) for a comprehensive review of the origin, dynamics, and activation of MBCs.

4 We call an MBC unambiguous if its activation can only be explained by sublimation of volatiles.
sublimation-driven activity of MBCs, the porosity of the target and the loss of ice due to the heat of impact were ignored. Porosity can play an important role, as porous materials have lower strength that causes impactors to penetrate deeper in the target, and also affects the geometry and morphology of the impact crater. For instance, while the results presented in Paper I were consistent with the ice-longevity model proposed by Schäfer et al. (2012a), this author suggests that a thin layer of solid material on the surface of an asteroid would be sufficient to preserve water-ice for the age of the solar system, if porosity causes impact craters to be deeper than 50 m, a competing theory by Prialnik & Rosenberg (2009) for ice-longevity in asteroid belt may also be applicable. Those authors suggest that water-ice inside an asteroid can sublimate during the evolution of the solar system causing the ice level to sink to depths below 50 m.

In this paper, we extend our simulations to include porous targets, and examine the degree to which porosity plays a role in the final depth and size of an impact crater, as well as the plausibility of the two ice-longevity models. To consider porosity, we implemented in our SPH code the $P\sim\alpha$ porosity model of Jutzi et al. (2008), and simulated the impact between a m-sized body and a km-sized object for different impact velocities, impact angles, and water contents of an MBC.

The outline of our paper is as follows. Section 2 explains our computational method and the implementation of porosity. Section 3 presents results of our impact simulations and a comparison between these results and those in Paper I. We conclude in Sections 4 and 5 by discussing the implications of the results and presenting highlights of our findings.

### 2. SPH Simulations and Initial Setup

To simulate impacts, we use a 3D SPH code developed by Schäfer et al. (2007, 2016) and Maindl et al. (2013). This code solves the continuity equation and the equation of the conservation of momentum in continuum mechanics. It also includes material strength and implements a full elasto-plastic model (see, e.g., Maindl et al. 2013, 2014). We model any specific material using the Tillotson equation of state (Tillotson 1962; Melosh 1996). Fracture and brittle failure are treated using the Grady–Kipp fragmentation prescription (Grady & Kipp 1993; Benz & Asphaug 1994, 1999). This prescription is based on flaws that are distributed in the material

| Object                  | $D_e$ (km) | $a$ (au) | $e$  | $i$ (deg) | $T_J$ | $v_{esc}$ (m s$^{-1}$) | References$^a$ |
|-------------------------|------------|---------|------|-----------|-------|------------------|----------------|
| 133P/(7968) Elst-Pizarro | 3.8 ± 0.6  | 3.157   | 0.165| 1.39      | 3.184 | 2.13             | 1              |
| 176P/(118401) LINEAR    | 4.0 ± 0.4  | 3.196   | 0.192| 0.24      | 3.167 | 1.95             | 1              |
| 238P/Read (P/2005 U1)   | 0.8        | 3.165   | 0.253| 1.27      | 3.152 | ...              | 1              |
| 259P/Garraudo (P/2008 R1)| 0.3 ± 0.2  | 2.726   | 0.342| 15.90     | 3.216 | 0.62             | 2              |
| 324P/La Sagra (P/2010 R2)| 1.1       | 3.099   | 0.154| 21.39     | 3.100 | 0.49             | 3, 4           |
| 288P/(300163) 2006 VW139| 3          | 3.050   | 0.200| 3.24      | 3.203 | ...              | 5              |
| P/2012 T1 (PANSTARRS)   | 2.4        | 3.154   | 0.236| 11.06     | 3.134 | ...              | 6              |
| 313P/Gibbs (P/2014 S4)  | 1.0        | 3.156   | 0.242| 10.97     | 3.132 | 0.86             | 7              |

$^a$1. Hsieh & Jewitt (2006), 2. Jewitt et al. (2009), 3. Hsieh et al. (2012b), 4. Hsieh et al. (2015), 5. Hsieh et al. (2012a), 6. Hsieh et al. (2013), 7. Hsieh et al. (2015).

**Figure 1.** Locations of the currently known MBCs in the asteroid belt. The background shows all asteroids and the positions of mean-motion resonance with Jupiter.
following a Weibull distribution with material-dependent parameters.

The colliding bodies are discretized into mass packages (known as SPH particles), with each package carrying all physical properties (e.g., mass, momentum, energy) of the part of the solid body it represents. As a result, depending on the type of the impactor or target material, particles may have different material parameters such as bulk and shear modulus and yield strength, or have different activation thresholds for the development of cracks. Each SPH particle moves as a point mass following the equation of motion.

