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Can collisional activity produce a crystallization of Edgeworth–Kuiper Belt comets?

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ABSTRACT

Kuiper Belt Objects and cometary nuclei are considered among the most pristine bodies of the outer Solar system. However, the composition of these objects might not reflect that of the planetesimals from which they accreted. They have experienced some collisional activity since the formation of the Edgeworth–Kuiper Belt, leading to a possible alteration of their structure and composition. Here, we examine the possible alteration of icy bodies (10 to 100 km radii) located in the primitive Edgeworth–Kuiper Belt due to the heat generated by collisions of planetesimals with sizes not exceeding 10 per cent of the target body. We use a cometary nucleus model initially made of a mixture of amorphous ice and dust to investigate the influence of the target's intrinsic properties on its post-impact thermodynamical evolution. We show that multiple collisions must be considered over long periods to trigger a continuous crystallization within a target owning a typical cometary composition. However, the collision rates we have determined are approximately 1000 times greater than those predicted for the current collisional environment in the Edgeworth–Kuiper Belt. This implies that the collisional processes that occurred over the age of the Solar system did not produce any phase transition of H₂O ice from amorphous to crystalline forms in cometary size bodies located in the primitive Edgeworth–Kuiper Belt.

Key words: comets: general – Kuiper Belt – Solar system: formation.

1 INTRODUCTION

Kuiper Belt Objects (KBOs) and cometary nuclei are considered among the most pristine objects of the outer Solar system. However, 90 per cent of the mass of the Edgeworth–Kuiper-Belt (EKB) was lost through collisions and ejections engendered by dynamical interactions with Neptune (Stern & Colwell 1997; Leinhardt, Stewart & Schultz 2008). Thus, it has been proposed that the population of KBOs has been greatly eroded due to collisions (Stern 1996) and that cometary nuclei themselves would derive from larger parent bodies (Davis & Farinella 1996; Coradini et al. 2008).

One possible consequence of the scenario of collisional erosion of the EKB is that comets and larger parent bodies might have suffered an alteration of their structure and composition due to the post-impact heat that made them evolve compared to the planetesimals from which they accreted. The alteration of these icy bodies may have notable effects because they are thought to have initially accreted from planetesimals composed of amorphous ice (Mousis et al. 2000). Hence, collisions with planetesimals may generate

enough heat in the subsurface of the target to initiate, in particular, a phase transition of H₂O ice from amorphous to crystalline forms, thus furnishing a plausible mechanism to explain the crystalline ice features observed on the surfaces of the brightest KBOs (Jewitt & Luu 2004; Rabinowitz et al. 2008). A study concerning the post-impact thermal evolution of an EKB crystalline comet was made by Orosei et al. (2001). These authors pointed out that multiple impacts could trigger a heat buildup inside the nucleus which could trigger a runaway crystallization, but these conclusions were supported only by a single-impact simulation.

Here, we study the thermodynamical evolution of comets and larger parent bodies in the 10–100 km size range that may result from multiple collisions in the primitive EKB. We investigate the range of parameters such as the projectile's size (which remains below the fragmentation limit), the collision rate and the target's intrinsic properties (dust content, fraction of trapped CO, heat capacity and conductivity) that may allow to trigger the crystallization within EKB comets. We show that the required collision rates are approximately 1000 times greater than those predicted for the current collisional environment in the EKB. This implies that the collisional processes that occurred over the age of the Solar system did not engender any phase transition of H₂O ice from amorphous to crystalline forms in EKB comets.

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2 THERMODYNAMIC EVOLUTION OF THE TARGET

