Sticking Properties of Silicates in Planetesimal Formation Revisited

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Abstract

In the past, laboratory experiments and theoretical calculations showed a mismatch in the derived sticking properties of silicates in the context of planetesimal formation. It has been proposed by Kimura et al. that this mismatch is due to the value of the surface energy assumed, supposedly correlated to the presence or lack of water layers of different thickness on a grain’s surface. We present tensile strength measurements of dust aggregates with different water content here. The results are in support of the suggestion by Kimura et al. Dry samples show increased strengths by a factor of up to 10 over wet samples. A high value of $\gamma = 0.2 \, \text{J m}^{-2}$ likely applies to the dry low pressure conditions of protoplanetary disks and should be used in the future.

Key words: methods: miscellaneous – planets and satellites: formation – planets and satellites: fundamental parameters – protoplanetary disks

1. Introduction

Surface energy is an important parameter that determines the sticking of dust particles during planetesimal formation. Kimura et al. (2015) discussed the specific value of surface energy of amorphous silica in great detail. They performed a comprehensive literature search, finding orders-of-magnitude differences between values of the surface energy deduced by varying authors. As essence for the variation, they pinned down the surface energy of a few times $0.01 \, \text{J m}^{-2}$ for the wet case and $\gamma \sim 0.2 \, \text{J m}^{-2}$ for the dry case, a large difference of up to an order of magnitude.

This is important in the context of modeling planetesimal formation. Dominik & Tielens (1997) used $0.025 \, \text{J m}^{-2}$ for quartz determined by Kendall et al. (1987). Based on their model, the sticking velocities below which a quartz grain of $1.2 \, \mu \text{m}$ diameter should stick to a wall should only be $0.09 \, \text{m s}^{-1}$. However, Poppe et al. (2000) find about $1 \, \text{m s}^{-1}$ sticking velocity. This is an order of magnitude larger than calculated. Similarly high values also show up in other laboratory experiments, e.g., by Blum & Wurm (2000). In any case, the sticking velocity scales with $\gamma^{3/6}$ (Dominik & Tielens 1997). Thus, the mismatch could be turned into agreement if the surface energy was higher by more or less a factor of 10, or $\gamma \sim 0.2 \, \text{J m}^{-2}$ (Kimura et al. 2015).

So the question is, can the lack of water at the protoplanetary disk’s low pressure conditions lead to such high values as suggested by Kimura et al. (2015)? In a number of experiments, we measured the tensile strength of dust aggregates composed of dry or wet grains to answer this question.

2. Experiment

The basic idea behind the tensile strength measurements is the Brazilian test that is sketched in Figure 1.

This procedure was used before for dust by Meisner et al. (2012), and recently for dust and ice aggregates by Gundlach et al. (2018). The measured force $F$ at which the aggregate breaks can be translated into a tensile strength $\sigma = 2F / (\pi d L)$—in our experiment with the aggregate diameter $d \approx 8 \, \text{mm}$ and cylinder length $L = 5-9 \, \text{mm}$. Figure 2 shows the experimental setup we used, including a half of a correctly broken cylinder. The experiment is carried out at normal atmosphere but with samples prepared in two different ways.

3. Samples

We used a commercial amorphous silica sample by Micromod (Sicastar plain) with a grain size of 1.2 $\mu \text{m}$. This sample is monodisperse and grains are spherical. They match the grains used in the earlier collision experiments referred to by Kimura et al. (2015).

3.1. Normal Atmosphere

One sample was not treated in any way. That means the dust was just taken from its bottle and pressed into a cylinder with varying filling factor $\Phi$ (volume fraction filled with material). The typical water content of these samples was determined by weighing samples before and after heating to 250°C for 24 hr. This shows a water content (mass fraction) of the sample of $6.6 \pm 1.1\%$, resulting in a corresponding uncertainty of $\Phi$. The surface water content corresponds to a homogeneous 25.3 ± 4 nm thick layer or about 84 ± 14 mono layers of water on the surface of each grain. The volume filling factor was corrected to the pure silica case to achieve a comparable factor.

