

Breaking the ice: planetesimal formation at the snowline

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Accepted 2011 August 1. Received 2011 July 21; in original form 2011 July 5

ABSTRACT

Recently Saito & Sirono proposed that large ice aggregates which drift inwards in protoplanetary discs breakup during sublimation, ejecting embedded silicate particles. This would lead to a concentration of small solid particles close to the snowline. In view of this model, we carried out laboratory experiments where we observed freely levitating ice aggregates sublimating. We find that frequent breakup is indeed very common. Scaled to a 10 cm aggregate, about 2×10^4 small silicate aggregates might result. This supports the idea that sublimation of drifting ice aggregates might locally increase the density of small dust (silicate) particles which might more easily be swept up by larger dust aggregates or trigger gravitational instability. Either way, this might locally boost the formation of planetesimals at the snowline.

Key words: methods: laboratory – planets and satellites: formation – protoplanetary discs.

1 INTRODUCTION

In protoplanetary discs small particles collide, stick together and form larger aggregates (e.g. Blum & Wurm 2008). This is usually regarded as a first phase of planet formation. One process with potentially wide impact on planet formation is radial transport of material. In a pressure gradient supported disc, the disc rotates somewhat slower than Keplerian. As solids are not supported by this pressure gradient, they feel a residual gravity and drift inwards (Weidenschilling 1977). In typical discs, metre-size bodies drift the fastest, moving about 1 au in 100 yr. Usually, this fast radial drift is regarded as hurdle on the way to planets, as it might lead to the loss of solids to the star, eventually. However, infall of mass from further out also provides means for a local concentration of solids further inwards. Two mechanisms of this kind, related to each other, were recently proposed by Saito & Sirono (2011) and Sirono (2011).

The basic idea proposed is that large aggregates drift inwards from the colder regions of the disc where the dominant mass fraction of solids is ice. They sublimate and during this phase fall apart in several pieces. Only the silicate cores embedded within the aggregates survive, and due to the fragmentation process a larger number of small particles or aggregates gather at or close to the snowline. As the fragments are smaller in size compared to their progenitor, the drift velocity is much smaller and the particles concentrate around the snowline. As a consequence, this might boost the formation of planetesimals. The density might rise to a level that gravitational instability leads to the formation of planetesimals (Wakita & Sekiya 2008). Also, in a turbulent disc an enhanced dust-to-gas ratio might be beneficial for planetesimal formation (Johansen, Youdin & Mac Low 2009). Last but not least, growth efficiencies in the hit-and-

stick scenario of planetesimal formation increase as well if larger bodies have a reservoir of small particles to collect (Blum & Wurm 2008). Whatever the details of further evolution, the breakup of large ice aggregates into smaller units while drifting inwards and the resulting concentration of small grains might be an important step in planetesimal and planet formation close to the snowline. Therefore, the models proposed by Saito & Sirono (2011) and Sirono (2011) offer interesting perspectives. The models have some distinctive features.

The model by Sirono (2011) considers sublimation under saturated conditions including sintering. In a numerical simulation, the author shows how water is redistributed in an ice aggregate to the largest grain within this aggregate, eventually. During this process, connections are broken and intermediately the aggregate is split into several smaller aggregates which eventually all sublimate completely. This model gets support from laboratory work where sublimating/sintering snow layers under saturated conditions are observed collapsing under gravity (Flin et al. 2003).

The model by Saito & Sirono (2011) is similar but considers only sublimation of ice aggregates (no sintering) in a water-vapour-free environment. Here, the basic set-up is that silicate cores are mantled by ice and these core–mantle grains form larger aggregates. Reaching the snowline the ice sublimates and all cores are assumed to be ejected as individual grains. This model is not supported by numerical calculations as the model by Sirono (2011). The fragmentation of the ice aggregates is a basic assumption and hence not discussed. In view of this, we carried out laboratory experiments for free particles suspended against gravity which very closely resemble the model by Saito & Sirono (2011) to study how many fragments would result from sublimation.