2.1 Nucleus model

The nucleus model employed in this work is based on the one-dimensional model developed by Marboeuf (2009). This model uses the finite volume method that aims at improving the conservation of the balance of mass and energy fluxes within the nucleus all along the orbit. Before and after the collision, we use the system of predictor–corrector resolution imposing a slow evolution of the system. During the time of the impact, we use an iterative fully implicit method to solve the equations of conservation of mass and energy because of the rapid temperature and pressure evolution (Marboeuf 2009). Except for the numerical treatment, our approach remains classic: the model considers a sphere (initially homogeneous, and with spherical symmetry at all times) composed of a porous pre-defined mixture of ices (essentially water ice) and dust in specified proportions. It describes heat transmission, gas diffusion, sublimation/recondensation of volatiles in the nucleus, dust release and mantle formation. Water ice can be initially amorphous or crystalline, depending on the formation location of the body in the Kuiper Belt or not. When the ice is amorphous, a fraction of the other volatiles can be trapped in the water ice matrix, while the remaining is condensed in the pores as pure ices. When heated, the fraction of volatiles condensed in the pores sublimates first, and then the other fraction trapped within the matrix is released during the transition from amorphous to crystalline water ice.

2.2 Insertion of collisional energy

We consider that the planetesimals are porous but not collisionally weak (Ryan, Davis & Giblin 1999). The impact strength Q_D^* (energy required to disrupt and disperse a body) first decreases with increasing target size at small sizes, goes through a minimum and then increases again for larger sizes (Leinhardt et al. 2008). Ryan et al. (1999) showed that the minimum impact strength Q_D^* should be of the order of $5 \times 10^4 \text{ J m}^{-3}$. Here, we assume that Q_D^* for a porous icy target impacted by a porous icy projectile is equal to $5 \times 10^4 \text{ J m}^{-3}$ in the case of cometary size bodies ($\sim 10 \text{ km}$) and $5 \times 10^5 \text{ J m}^{-3}$ in the case of larger parent bodies. In this work, the collision between the projectile and target is characterized in terms of the fraction f^c of collisional kinetic energy delivered as heat to the target by the impactor itself. Immediately after collision, impact heat is transferred to the nucleus and its propagation within the body is described following the approach of Orosei et al. (2001) and Mousis et al. (2005). As in Mousis et al. (2005), the distribution of impact heat results in a homogeneous energy density deposited in the subsurface within a cylindrical volume, the cross-section and depth of which correspond, respectively, to the impactor's diameter and radius. Because of the one-dimensional nature of the model, lateral heat diffusion is neglected. As pointed out by Orosei et al. (2001), this method has some limitations. In particular, this will increase the energy locally available to heat the matrix, and hence improve the chances of internal modification of the target. Also, successive collisions will all occur on the same spot of the target. To be more in line with the usual one-dimensional assumption, one can consider that the energy is deposited uniformly on the entire surface of the target for each collision, hence the overestimate of the effect of collisions. As will be seen later, this is consistent with the determination of an upper limit of the effect of collisions on the target. Note that we do not account for the ablation of matter,

effects of erosion or destruction which can be caused to the target by the impactor. We restrict our study to the energy contribution of a collision of a projectile on a planetesimal. Original accretion and radioactive heating are also neglected in our calculations.

If we consider that the target and the projectile have the same physical composition, the energy per unit volume delivered by the impactor in the subsurface of the target is equal to

$$Q_i^{\text{col}} = f^c \frac{2}{3} \rho_t v_p^2 \quad (\text{J m}^{-3} \text{ s}^{-1}), \quad (1)$$

where ρ_t is the mass density of the target, v_p is the relative velocity between the target and the projectile and f^c is the fraction of kinetic energy of the projectile transferred as heat into the target.

In order to avoid $Q_i^{\text{col}} > Q_D^*$, we impose a limit on the size of the projectile. Using a limit of half the strength Q_D^* , the relation between the radius of the projectile and the one of the target is given by

$$\frac{R_p}{R_c} = \left(\frac{Q_D^*}{\rho_p v_p^2} \right)^{1/3}, \quad (2)$$

where R_p and R_c are the radius of the projectile and the target, respectively.

2.3 Parameters

At the beginning of the computation, the objects have a homogeneous composition made of amorphous H_2O ice, CO and dust. The orbital and physical parameters defining our model of comet or parent body are given in Table 1. These values are typical of cometary nuclei produced in the trans-Neptunian region (Morbidelli 1998). The surface temperature of the target is an important parameter because it can provide the extra amount of energy needed to trigger

Table 1. Initial parameters of the target.

