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Comets formed in solar-nebula instabilities!

B. Gundlach, J. Blum, S. Mühle, and J. M. Trigo-Rodriguez

Institut für Geophysik und extraterrestrische Physik, Technische Universität Braunschweig, Germany (b.gundlach@tu-bs.de)

Abstract

When comets approach the Sun, the energy flux through the surface dust layers increases and causes the sublimation of the underlying ices. The outgassing then leads to the observed emission of gas and dust. However, the ejection of dust requires that the forces binding the dust particles to the comet nucleus must be overcome by the forces caused by the sublimation process. This relates to the question of how large the tensile strength of the overlying dust layer is. Homogeneous layers of micrometer-sized dust particles typically possess tensile strengths of 10^3 to 10^4 Pa. This values exceeds by far the maximum sublimation pressure of water ice in comets. It is therefore unclear how cometary dust activity is driven.

During this conference, we discuss how two different formation scenarios (the mass transfer scenario and the gravitational instability scenario) can influence the surface structure of cometary nuclei. With the aid of laboratory experiments, we can explain cometary dust activity if we assume that cometary nuclei are formed by the gravitational instability scenario. In the case of the mass transfer scenario, the tensile strength of the surface layers is too high to sufficiently eject dust particles from the surface.

1 Formation scenarios

The growth of millimeter- to centimeter-sized agglomerates inside the snow line of the solar nebula by direct sticking is now well established [1, 2]. The further growth to planetesimal-sized objects is still under debate, with two major scenarios under consideration: the mass transfer scenario (1) and the gravitational instability scenario (2).

(1) During collisions, direct sticking is mostly prevented by bouncing among the dust aggregates in the protoplanetary disc. Only particles with collisions velocities lower than the sticking threshold can further grow, whereas the fastest collisions lead to fragmentation with mass transfer [3, 4, 5]. It has been shown that this latter process can form planetesimals although the timescales are rather long and details about counteracting processes (e.g., erosion) need to be clarified. If comets have formed by mass transfer, the surface would consist of an homogeneous dust layer composed of micrometer-sized particles.

(2) Alternatively, [6] showed that cm-sized particles can be sufficiently concentrated by the streaming instability [7] so that the ensemble becomes gravitationally unstable, which can also lead to planetesimal formation. Also here, several details need to be clarified before this process can be regarded as established, e.g. the collisional fate of the dust agglomerates within the instabilities, fragmentation of the collapsing cloud and the mass distribution function of the resulting plan-

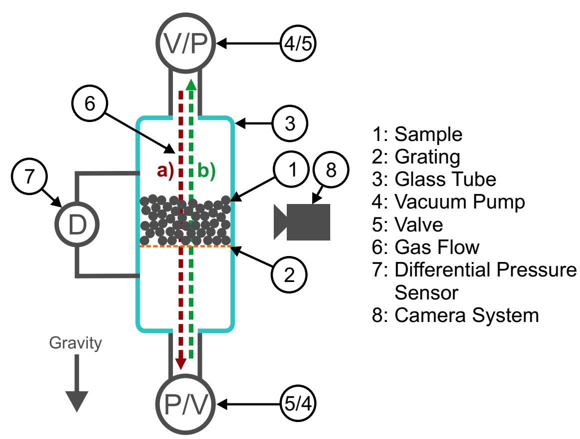

Figure 1: Schematic diagram of the experimental setup used for the tensile strength measurements of granular samples [9]. Two different versions of this experiment were used in this work. First, the gas flow was used to compress the samples (a; red arrow; the pump (P) and the valve (V) are located at the bottom and at the top of the schematic diagram, respectively). Then, the gas flow was inverted in order to measure the tensile strength of the granular samples (b; green arrow; the pump (P) and the valve (V) are located at the top and at the bottom of the schematic diagram, respectively).

etesimals, and the required high metallicity of the solar nebula. Cometesimals formed by gravitational instability posses an hierarchical surface layer consisting of millimeter- to centimeter-sized agglomerates [8].