The experiments are based on a levitation technique which was only recently developed. Kelling & Wurm (2009) showed that porous dust particles levitate over a hot surface at low (mbar)

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pressure. This is due to thermal creep in a temperature gradient which transports gas downwards through the pores of the particles. This flow leads to a slight pressure increase below the particle which is sufficient to compensate its gravity. The same effect is used here but at lower temperatures. Details are given below. With this technique it is possible to observe free, levitating ice aggregates while they sublime and breakup which gives a direct measure of the number of times a given aggregate breaks up before it is completely sublimated. The aggregates in our experiments move in a quasi-2D way where gravity and compression due to gravity are only minor factors.

2 LABORATORY EXPERIMENTS

We levitate ice aggregates at low pressure (mbar) which allows a sublimation of freely moving particles where the breakups of particle parts get directly observable and the number of breakups per time can be counted. The levitation of the particles is based on an overpressure between aggregates and underlying surface (Kelling & Wurm 2009). This overpressure is generated by thermal creep through the pores of the particle. The thermal creep is induced by a temperature gradient, and this temperature gradient is externally generated by cooling the top of the experiment chamber with liquid nitrogen. The pressure increase by thermal creep is also known as the Knudsen compressor (Knudsen 1909). The compression depends on the ambient pressure and allows a particle lift in the mbar pressure range. A particle will levitate at a height where the gas flow to the sides decreases the pressure difference to exactly the level that the weight of the particle is balanced (see Fig. 1).

The actual set-up consists of a Peltier element ($5 \times 5 \text{ cm}^2$), on which an aluminium plate is placed. The plate is slightly concave to confine the aggregates to a limited area. The typical measured temperature on the aluminium plate surface is 260 K. On top of the

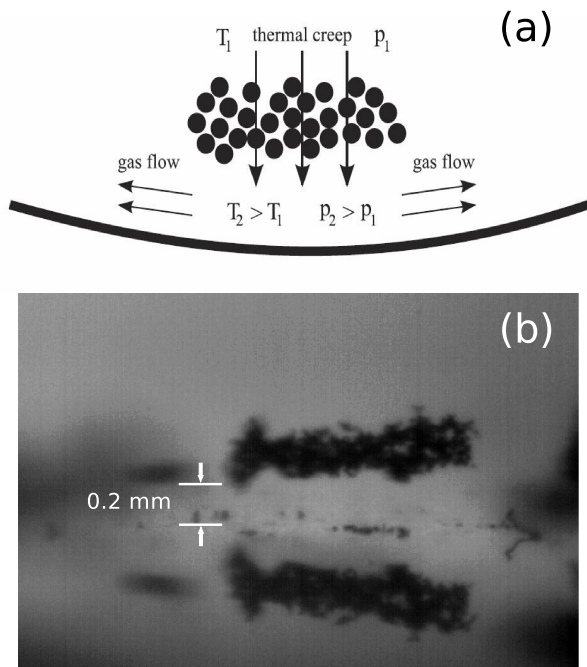


Figure 1. (a) Levitation induced by thermal creep (the Knudsen compressor). The air flows through the pores from the cold to the warm side, building up a pressure (Kelling & Wurm 2009). (b) Side view of a levitated ice aggregate on a Peltier element and its reflection.

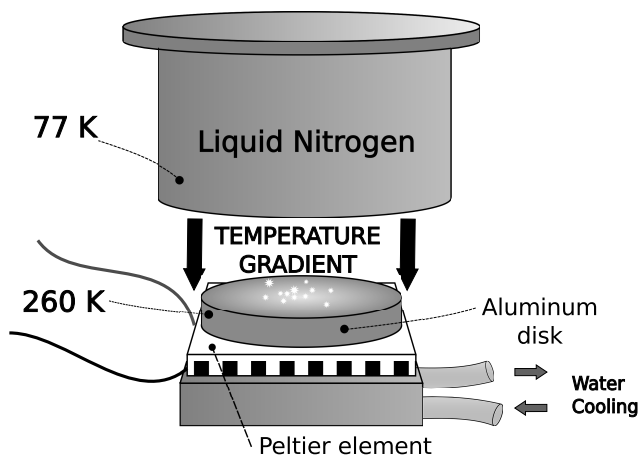


Figure 2. Sketch of the set-up used for ice aggregate levitation. Experiments are carried out at a pressure of few mbar.

set-up, a reservoir of liquid nitrogen at 77 K is placed. A sketch of the set-up can be seen in Fig. 2.

