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One step closer to unveiling the planetesimal-formation process

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Abstract

The formation of planetesimals has successfully been modelled by consecutive sticking collisions all the way from µm-sized dust to km-sized bodies as well as by first forming mm-sized dust aggregates which then undergo hydrodynamic spatial concentration until their collective gravitational attraction results in a gentle collapse to multi-km-sized objects. With more and more empirical evidence emerging from laboratory measurements, numerical modelling and observations, the two-stage scenario now seems to be the most likely. Here I will show the evidence that speaks in favour of a gravitational-collapse model.

1. The two competing models of planetesimal formation

It is undisputed that planetesimal formation in protoplanetary discs (PPDs) starts with (sub-)µm-sized solid grains of dust (metals, oxides, silicates, organic materials, depending on the ambient temperature) and/or ice (H_2O, CO_2, CO, NH_3, CH_4). These grains experience mutual collisions, which initially are so gentle that they always result in the sticking of the grains and, thus, lead to the formation of aggregates. With increasing aggregate size (assuming a fractal dimension of the aggregates >2), the collision velocities systematically increase. At some point, the collision speed exceeds the sticking threshold of the aggregates, whereupon the initial growth stage ends (see Ref. [1] for a recent review about the dust-aggregate collision model). Depending on the PPD model and the grain properties (particle size and material), the final aggregate size is in the range ~0.1-10 mm [5,3]. This first growth stage is common for the two competing planetesimal-formation models, which will be presented hereafter. Details and references about the models, including benefits and problems as well as the properties of the resulting planetesimals, can also be found in Ref. [1].

1.1 The collisional-growth model

Laboratory experiments have shown that for collision velocities exceeding the fragmentation threshold of the smaller of the two colliding dust aggregates, growth of the larger aggregate by mass transfer from the fragmenting aggregate can occur. Although the growth rate of this process is relatively small, it can in principle ultimately lead to the formation of bodies with sizes on the order of 1 km.

1.2 The gravitational-collapse model

If sedimentation towards the PPD mid-plane or hydrodynamic processes can locally concentrate the typically mm- to cm-sized aggregates (“pebbles”) resulting from the first growth stage, the streaming instability is capable of further concentration until a gentle gravitational collapse occurs. The resulting planetesimals are typically 100 km in size (with a power-law size distribution) and the required timescales are much shorter than for the collisional-growth model.

2. Planetesimal properties and empirical evidence from cometary nuclei

Due to the different physical process eventually leading to planetesimals in the two models described in Sect. 1, their properties differ considerably, which provides the opportunity for empirical tests with planetesimals in the Solar System (see Ref. [1] for details).

2.1 Properties of planetesimals formed by the collisional-growth model

Due to the high collision velocities in the mass-transfer regime (typically 50 m s^{-1}), the growing planetesimals possess a porosity of only ~60%, a tensile strength of ~10^3-10^4 Pa, and no characteristic particle size between the dust grains (~1 µm) and the planetesimal size (~1 km).

2.2 Properties of planetesimals formed by the gravitational-collapse model

Depending on the size of the final planetesimal, the "pebbles" from the gravitationally collapsing cloud either survive intact (size $\lesssim$ 10-50 km) or are being crushed during the collapse or hydrostatically inside the planetesimal (size $\gtrsim$ 10-50 km). In the latter case, the planetesimal properties are comparable to those of the bodies formed by collisional growth, except for the final planetesimal size. However, for small planetesimals, a porosity of ~70-80%, a tensile strength of ~1-10 Pa, and the occurrence of a characteristic size scale between the dust grains (~1 µm) and the planetesimal size (~1-10 km), namely the "pebble" size of ~1-10 mm is expected.

2.3 Cometary nuclei as evidence for planetesimal formation by a gravitational collapse of a "pebble" cloud

Cometary nuclei, with typical sizes of 1-10 km are the ideal objects to search for empirical evidence about their formation, because they are small enough to preserve dust "pebbles" if they were formed by the gravitational collapse and they experienced at most sub-catastrophic collisions, which kept major parts of the original planetesimal matter structurally intact [4].

With recent advances in investigations of comets, the following evidences have been collected in favour of the gravitational-collapse model (see Ref. [1] and references therein for more details):

- The presence of fractal particles in the coma of comet 67P, as found by the Rosetta mission, can only be explained if these aggregates were remnants from the solar nebula and were safely stored in between cm-sized denser entities, the "pebbles" [2]. The fractal particles bear evidence that comets are very primitive and contain (fractal and non-fractal) dust aggregates from the formation era of the Solar System.
- With the Rosetta/Philae spacecraft having visited comet 67P, it is very likely that the overall porosity of the nucleus is between 69% and 75% (depending on the composition of the comet) and that the tensile strength is in the range 1-10 Pa. These values match the predictions by the gravitational-collapse model.
- The dust activity of comets is caused by the outgassing of volatile species, primarily of water ice. Thermal models of the sub-surface regions of comets when they approach the Sun make predictions about the ice temperature under the desiccated dust layer. Converting this temperature into an outgassing rate and a local gas pressure shows that it is very unlikely that this pressure ever exceeds ~1 Pa. Thus, in order to overcome the cohesion of the dust layer above the ice, its tensile strength must be accordingly small. The gravitational collapse model inherently predicts this for aggregate sizes of ~1 cm or above. In fact, most of the dust mass released by comets is in particles of typically this size (or larger).

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