2 Experimental investigation

The tensile strength of homogeneous dust layers (mass transfer scenario) was already measured and is in the range between 10^3 Pa and 10^4 Pa. Thus, we have measured the tensile strength of loose arrangements of dust aggregates by using the experimental setup shown in Fig. 1 [9]. At the beginning of the experiments, the sample (1) was carefully positioned on a grating (2) inside a glass tube (3). Then, the glass tube was carefully and slowly evacuated by a vacuum pump (4) down to a pressure of $\sim 10\,\mathrm{Pa}$. A needle valve (5) enabled the generation and control of a gas flow through the sample (6). By inversion of the gas flux direction, a static compression of the samples prior to the tensile-strength measurements was applied. The pressure difference beneath and above the sample was measured by a differential pressure sensor (7). During the experiments, the sample was observed by a camera system (8).

Fig. 2 shows two different samples with different aggregate sizes, $(0.66 \pm 0.14)\,\mathrm{mm}$ and $(1.29 \pm 0.29)\,\mathrm{mm}$, before and after the break-up of the material. The resulting tensile strength with respect to the prior compression of the samples (aggregate size: $(0.66 \pm 0.14)\,\mathrm{mm}$) are visualized in Fig. 3.

3 Result

The mass-transfer model predicts comets with much too high tensile strengths of the surface layer (10^3 to 10^4 Pa). For the gravitational-instability formation scenario of cometesimals, the tensile strength of the surface layers is much lower ($\sim 1\,\mathrm{Pa}$) as proven by our experiments. If comet nuclei are leftover cometesimals, whose formation is described by one of the two competing planetesimal-formation models (mass transfer or gravitational instability), then only the gravitational-instability model can explain the dust activity of comets.

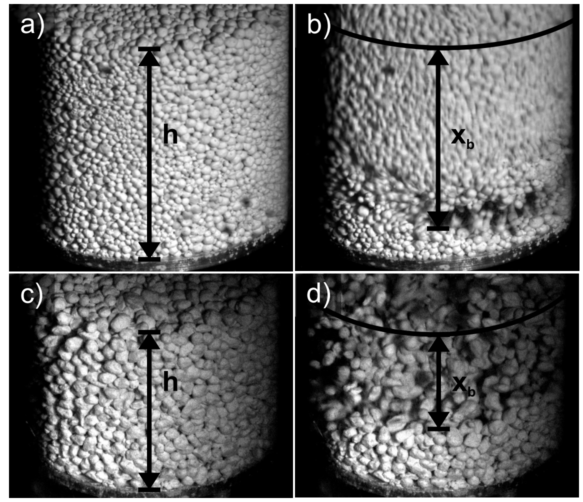

Figure 2: Dust-aggregate samples before (left images) and during the break-up of the samples (right images) [9].

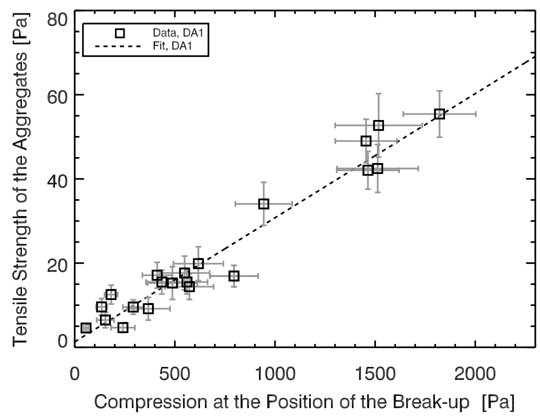

Figure 3: Derived tensile strengths of the aggregate samples (size of the aggregates: $(0.66 \pm 0.14)\,\mathrm{mm}$) as a function of the compression pressure at the position of the break-up (squares) [9]. The dashed line shows the least-squares linear fit applied to the data. The uncertainties of the tensile strength measurements are denoted by the gray error bars. The uncompressed tensile strength of the DA1 samples is $(1.3 \pm 0.9)\,\mathrm{Pa}$. The slope of the tensile strength vs compression curve is $(2.9 \pm 0.2) \times 10^{-2}$.

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