At the low pressure, the ice sublimates at a convenient rate (within a few minutes). As seen in Fig. 1(b) the levitating aggregates are typically fractions of an mm in thickness which is small compared to the total area of ice coverage of about 10 mm. This reduces the problem effectively to a 2D problem and breakups can well be observed from a top view of the ice particles (Figs 3 and 4). To do so, the nitrogen reservoir has a central clearance (not indicated in Fig. 2).

In the experiments, gravity is well balanced by the pressure difference. Only small forces remain, which can lead to an interaction between different particles, i.e. if contacts break, aggregate parts are usually drifting apart. Due to the flat and porous structure, vertical breakups with a succeeding compaction (aggregate parts fall downwards) are expected to be rare though we cannot rule out such events. We only consider observable breakups here, where one part of an aggregate clearly separates from another part. In each

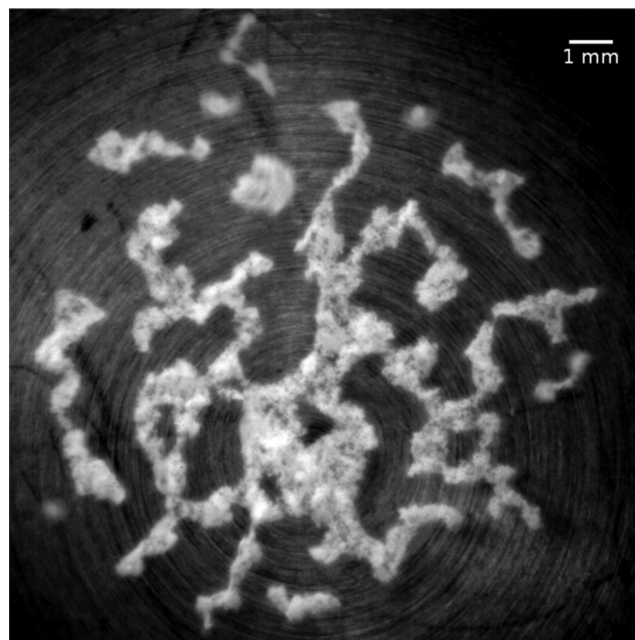


Figure 3. Top view of an ensemble of ice aggregates.

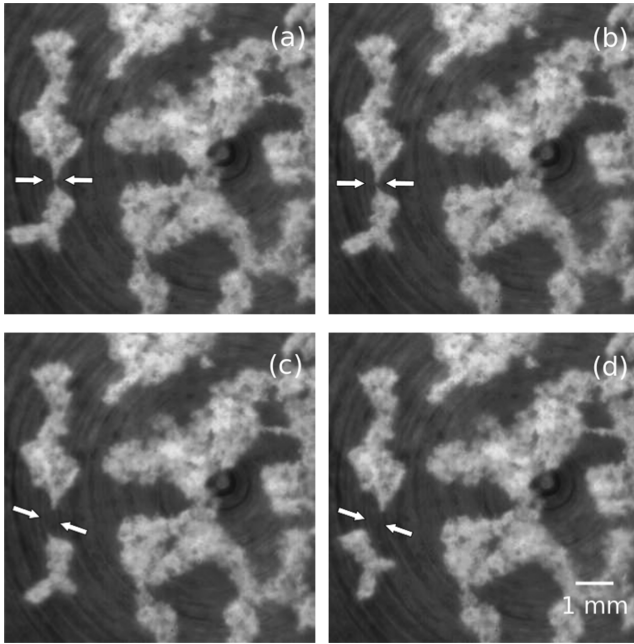


Figure 4. Example of an observed aggregate breakup. In this sequence it can be observed in (a) how the lower part of the left aggregate is still connected to the upper part. In (b), the lower part has displaced slightly to the right but still remains connected. In (c), the aggregate is clearly broken and the lower part separates from the upper one. Finally, in (d) the two parts will continue their paths separately.

