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Compaction of ice pebbles in collapsing pebble clouds and the dust-to-ice ratio of comets

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Abstract

The gravitational collapse of pebble clouds formed in the streaming instability provides a mechanism for comet formation, which agrees well with the observed properties of comets, such as their low density. We numerically investigated the collapse of an ensemble of porous ice and silica pebbles and studied the final filling factor of these pebbles. Based on these results, we estimated the dust-to-ice ratio of the cometesimal and its dependency on initial conditions.

1 Introduction

Comets are believed to have formed as icy planetesimals from dust and ice grains beyond the ice line in the Solar Nebula about $4.5\,\mathrm{Gyr}$ ago. However, growth from $\mu\mathrm{m}$-sized particles to km-sized bodies is difficult because bouncing [10] and fragmentation [1, 4] stall growth. The streaming instability circumvents those growth barriers by strongly concentrating dust and ice pebbles, leading to the formation of gravitationally bound clumps, which can collapse into a solid object, such as a cometesimal [6, 8].

Cometary densities are low ($\sim 0.4\,\mathrm{g\,cm^{-3}}$). Collapsing pebble clouds are a suitable environment to explain this [2, 3, 7]. Low-velocity bouncing collisions during the collapse yield a body with a pebble packing fraction of $\phi_\mathrm{p} \approx 0.6$. Additionally, dust growth in the Solar Nebula produces pebbles with a filling factor of $\phi \approx 0.4$ [10]. Thus, the total filling factor of the comet is $\phi_\mathrm{c} = \phi_\mathrm{p} \times \phi = 0.24$, in agreement with the observed low density [7].

2 Method

We conducted numerical simulations of collapsing pebble clouds with a pre-existing Monte Carlo method [9, 8] and followed the evolution of the volume filling factor of the pebbles. We adapted the collision model for porosity and water ice by scaling the threshold velocities for sticking, bouncing, and fragmentation, and the compression curve of ice by a factor of ten [5].

In our study, we used $1\,\mathrm{cm}$ pebbles with varying initial filling factor, ϕ_0, from 0.001 (very porous) to 0.4 (compact). We investigated three cloud masses corresponding to a $5\,\mathrm{km}$ (low-mass), a $50\,\mathrm{km}$ (intermediate-mass), and a $500\,\mathrm{km}$ (high-mass) object with a bulk density of $0.4\,\mathrm{g\,cm^{-3}}$. We simulated the collapse of ice and silica pebbles separately and used the results to derive a dust-to-ice ratio, ξ, for the cometesimal.

3 Results

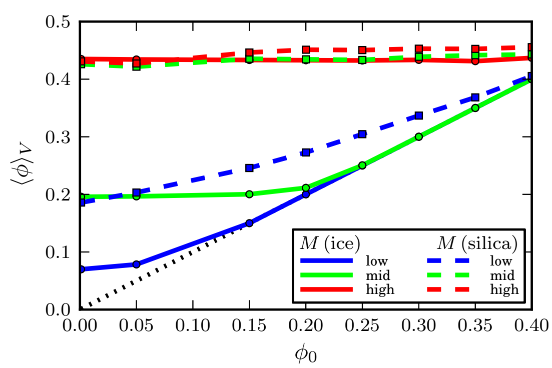

Figure 1: Pebble compaction. Final filling factor of the pebbles as a function of their initial filling factor. Different coloured lines correspond to different pebble cloud masses. Solid lines correspond to ice pebbles and dashed lines to silica pebbles. Along the black dotted line, the final filling factor equals the initial filling factor.

Our simulations showed that silica pebbles are sig-

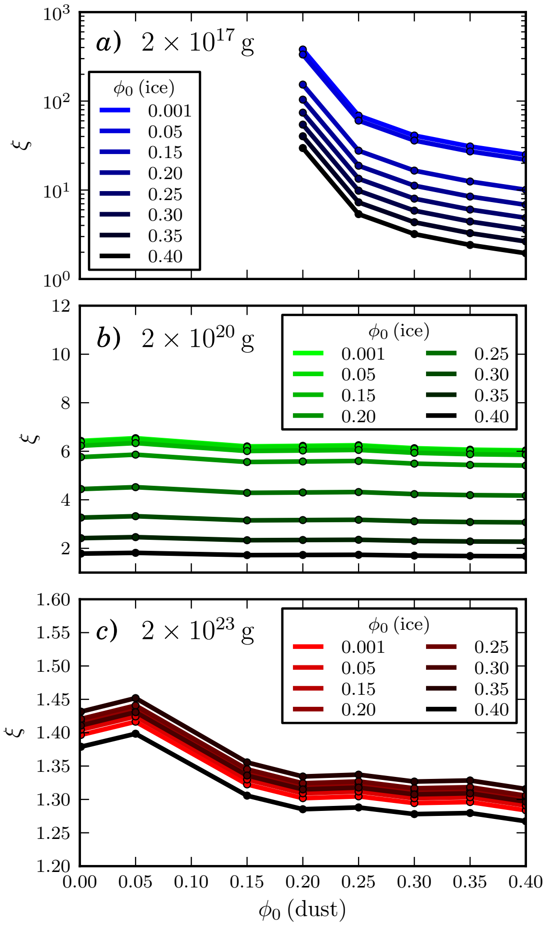

Figure 2: Dust-to-ice ratio, ξ, of the comet as a function of initial filling factor of the pebbles. *a*) low-mass cloud; *b*) intermediate-mass cloud; and *c*) high-mass cloud.

nificantly compressed during the collapse acquiring a filling factor of $\phi \approx 0.19 - 0.45$ (Fig. 1). In contrast, ice pebbles are barely compressed and retain their initial filling factors, unless the cloud is massive (Fig. 1). Thus, the dust-to-ice ratio varies strongly with initial conditions taking values between 380 and 1.3 (Fig. 2). Starting with compact ($\phi_0 = 0.4$) ice and dust pebbles in the low-mass cloud, the dust-to-ice ratio is about 2. ξ is insensitive to ϕ_0 of the silica pebbles in the intermediate- and high-mass case. In the high-mass case, the dust-to-ice ratio is also insensitive to ϕ_0 of ice.

4 Conclusion

We found that silica pebbles are significantly compressed during the collapse of a pebble cloud, whereas ice pebbles retain most of their initial porosity because of their ten times higher compression strength. Thus, the dust-to-ice ratio of a comet required to account for the low density varies strongly with initial conditions. If both ice and silica pebbles posses an initial filling factor of 0.4 in the low-mass cloud, the dust-to-ice ratio takes a value of ~ 2. For the intermediate- and high-mass cloud, the dust-to-ice ratio is insensitive to the initial filling factor of the silica pebbles. In the high-mass case, also the initial porosity of the ice pebbles does not play any role.

Acknowledgements

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