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Low velocity collisions of porous planetesimals in the early solar system

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ABSTRACT

The ESA Rosetta mission has shown that Comet 67P/Churuymov–Gerasimenko is bi-lobed, has a high average porosity of around 70%, does not have internal cavities on size scales larger than 10 m, the lobes could have individual sets of onion shell-like layering, and the nucleus surface contains 100 m-scale cylindrical pits. It is currently debated whether these properties are consistent with high-velocity collisional evolution or if they necessarily are surviving signatures of low-velocity primordial accretion. We use an Eulerian hydrocode to study collisions between highly porous bodies of different sizes, material parameters and relative velocities with emphasis on 5–100 m/s to characterize the effects of collisions in terms of deformation, compaction, and heating. We find that accretion of 1 km cometesimals by 3 km nuclei at 13.5 m/s flattens and partially buries the cometesimal with ∼1% reduction of the bulk porosity. This structure locally becomes more dense but the global effect of compaction is minor, suggesting that low-velocity accretion does not lead to a 'bunch of grapes' structure with large internal cavities but a more homogeneous interior, consistent with Rosetta findings. The mild local compaction associated with accretion is potentially the origin of the observed nucleus layering. In 2D axially symmetric impacts hit-and-stick collisions of similarly-sized nuclei are possible at velocities up to 30 m/s where deformation becomes severe. The bulk porosity is reduced significantly, even at 30–50 m/s relative velocity. To avoid hit-and-run collisions the impact angle must be less than 35°–45° from the surface normal at 10 m/s, and even smaller at higher velocities. Impact heating is insignificant. We find that the small cross section of the 67P neck may require a ≤5 m/s impact, unless the cohesion exceeds 10 kPa. We conclude that bi-lobe nucleus formation is possible at velocities typically discussed in hierarchical growth scenarios. Impacts of a 7 m projectile at 100–500 m/s create a rimless cylindrical shaft with vertical walls, up to 50 m wide and 70 m deep. These shafts bear some resemblance with the pits on 67P, particularly if the depth-to-width ratio is reduced by nucleus erosion. Collisions between similarly-sized nuclei above 100 m/s lead to complete disintegration, and even small fragments suffer different degrees of compaction. Thus, we strongly doubt that 67P has been subjected to high-velocity collisions by projectiles larger than those that might have formed the pits, or is the fragment of a larger parent body. We suggest that the observed properties of 67P are more consistent with primordial accretion.

1. Introduction

A main objective of the Rosetta mission is to constrain comet formation theories by measuring physical and chemical properties of 67P/Churyumov–Gerasimenko. Different formation scenarios of planetesimals in the early solar system have been discussed in the literature. Weidenschilling (2004, 2008) studied the coagulation of grains into macroscopic bodies driven by differential rotation of nebular gas and dust, modified by drag interaction and turbulence. The resulting hierarchical growth by collisions produces 'rubble pile' structures with sizes up to ∼100 km on timescales of the order of 10^6 years what is within the lifetime of the solar nebula. The impact velocities in the nebula are up to some tens of m/s depending on the particle sizes. Johansen et al. (2014) consider the assembly of gravitational unstable 'pebble clouds' by gas-grain streaming instabilities in the solar nebula. Wahlberg Jansson and Johansen (2014) showed that the formation time of comets is quite short (< 10,000 years) in this scenario. The collision velocities depend on the mass of the cloud and also reach a maximum of some tens of m/s in massive clouds at the end of the formation process.

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A range of 5–10 m/s is found typical for the dispersion of relative velocity of kilometer-sized objects during most of the runaway coagulation regime of big KBOs (Schlichting and Sari, 2011). Final sizes of the objects and physical properties, such as porosity and strength, depend on interplay of fragmentation and coagulation and, therefore, on the total mass of the cloud. Davidsson (2016) argues that massive TNOs up to 400 km formed in agreement with the second picture. Some of these later assemble in high velocity collisions to form large >1000 km diameter TNOs. However, comets grow according to Davidsson (2016) by hierarchical agglomeration of material left over after TNO formation. Further growth is a quite slow process and therefore comets can be considered as primordial rubble piles what is in agreement with recent findings by Rosetta. In case number densities and the degree of dynamical excitation are sufficiently high, comets may suffer collisions in their reservoirs. Morbidelli and Rickman (2015) conclude from the Nice Model of Solar System evolution that typical km-sized comet nuclei are predominantly fragments resulting from high velocity collisions in the order of 1 km/s. However, the frequency and velocity of such collisions depends on the initial mass of the preplanetary disk, on the degree of dynamical excitation and on the time scale to its dispersal due to planetary migration. Neither parameter is well constrained. In all scenarios the collision velocities play a fundamental role in forming the final bodies. The purpose of this paper is to investigate how impacts of different velocities, sizes and material properties modify the collision partners. This is of importance to interpret the exciting observations of space missions to comets as Deep Impact/Epoxi, Stardust and Rosetta in terms of formation and early evolution conditions. Therefore, we performed 2D and 3D hydrocode simulations where we treat one- or two-component materials with the help of an equation of state (EOS). This is complemented by an implementation of the P-alpha model (Hermann, 1968; Swegle, 1980) as a description of porous materials under dynamic conditions and other constitutive assumptions. We investigate the result of collisions in terms of density changes and other material modifications. The change of shape and the duration of the contact phase are byproducts of the simulations. Different combination of model parameters such as internal strength, initial velocities and sizes of both colliding bodies are studied. Jutzi and Asphaug (2015) follow a similar goal but apply an SPH (smoothed particle hydrodynamics) algorithm, a different numerical technique to model the collisions. They mainly investigate such features as layering and the final shape after the impact but not the detailed modifications of the internal structure and apply much lower velocities.