Parameter	Value
Orbital	
Semimajor axis (au)	35
Eccentricity	0
Material	
Initial temperature (K)	46
Emissivity	1
Albedo	0.05
Initial structure of ice	Amorphous
Initial porosity P_o^i	50 per cent
Density of water $\rho_{\text{H}_2\text{O}}$ (kg m^{-3})	920
Density of dust ρ_{dust} (kg m^{-3})	3000
Heat capacity of water $C_{\text{H}_2\text{O}}$ ($\text{J kg}^{-1} \text{ K}^{-1}$)	$7.49 \text{ T} + 90^{(a)}$
Heat conductivity of amorphous ice $K_{\text{H}_2\text{O}}$ ($\text{W m}^{-1} \text{ K}^{-1}$)	$7.1 \times 10^{-3} \text{ T}^{(b)}$
Heat conductivity of crystalline ice $K_{\text{H}_2\text{O}}$ ($\text{W m}^{-1} \text{ K}^{-1}$)	$567/\text{T}^{(b)}$
Crystallization latent heat H_{cr} (J mol^{-1})	$1620^{(c)}$
Heat capacity of dust C_{dust} ($\text{J kg}^{-1} \text{ K}^{-1}$)	$3 \text{ T}^{(d)}; 1200^{(e)}$
Heat conductivity of dust K_{dust} ($\text{W m}^{-1} \text{ K}^{-1}$)	$10^{-4(f)}; 10^{(g)}$
J_{dust} (dust/ice mass ratio)	0.1; 1; 10
J_{CO} (mol ratio CO/ H_2O)	0–10 per cent

^(a)Giauque & Stout (1936), ^(b)Klinger (1980), ^(c)Ghormley (1968), ^(d)Enzian, Cabot & Klinger (1997), ^(e)Ellsworth & Schubert (1983), ^(f)Mendis & Brin (1977), Tancredi, Rickman & Greenberg (1994), ^(g)Huebner et al. (2006).

the crystallization process or other structural changes at the time of a collision. Here, we impose a uniform temperature throughout the nucleus corresponding to the equilibrium temperature for a highly conducting black sphere orbiting at 35 au from the Sun. The phase transition of H₂O ice from amorphous to crystalline forms is assumed to be exothermic¹ and irreversible. The study focuses on bodies of 10 and 100 km radius. The objects of 10 km correspond to the comet size bodies originating from destructive collisions of larger parent bodies or residues of planetesimals formed *in situ*. The objects of 100 km radius correspond to the parent bodies that can survive in the collisional environment of the EKB (Davis & Farinella 1997).

The physical parameters of the components of the planetesimals are somewhat uncertain. The literature abounds with values of the heat capacity and thermal conductivity of dust's grains that can vary by orders of magnitude. Similarly, the value of the dust/ice mass ratio J_{dust} and the fraction of volatiles contained in planetesimals are uncertain. The value of each of these parameters strongly influences the thermal behaviour of the core target after an impact, as they control how a nucleus can accumulate energy or diffuse it more quickly. More precisely, the lower the total heat capacity of the material, the higher the temperature just after an impact. The ability of the object to spread its energy or to conserve it locally is affected by the thermal conductivities of the various components of the solid matrix's nucleus. These parameters could create or eliminate the conditions of a partial or complete crystallization of the core target. Similarly, the mass ratio J_{dust} determines the contribution of the dust's heat capacity and thermal conductivity to the whole body. Finally, the amount of volatile condensed within the target also influences its thermal behaviour as it can absorb a significant fraction of the collisional energy during its phase transition from solid to gas.

Table 1 summarizes the range of parameters that have been tested in our simulations. We have considered the whole range of published values for the heat capacity and thermal conductivity of the dust. Similarly, we have used extreme values (0.1 and 10) as well as a more realistic value of 1 for the dust/ice mass ratio J_{dust} . Since CO is the second most abundant volatile species observed after H₂O in cometary nuclei (Bockelée-Morvan et al. 2004), we also opted to include this species in our model by varying the molar ratio J_{CO} between 0 and what seems to be a realistic maximum of 10 per cent. According to Coradini et al. (2008), the porosity of a body can vary between 30 and 80 per cent. Moreover, variations in J_{dust} (from 0.1 to 10) generate a change in the overall porosity of the core target which depends on its size. But since the variation is by less than an order of magnitude, we opted to take an initial porosity P_o^i of 50 per cent overall the target regardless of its initial physical and chemical composition. For the collisional parameters, we fixed f^c to 10 per cent (Orosei et al. 2001) and the collision velocity to 1 km s⁻¹ (Stern 1996; Davis & Farinella 1997; Durda & Stern 2000), corresponding to the current mean relative velocity in the EKB. These values and the values of Q_p^i imply that the size of the largest impactor must not exceed about 10 per cent of that of the target.