To include porosity, we implemented an extension of the so-called $P-\alpha$ model by Herrmann (1969) as described by Jutzi et al. (2009). Conceptually, this model is based on dividing the change in the volume of a porous material into two parts: the pore-collapse of the porous material, and the compression of the matrix material. These two parts are connected via a distention parameter $\alpha$ defined as

$$\alpha = \frac{\rho_s}{\rho}. \tag{1}$$

In this equation, $\rho$ is the density of the porous material, and $\rho_s$ is the density of the corresponding matrix material. Following Carroll & Holt (1972), the pressure of the porous material ($P$) can be expressed as a function of the distention parameter ($\alpha$) and the pressure of the solid material ($P_s$) as

$$P = \frac{1}{\alpha} P_s(\rho_s, E_s) = \frac{1}{\alpha} P_s(\alpha \rho, E). \tag{2}$$

Quantities $\rho_s$, $\rho$, $E_s$, and $E$ in Equation (2) represent the density and internal energy of the solid and porous material, respectively. The internal energy corresponds to the energy contained inside the system due to the thermodynamical state of its internal parts excluding the kinetic energy of the object due to its bulk motion and its potential energy due to an external force. We note that in Equation (2), it has been assumed that the energy of the surface pores (i.e., the energy necessary to change the assembly of pores on the surface of an object) are negligible; therefore, the energy of the porous material is equal to that of the solid material (i.e., $E = E_s$, Carroll & Holt 1972). We use the Tillotson equation of state (Tillotson 1962) to calculate the pressure as a function of $\rho$, $E$, and $\alpha$.

### 3. Results of Impact Simulations

We considered a similar setup as in Paper I, and simulated the impact between a m-sized impactor and a km-sized target. Because we are interested in the effect of porosity, we carried out simulations for four different cases: a dry and non-porous target; a non-porous target with 50% water-mass fraction of non-porous ice; a dry and porous target with 50% porosity (i.e., $\alpha = 2$); and a 50% porous target containing 50% water-mass fraction of 50% porous ice. We considered the impactor and the solid part of the target to be basalt, and because the size of the impactor is much smaller than the target, we considered the impactor to be non-porous. The material parameters for basalt and ice used in the Tillotson equation of state, and the Weibull parameters for the flaw distributions are given in Table 2.

We resolved the combined system of the impactor and target into approximately 500,000 SPH particles. Because compared with the time of the influence of the gravitational force of the target body, the impact timescales are very short (the collision velocities are in the order of $\text{km s}^{-1}$, whereas the MBCs’ surface escape velocities are less than a few $\text{m s}^{-1}$, see Table 1), we simulated collisions without self-gravity (see Maindl et al. 2015 for more details). To analyze the evolution of the system during each impact, we took 100 snapshots every 0.4 ms. In between snapshots, time integration was continued with an adaptive step-size.

We carried out simulations for impact velocities of 1.5, 2.5, 3.5, 4.4, and 5.3 $\text{km s}^{-1}$. These values were chosen based on the study by Bottke et al. (1994), which showed that for objects of 50 km and larger, impact velocities in the asteroid belt have a mean value of $\sim 5.3 \text{ km s}^{-1}$ with a most probable value at 4.4 $\text{km s}^{-1}$. We considered an abundance of objects smaller than 50 km with similar orbital elements (e.g., semimajor axis, eccentricity, inclination) in the asteroid belt (i.e., $e \lesssim 0.25$). Given the small size of these objects and therefore their small gravitational interactions, collisions between these bodies will occur with relative velocities much smaller than a few $\text{km s}^{-1}$. Combining this assumption with results from Bottke et al. (1994), we considered a range of impact velocities from 1.5 to 5.3 $\text{km s}^{-1}$. The impact angles were chosen to be 0°, 30°, and 45°.

Figure 2 shows snapshots of the final craters of two sets of simulations for an impact velocity of 4.4 km s$^{-1}$. The target is a mixture of 50% porous basalt and 50% porous water-ice, and has a 50% water-mass fraction. The left column shows the impact for a head-on collision and the right column shows the results for an impact angle of $\beta = 30^\circ$. Orange represents porous basalt and blue is porous water-ice. As expected, water-ice is exposed in the interior part of the impact crater and is also scattered out due to the impact. Movies of these simulations can be found in the supplementary material.