Except for cratering of a flat target where a constant acceleration of gravity is included, self-gravity is neglected in the simulation runs. As a proxy for the effects of gravity, the timescale of collapse of a crater of diameter D under gravity is $0.54(D/g_s)^{1/2}$ (Melosh, 1989) and for $D = 3$ km diameter and $g_s = 2.44 \times 10^{-4}$ m/s^2, see Pätzold (2016) for the average surface gravity g_s, this leads to about 30 min. However the duration of significant deformation and stress relaxation is of the order a few minutes at most, for the EOS, constitutive model parameters and body sizes used in the simulation runs.

In Section 2 we introduce our model. The results of our parameter study are presented in Section 3. In Section 4 the findings are discussed on the background of the Rosetta results. Conclusions to comet formation scenarios are given.

2. Model description

2.1. Hydrocode

The Backward Euler (BE) hydrocode is an upgrade of the multi-material method by de Niem et al. (2007). The overall formulation is an Eulerian finite volume method, consisting of Lagrangian and remap steps carried out in dimensional splitting. The algorithm is parallelized using the MPI (message passing interface) library. Multiple materials are handled with a piece-wise linear VOF (volume-of-fluid) scheme to resolve the material interface on sub-cell level (Gueyffier et al., 1999). Both Lagrangian and remap steps are second-order accurate spatially and temporarily. The pressure EOS is an analytical model, see Section 2.3 for details. A hypoelastic formulation is applied for the deviatoric stress, where the yield criterion is the Lundborg (1968) model, characterized by cohesion, coefficient of friction and the Hugoniot elastic limit of yield stress. The tensile fracture criterion is based on the largest eigenvalue of the total stress. If this threshold is violated the deviatoric stress is set zero and if pressure is negative its magnitude is reduced to the tensile strength limit, identified with the cohesion parameter of the Lundborg (1968) model for simplicity. For a porous material the yield criterion is valid in terms of the pressure and shear stress of the effective medium. A detailed description of our model for porous materials is in Section 2.2. The positioning of variables is MAC-staggered (Predebon et al., 1991; McGlaun et al., 1990): density, internal energy and deviatoric stress components are cell-centered while normal velocities are approximated at the midpoint of cell faces. A particular advantage of the Backward Euler strategy is that integration during the Lagrangian step is performed using a semi-implicit method in time. Technically the solution of the momentum equation leads to several tridiagonal linear systems for velocities in an extension of the method by de Niem et al. (2007). The computationally most expensive part is the parallel solution of tri-diagonal systems using the method of Mattor et al. (1995). The basic version of the code was developed for 2D cylindrical coordinates, the 3D version is for Cartesian coordinates.

2.2. Porous material description

Describing porous collision partners is crucial for the purpose of the paper. A particularly successful physical model for shock propagation and other physical effects in dry porous materials is the so-called P-alpha model by Hermann (1968), a clarifying review was provided by Swegle (1980). Dry porosity means that voids between grains or cavities are empty. So the resistance to compaction results from contact- or surface forces of the solid matrix material. Numerical methods have been described such as the epsilon-alpha model by Wünnemann et al. (2006) for a grid-based Eulerian hydrocode and the implementation by Jutzi et al. (2008) for Lagrangian SPH. Both groups of authors considerably modified the original Hermann (1968) model and their methods are time-explicit. In contrast our semi-implicit algorithm critically depends on such details as the bulk modulus of the porous medium and the correct evolution equation for the matrix volume fraction.

Models of porous materials contain an internal variable: the matrix volume fraction $\Phi \in (\Phi_0;\ 1)$ (=one minus porosity) such that the density of the effective medium is given by $\rho = \Phi \rho_s$ in terms of that of the solid matrix ρ_s (Swegle, 1980). The time evolution of Φ is described by a differential equation that is solved during the Lagrangian step. In an Eulerian grid-based hydrocode Φ is a history variable, and advected applying the VOF technique; the product of Φ and the material volume fraction is remapped. Here it is assumed that the pressure P_s of the matrix material evolves adiabatically (Swegle, 1980)

$$\frac{dP_s}{dt} = K_s \frac{\dot{\rho}_s}{\rho_s}, \tag{1}$$

where all time derivatives are Lagrangian, K_s denotes the adiabatic bulk modulus of the solid matrix, and using $\rho_s = \rho/\Phi$

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