3 RESULTS

We first study the influence of the physical parameters of the target on its thermodynamic evolution after a single collision. From the

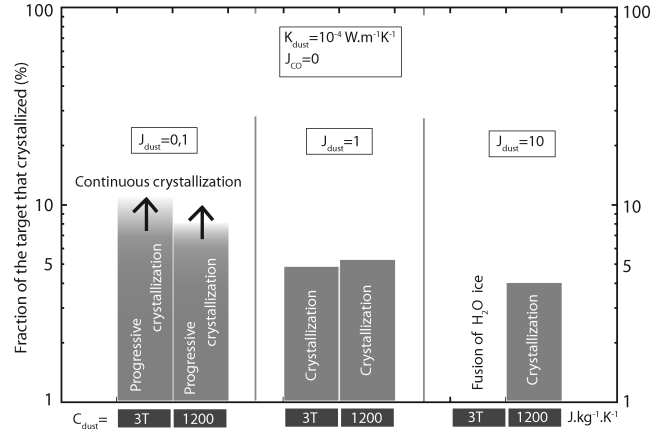


Figure 1. State of crystallization of the ice after a collision with a projectile of 300 m for models without CO. Crystallization never stops for $J_{\text{dust}} = 0.1$.

results obtained, and choosing the settings that enhance the internal modifications of the target nucleus, we then determine the frequency of collisions required to generate a continuous crystallization of the target nucleus.

3.1 Single collision

Here, we fix the size of the target (10 km) and the projectile (300 m) in order to study the effect of each of the variable parameters described in the previous section, varying them one at a time. The influence of the size of both the target and the projectile is discussed later. Fig. 1 summarizes the influence of the heat capacity of dust and the dust/ice mass ratio for a CO-free target and a low thermal conductivity of dust ($K_{\text{dust}} = 10^{-4} \text{ W m}^{-1} \text{ K}^{-1}$).

For a model with $J_{\text{dust}} = 1$, the variation of conductivity shows little effect on the crystallization of the target for any value of the heat capacity of the dust's grains. Low dust conductivities ($K_{\text{dust}} = 10^{-4} \text{ W m}^{-1} \text{ K}^{-1}$) slow the crystallization, but increase the thickness of the ice crystallized within the nucleus. When we impose a greater value ($K_{\text{dust}} = 10 \text{ W m}^{-1} \text{ K}^{-1}$) for dust conductivity, the time of crystallization is shortened, but its depth decreases slightly, because more of the generated heat can escape through the surface before the ice crystallizes. The dust conductivity has an effect on the depth of the crystallization but not really on its trigger. The depth of crystallization corresponds roughly to the thickness of energy deposition zone during the impact.

For a core composed mainly of ice ($J_{\text{dust}} = 0.1$), regardless of the heat capacity and thermal conductivity of dust grains, a single collision is sufficient to generate a total crystallization of the core target. For a low dust heat capacity ($C_{\text{dust}} = 3 \text{ T J kg}^{-1} \text{ K}^{-1}$, Model A) and a large fraction of dust $J_{\text{dust}} = 10$, the surface layers of the target are liquefied, but our model cannot handle this physical process. For the same dust/ice mass ratio, but with a large dust heat capacity ($C_{\text{dust}} = 1200 \text{ J kg}^{-1} \text{ K}^{-1}$, Model B), crystallization occurs.