3.2. Heated Samples

The second kind of sample consists of samples heated to remove surface water. Measurements were carried out immediately after the sample was taken out of the oven. About five samples were heated at one time and measured in sequence. A whole sequence took about 10 minutes. During the measurements, the samples could recollect water, but due to their compact nature, the diffusion times into the dust
aggregates are much longer than the measurement times, and we consider these aggregates to be dry. The debris was used again for the preparation of new samples. To do so, the fragments were crushed in a mortar and then again pressed into cylindrical agglomerates and, in this case of dry samples, finally heated to 250 °C for 24 hr. To rule out sintering during the heating procedure, we heated a sample for 24 hr at 300 °C and afterwards observed no sinter-necks via SEM (Figure 3).

4. Results

Figure 4 shows the comparisons of the tensile strength measurements for wet and dry samples. The wet samples show a clear power-law dependence on the filling factor, as was known before (Meisner et al. 2012). The dry samples are somewhat less constrained, with more variation. However, the data of both subsets differ by an order of magnitude. As tensile strength directly depends on the sticking of individual contacts and as aggregates only differ in water content, this directly translates to a difference in surface energy according to Rumpf’s equation (Rumpf 1970)

$$\sigma = \frac{9\Phi N}{8\pi d^2} (f_c \gamma).$$

Here, N is the coordination number, which is of the order of five. The contact force inserted is $F_c = f_c \gamma$, as all forces of importance are proportional to $\gamma$. This includes the pull-off force, the rolling force, and essentially also the sliding force.

We therefore conclude that dry samples can have a factor 10 higher surface energy than wet samples. Omura & Nakamura (2017) found, in greater detail, that the contact force entering for very cohesive dust is somewhere between the rolling force and sliding force, depending on the porosity. If the coordination number is low, more particles can roll. For our dense aggregates, the relevant force should be closer to sliding. For the ratio between the sliding and rolling forces for silica beads of similar size, Omura & Nakamura (2017) calculate a factor of about 100. Using a rolling force of $F_r = 6\pi \gamma \xi$ with a critical displacement of 0.2 nm (Dominik & Tielens 1997) the factor $f_c$, if we assume sliding, is about $f_c = 0.12\pi \mu m$. If we insert this into Equation (1), we obtain $\gamma = 0.013 J m^{-2}$ for the wet case based on pure sliding. The real value will be somewhat higher, as on average some particles will still be allowed to roll. Details are beyond the scope of this work, but this estimate is in agreement with the literature values compiled by Kimura et al. (2015).

We attribute the strong variation in the dry samples compared to the wet samples to the preparation process. The
data show higher tensile strengths for dry samples, and thus the resulting fragments after an experiment are more stable in the dry case. As these fragments are crushed and pressed into a cylindrical shape for the following experiments, some substructure within the pressed agglomerate might remain after the preparation process and weaken the resulting agglomerates. This explanation most likely applies to the extremely low values around $\Phi \sim 0.48$ in Figure 4, since these points were created at the end of our measurements and so out of the most often recycled material. Similar effects have been observed by Schräpler et al. (2012).

We did not analyze the structure of the aggregates further, nor did we optimize the preparation process, as we think the data already make the point sufficiently clear that surface water changes the surface energy strongly for the silica grains. Kimura et al. (2015) actually also consider some variation for two values $\gamma \sim 0.15$ J m$^{-2}$ and $\gamma \sim 0.25$ J m$^{-2}$ for specific experiment cases as best match. Our experiments show that such high values might indeed be justified.

5. Conclusion

We find that the water content on the surface of silica grains has a significant influence on the value of the surface energy. We compared the surface energy of dry and wet samples. They can differ up to a factor of 10. We did not directly measure values under vacuum conditions or under low pressure, but following the arguments by Kimura et al. (2015), these should be similar to the values of the dry samples. Our findings therefore support the suggestion by Kimura et al. (2015) that choosing a high value for the surface energy on the order of $\gamma \sim 0.2$ J m$^{-2}$ would be appropriate to match calculations to the experiments. As conditions in protoplanetary disks also match the dry cases of the experiments, conclusions drawn from the specific experiments so far still apply, i.e., that the sticking threshold of micrometer grains is on the order of 1 m s$^{-1}$.

In any case, following Kimura et al. (2015), we propose the use of high values for the surface energy for numerical simulation on dust growth of silicates to obtain consistent and protoplanetary disk–like results.

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