A comparison between these results and those of non-porous simulations points to interesting differences. The most prominent difference is in the shape and morphology of craters. Figure 3 shows impact craters of simulations with porous (top) and non-porous (bottom) targets. Both objects have a water-mass fraction of 50%. The impact velocities in all simulations are 4.4 $\text{km s}^{-1}$. As shown here, craters in the porous targets are noticeably deeper and narrower, and extend in the direction of impact velocity. In contrast, the craters in non-porous targets are shallower and much wider. Figure 4 shows this more clearly and for all our simulations with different target material and different impact velocities.

Figures 2 and 3 also show that craters form in a very short time and have irregular shapes. This asymmetry in the shapes of the final craters seems to be in contrast with the works of Collins (2014) and Milbury et al. (2015), who assumed that except for the most oblique cases, all impacts produce approximately radially symmetric craters. We believe that the reason for the quick formation of craters in our simulations and their irregular shapes lies in the fact that the gravity of our targets (i.e., MBCs) are negligible. Gravity is the main factor in forming final craters from transient ones. In the absence of gravity, the plastic flows during the impact phase stop rather
Table 2
Material Parameters for Basalt and Ice

| Material | \( \rho_0 \) (kg m\(^{-3}\)) | \( A_T \) (GPa) | \( B_T \) (GPa) | \( E_0 \) (MJ kg\(^{-1}\)) | \( E_\infty \) (MJ kg\(^{-1}\)) | \( a_T \) | \( b_T \) | \( c_T \) | \( \beta_T \) | \( K \) (GPa) | \( \mu \) (GPa) | \( Y_0 \) (GPa) |
|----------|-----------------|----------------|----------------|-----------------|-----------------|--------|--------|--------|--------|--------|--------|--------|
| Basalt   | 2700            | 26.7           | 26.7           | 487             | 4.72            | 0.5    | 1.50   | 5      | 5      | 26.7   | 22.7   | 3.5    |
| Ice      | 917             | 9.47           | 9.47           | 10              | 0.773           | 0.3    | 0.1    | 10     | 5      | 9.47   | 2.8    | 1      |

Note. The quantity \( \rho_0 \) is the bulk density of the object. The 10 quantities \( \rho_0, A_T, B_T, E_0, E_\infty, a_T, b_T, c_T, \beta_T \) are the parameters used in the Tillotson equation of state (Melosh 1996). The remaining quantities, \( K, \mu, \) and \( Y_0 \) are the bulk modulus, the shear modulus, and the yield stress, respectively. Values for basalt and ice are taken from (Benz & Asphaug 1999). Note that \( A_T \) and \( B_T \) are set equal to the bulk modulus.
quickly after the impact. In our systems, the MBCs do not have much gravity, and as a result, the craters are formed quickly and are solely strength-dominated. We refer the reader to Collins et al. (2009) for crater formation in oblique impacts without gravity.

Because craters are irregularly shaped in porous targets, we determined their depth by directly measuring the distance between the lowest point of their crater to the surface of the target. To determine the surface area of a crater, we followed the methodology presented in Paper I, and calculated the area by fitting an ellipsoid to the crater. We refer the reader to Sections 3.1 and 3.3 of Paper I for more details on the technical aspects of our calculations. The increase in the penetration of the impactor in a porous target can then be

Figure 2. Snapshots of the collision of a m-sized object with a porous basaltic target with 50% water-mass fraction. The degree of porosity is 50%. The impactor is pure basalt with no porosity (red). The impact velocity is 4.4 km s\(^{-1}\). The impact angle is \(\beta = 0\) (left) and 30° (right). The orange color represents porous basalt and blue is for porous ice. The panels show 2D slices of 3D data.
(Animations (a and b) of this figure are available.)
Figure 3. Comparing the depths and surface areas of impact craters with and without porosity. The target in the top panels is porous basalt with 50% water-mass fraction. The target in the bottom panels is non-porous basalt with 50% water-mass fraction. The impact velocity in all panels is 4.4 km s$^{-1}$. In the top panels, orange represents porous basalt and blue is for porous ice. In the bottom panels, orange represents non-porous basalt and blue is for non-porous ice. The panels show 2D slices of 3D data.