The presence of CO in significant amount (10 per cent in mol of H₂O) in the core reduces the depth of crystallization and prevents its progression in the target nucleus by absorbing collisional energy during its sublimation. The gas then transports this energy both inwards and outwards by diffusion, returning a large fraction of the energy to the hotter regions, and delivering the other part to deeper regions that are unable to benefit from this energy input to crystallize, as they are too cold. This creates a slowly evolving energy barrier below which the target nucleus remains unperturbed.

¹ Kouchi & Sirono (2001) have shown that the crystallization of amorphous water ice containing impurities can become endothermic.

The results obtained with a model composed entirely of water ice and dust are then an upper limit value of the state of crystallization of the core target.

3.2 Multiple collisions

In the previous study, we determined the physical parameters which inhibit or enhance the alteration of the ice structure and composition of the core target after one collision. Using the previous results, we now search for the minimal collision frequency that will allow the spread of the crystallization inside the core for Models A and B with a mass ratio J_{dust} equal to 1, and for Model B with a mass ratio J_{dust} equal to 10. We consider 10 and 100 km size nuclei made solely of amorphous water ice and dust in order to favour their physical differentiation. Model A with a high dust/ice mass ratio is not considered here as it results in the fusion of the upper layers after a single collision. Since low thermal conductivity of the dust grains favours progression of the crystallization, we use $K_{\text{dust}} = 10^{-4} \text{ W m}^{-1} \text{ K}^{-1}$.

For each target size (10 and 100 km), we consider impactors from metre-size up to the maximum allowed size before fragmentation (10 per cent of the target size). Figs 2 and 3 give the minimum time interval between collisions for a given impactor size resulting in the progression of crystallization for all models. The grey area on the right of both the figures indicates impactor radii larger than the allowed maximum.

These figures show that the time interval between collisions needed to create a continuous crystallization of the target decreases with decreasing projectile size. This results from the balance of the crystallization time (roughly constant) and the time for heat diffusion through the upper layers, which decreases as the projectiles get smaller. In all cases, crystallization is progressing only if the time interval between each collision becomes excessively short. Thus, models with a reasonable ($J_{\text{dust}} = 1$) and large ($J_{\text{dust}} = 10$) dust/ice mass ratio crystallize continuously if the time intervals between collisions are about 5000 to 10 000 years for all models (target of 10 and 100 km combined) with a 1 km impactor. To generate an increase of the fraction of the target nucleus that crystallized, we determined that one collision should occur every 1 to 10 years for small impactors. Delaying or stopping the successive collisions that

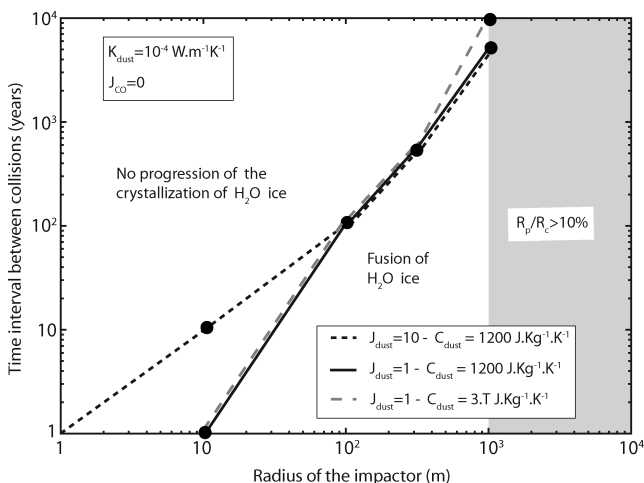


Figure 2. Time interval between collisions that allows the progression of the crystallization according to the radius of the impactor. Target of 10 km radius. The area below the curves corresponds to a collision frequency so high that it will trigger a transition from water ice to liquid water.