experiment, a movie is taken from the sublimating ice particles. On the dark background, a separation can easily be seen by eye while scanning frame by frame through the movie afterwards. The number of breakups and the times of each breakup are the results of a visual analysis of the movie without any further image analysis.

We also count breakups where two aggregate parts separate but are still connected at another location, i.e. bend and open at the breakup point. However, such events only account for about 10 per cent of all cases. This is in agreement with the formation of the aggregates by hit-and-stick growth during preparation, where every individual ice grain only has two neighbours.

Particle preparation. Ice particles were prepared under atmospheric conditions (1 bar, laboratory humidity). Individual ice grains condensate in the vicinity of the pipe’s surface that connects the liquid nitrogen tank and the set-up’s liquid nitrogen reservoir. These ice grains collide, stick together and form aggregates, which can be observed by microscopy. Fig. 5 shows a snapshot of the preparation phase. We did not specify the morphology or structure of the individual grains in more detail. The aggregates are taken from the pipe’s frozen surface and put into the set-up using a small spoon cooled by liquid nitrogen. Also, the transfer of particles into the experiment chamber might induce modifications, e.g., by direct condensation of water vapour but essentially the ice particles observed in the experiments are grown aggregates.

As aggregates the particles are an appropriate model for large particles in protoplanetary discs which are also assumed to be formed by aggregation (Blum & Wurm 2008).

An example of the evaporation rate is seen in Fig. 6 which shows the evolution of the evaporating ice during an individual experiment as fraction of the image covered by ice. The sublimation can well be described as linear with time but with a pronounced change in slope at about 25 s. Within the scope of this Letter, we consider

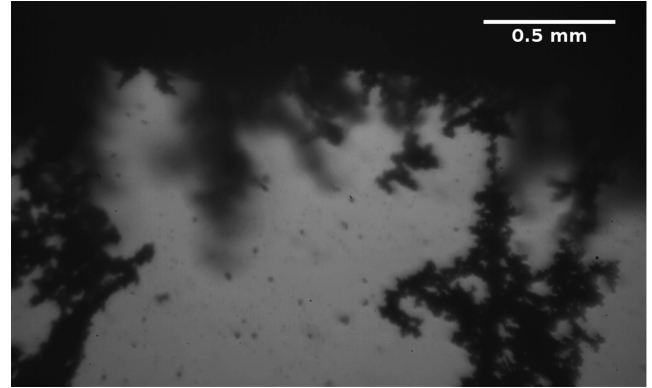


Figure 5. Example from the preparation process. Atmospheric water vapour condenses into ice grains (small particles) around a cold liquid nitrogen pipe (top black area). They collide and stick to aggregates which stick to the pipe.

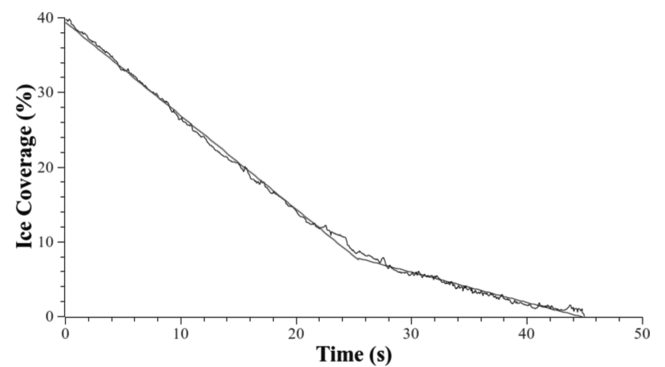


Figure 6. Evaporation for a selected experiment. Shown is the fraction of the image covered by ice over time. A change in slope is visible at 25 s.