Figure 4. Graphs of the depth (left) and surface area (right) of impact craters in terms of impact velocity for porous and non-porous targets, and with different water contents.
attributed to the fact that compared with non-porous objects, porous targets, especially those with mixture of water-ice, have lower material strength. As a result, when these objects are impacted, the momentum and energy of the impact carry the impactor deeper in the target, whereas in non-porous objects, the rapid compaction of the target at the impact site causes the

Figure 5. Graphs of the scattered ice in terms of impact velocity for porous and non-porous targets.

Figure 6. Graphs of the accumulative mass of the ejected ice in terms of its velocity for different impact scenarios and impact velocities. The top panel corresponds to impacts for which the vertical component of the impact velocity is smaller (left) or larger (right) than 3 km s\(^{-1}\). The bottom panels show ice ejection for a head-on (left) and a 30° (right) collision. As shown here, in all scenarios the velocity of the ejected ice is larger than 20 m s\(^{-1}\). The escape velocity of the currently known MBCs is smaller than 2.2 m s\(^{-1}\). This figure shows that all ice is ejected and the amount of re-accreted ice is negligibly small.
energy of the impact to be transferred laterally creating a less deep but wider crater. An important implication of the results shown by Figure 4 is that crater depths are still smaller than 15 m, suggesting the model by Schörghofer (2008) as the most viable ice-longevity model in the asteroid belt.

It has been suggested that the activity of an MBC, in addition to ice sublimation from the bottom and interior of an impact crater, may also be due to the sublimation of scattered ice that was re-accreted on the surface of the MBC. To examine this scenario, we calculated the amount and velocity of ejected ice after each collision; Figures 5 and 6 show the results. Figure 5 shows the amount of scattered ice in terms of the impact velocity and Figure 6 separates this quantity into groups based on the ejection velocity of scattered ices. The vertical axis in this figure shows the accumulative mass of the ejected ice and the horizontal axis shows its velocity. Each curve corresponds to a different impact velocity for both porous and non-porous targets. As shown here, in all simulations, the ejection velocity of ice is larger than 20 m s$^{-1}$. An examination of Table 1 indicates that this ejection velocity is almost 10 times greater than the largest escape velocity of the currently known MBCs, implying that almost all ejected ice is lost and there is basically no re-accretion. This strongly suggests that the activity of MBCs is most likely due to ice sublimation from multiple impact sites.

We also studied the change in the porosity of the target due to an impact. Figure 7 shows variations in the porosity of the targets of Figure 2 during an impact. The color coding represents the value of the distention parameter $\alpha$, corresponding to the porosity of the target. Yellow represents 50% porosity where $\alpha = 2$ and black corresponds to no porosity where $\alpha = 1$. The left column corresponds to a dry, porous target, and the right column represents the same object with 50% water content. As shown here, the material on the surface of the impact crater is strongly compacted, with the strongest compaction occurring at the bottom where the target becomes non-porous. As the shock of the impact propagates throughout the object, the degree of compaction lessens at deeper distances, suggesting that away from the impact site and well inside the object, the target maintains its original porosity. Our simulations show that the propagation of shocks do not cause the target to disintegrate, and therefore, in addition to maintaining its original porosity, the target maintains its original water content as well. The latter has important implications for the delivery of water to the accretion zone of Earth with water-carrying planetesimals and planetary embryos. As the orbits of these objects evolve during their dynamical evolution and they reach the accretion zone of Earth, they are repeatedly impacted by planetesimals and planetary embryos. However, as shown here and given the sizes of these objects, they can still maintain their water-ice deep inside until they are accreted by the still-forming Earth. Movies of the simulations of Figure 7 can be found in the supplementary material.

4. Discussion

We carried out an extensive analysis of the impact of a m-sized body with a km-sized MBC. We extended our previous simulations (Paper I), where objects were considered to be non-porous, to more realistic cases where the porosity of an MBC is taken into account. We carried out simulations for different values of impact velocities and impact angles, and considered different water contents for the target. The results of simulations indicate that, as expected, substantial amount of water-ice is exposed on the interior surface of impact craters, providing a viable pathway for triggering activity of MBCs. The results also indicated that the depth and size of craters increase for porous targets; however, the increase in depth is still within the regime (<15 m) where the ice-longevity model by Schörghofer (2008) applies.

In addition to being more realistic, our new simulations advanced those in Paper I by including vaporization due to the heat of impact. We treated phase transition during ice vaporization at the time of the impact by using the Tillotson equation of state. The results are shown in Figure 8. As shown here, and in agreement with the results obtained from observations, the amount of ice vaporized during an impact is very small. For instance, for the case of 176P/(118401) LINEAR, the entire ice vaporization due to an impact is less than five tons, whereas the rate of ice sublimation due to the activation of this body is ~720 kg day$^{-1}$. Other MBCs sublimate about an order of magnitude higher per days. This finding suggests that when modeling impacts as a way of excavating sub-surface ice to trigger activation of MBCs, vaporization due to impacts can be safely ignored.