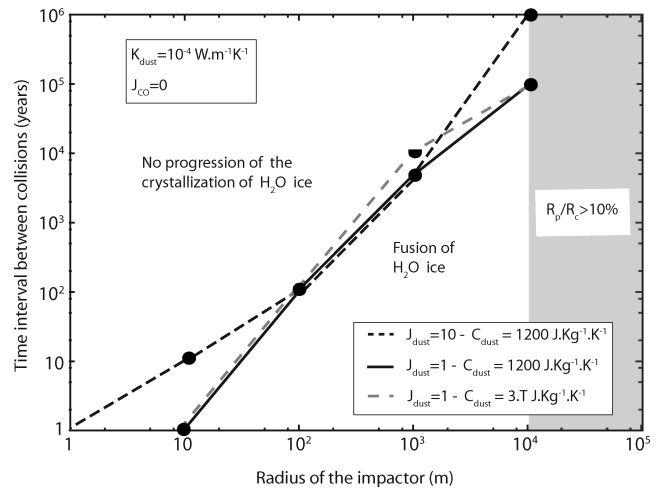


Figure 3. Same as Fig. 2, but for target of 100 km radius.

occur at regular time interval, the progression of the crystallization of the core stops gradually (area above the curve). Increasing the time interval between two collisions by an order of magnitude just warms the core target without necessarily creating the thermal conditions of a progression of crystallization. Conversely, reducing the time interval by an order of magnitude for the largest impactors ($R_p > 100 \text{ m}$) creates the conditions for thermal melting of the water ice matrix (area below the curve). Because of the high-energy input, the temperature of the medium exceeds the melting point of water ice. Our model is not designed to account for such a phase transition, and therefore stops at this point.

Finally, the conditions for a progression of the crystallization of the core target result from a balance between the temperature increase generated during a collision (which depends mainly on the heat capacity of the various components), dispersion of collisional energy to the surface and the rest of the core, and the time interval between two energy inputs. Any unbalance in this combination of parameters can lead to lack of progression of crystallization or fusion of the matrix of ice.

4 DISCUSSION AND CONCLUSIONS

The collision rate required to allow for an in-depth crystallization is way too high compared to the predictions by Durda & Stern (2000). These authors predict that a target object of 100 km radius, located at about 35 au, suffers one collision every 3.5×10^9 years with an impactor of 10 km, one collision every 6.5×10^7 to 1.5×10^8 years with a 1 km impactor and one collision every 1000 to 6000 years with an impactor of 4 m. For the same impactor sizes, continuous crystallization requires one collision every 10^4 to 10^6 years ($R_p = 10 \text{ km}$), 10^4 years ($R_p = 1 \text{ km}$) and 1 to 10 years ($R_p = 10 \text{ m}$). Only models with a low dust/ice mass ratio ($J_{\text{dust}} = 0.1$) and without CO condensates ($J_{\text{CO}} = 0$) within the solid matrix showed a progression of the crystallization front with a single collision from impactors larger than 100 m in radius.

In all our simulations, we have constantly favoured crystallization of the amorphous water ice, while neglecting fractures and upper layer removal that would naturally occur for a collision between two bodies. We assumed that the collisions were non-destructive and non-erosive. The target retained its integrity whatever the number of collisions, which encouraged the accumulation of heat provided by the successive collisions within the target core. Because our

model is one dimensional, the successive collisions take place on the same geographical area of the target which again favours the accumulation of heat in the nucleus. In addition, the tests were performed by selecting parameters (thermal conductivity of the dust, lack of volatile) that favour the physical and compositional transformations. Finally, the possible internal evolution of the target core is based on the assumption that the water ice component is in the amorphous solid state at the origin (Kouchi et al. 1994) and that the phase transition from amorphous ice to crystalline ice is an exothermic reaction. If this reaction is endothermic (see footnote in Section 2.3), the energy of collisions would not generate any differentiation of the structure and composition of the core target.

Despite all those favouring factors that could foster an internal transformation of the target on the long term, we find that the frequency of collisions which would allow the evolution of the target is way too high. These high-collision rates, and moreover on the same geographic area of the target nucleus (Model 1D), seem impossible over a long period. Increasing the collision rate leads to the fusion of the water ice from the solid matrix, while decreasing it stops the progression of the crystallization.

Given the limitations imposed by the model, the approximations and the choice of parameters that have been made (which helped to boost the process of differentiation), we conclude that in the case of a planetesimal reasonably dusty with different ices, the structural changes take place only at the site of the collision and to a depth of about the size of the impactor and does not progress within the target. Clearly, the collisional process that occurred over the age of the Solar system was not the cause of significant physical and chemical internal alterations.

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