As mentioned earlier, the combination of the high material strengths of our targets (see Table 2), the small sizes of our impactors, and the very low surface gravity of MBCs points to the fact that our impacts and their final craters are strength-dominated. This has strong implications when comparing our results with previous studies, in particular those of Richardson et al. (2007), who used the mathematical model developed by Holsapple (1993) and presented a thorough study of many impact properties of comets. A comparison of our results with theirs indicates that although our results are comparable with their findings within the order of magnitude, our crater diameters are smaller. This is not unexpected, as our impacts involve asteroids, which naturally have higher dynamic material strengths (Asphaug et al. 2002) compared with soft targets such as comets (Basilevsky et al. 2016). For instance, our assumed porous, wet MBC material has an average density of 685 kg m$^{-3}$. With an effective MBC diameter between 0.3 km and 4.0 km (see Table 1), the mean surface gravity of our targets range from 0.057 mm s$^{-2}$ to 0.38 mm s$^{-2}$, mostly lower than Richardson et al. (2007)’s nominal value of 0.34 mm s$^{-2}$. Given the range of our impact velocities (1.5–5.3 km s$^{-1}$), our crater diameters fall between 3 m and 13.3 m, which, quite understandably, are smaller than those presented by Richardson et al. (2007). The crater diameters estimated by these authors range between 22 and 26 m, and correspond to considerably faster projectiles (10.2 km s$^{-1}$) impacting softer targets.

Our assessment of the amount of the re-accreted ice after an impact indicated that, because of the low gravity of the target, except for cases where the impact velocities are very low, most scattered ice particles are lost and are not accreted back. This finding is consistent with previous results as reported in Paper I, and confirms that the activation of MBCs must be due to ice sublimation from multiple impact sites.

In this study, we did not consider a regolith layer on the top of the target. We assumed a random distribution for ice inclusions and considered ice to exist everywhere throughout the target, including its top surface. Although the inclusion of a regolith layer might have resulted in craters with slightly
smaller depths, the scattered fragments of the regolith layer could impact other parts of the target and expose ice in other sites causing underlying ice to be exposed in a larger area. The latter may compensate for smaller ice re-accretion and smaller ice exposure in the main impact crater. This scenario is currently being investigated.

5. Concluding Remarks

We close this study by presenting highlights of our findings.

1. Impacts of small bodies present a viable mechanism for exposing sub-surface volatiles, including water-ice to trigger sublimation-driven activity of MBCs.

Figure 7. Snapshots of the variation of the porosity of the target in Figure 1 during an impact. The color coding represents the value of the distention parameter $\alpha$ corresponding to the degree of compaction and porosity of the object. To better demonstrate changes in porosity, we show in the left column a dry, basaltic target with 50% porosity ($\alpha = 2$), and in the right column we use the same target, but this time with 50% water-mass fraction of porous ice. As shown here, the object is compacted at the site of the impact and the compaction extends to its inner parts as the shock of the impact propagates inside the body. However, most of the interior part of the target maintain its original porosity. The panels show 2D slices of 3D data.

(Animations (a and b) of this figure are available.)
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Figure 8. Graphs of the vaporized ice due to the heat of impact in terms of the impact velocity for porous and non- porous targets.

2. The loss of ice due to the heat of impact is negligible.

3. Most of the ejected ice particles are lost and not re-accreted.

4. A comparison between ice sublimation from impact craters obtained from our simulations with results of observations suggests that the activity of the current MBCs is most probably from multiple impact sites.

5. Results of simulations suggest that the water content of MBCs and those of their parent asteroids needs to be larger than those traditionally considered in the models of terrestrial planet formation so that the sublimation of the exposed water-ice can account for the rate of sublimation obtained from observations of these objects.

6. If the activation of MBCs is due to the sublimation of sub-surface water-ice, this ice must be buried within the top 15 m. This result points to the model of ice-longevity by Schörghofer (2008) as the most viable model for the retention of water-ice in the asteroid belt. That author suggested that a small layer of regolith on the outer surface of an asteroid can allow the body to maintain its sub-surface water-ice for the age of the solar system.