either one or two linear approximations for all sublimation curves. We then get constant sublimation rates

$$a = \frac{dA}{dt} = \text{constant}, \quad (1)$$

where a is $-1.25 \pm 0.01 \text{ mm}^2 \text{ s}^{-1}$ initially ($<25 \text{ s}$ in Fig. 6) and $-0.41 \pm 0.01 \text{ mm}^2 \text{ s}^{-1}$ for the later times in the given example. This is a difference of about a factor of 3.

For the breakup rate (number of observed breakups per second), we observe similar splits in two parts as for the evaporation rate which are correlated in time. This is shown in Fig. 7.

To quantify the total number of breakups for a given size, we measure the breakup rate and the total time it takes for the aggregate to sublimate from the initial size. This time is determined by the sublimation rate a and the initial particle size. As initial particle size we considered the 2D radius of gyration of the particle system at the beginning of an experiment defined as

$$r = \sqrt{\frac{\sum_i (r_i - r_s)^2}{N_p}}, \quad (2)$$

with r_i being the coordinates of the i th pixel covered by ice and r_s being the coordinates of the centre of mass, and N_p is the total number of pixels.

Fig. 8 shows the ice surface coverage A over size r . The data follow a power law with power $d = 2.0 \pm 0.2$. This is consistent with a porous but otherwise uniform coverage of ice in 2D independent of size or $d = 2$. Taking $d = 2$ the ice-covered area can be approximated by $A = br^2$, with $b = 2.20 \pm 0.26$.

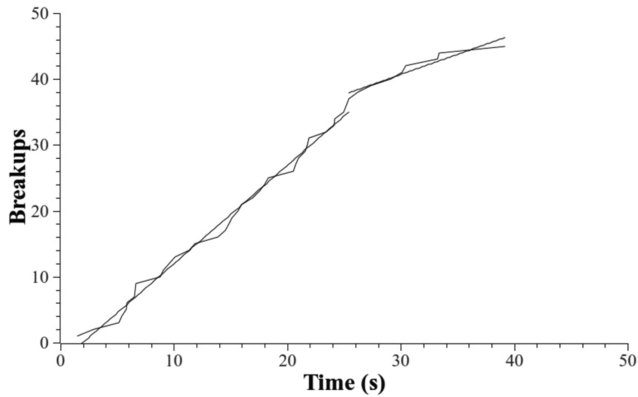


Figure 7. Number of breakups over time. Also here a linear dependence can be observed which is split in time in two parts. The split is correlated to the split in evaporation rate of the same experiment (see Fig. 6).

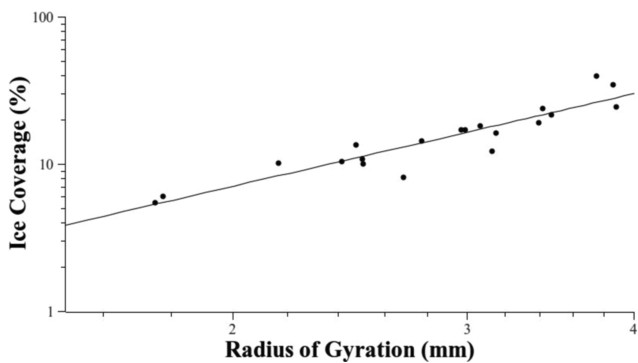


Figure 8. Area covered by ice over the size of an aggregate at the beginning of an experiment. Each data point represents an individual experiment.

In the cases where we have to consider two distinct breakup rates, we relate the second breakup rate to the size at the time the breakup rate changes (Fig. 7). If a change in sublimation rate is not obvious (mostly for the smaller aggregates), only one average breakup rate and one size are considered.

Fig. 9 shows the breakup rate dependence on size. Upper and lower values are correlated to the difference in sublimation rate. The average breakup rate differs by about a factor of 3 which is the same factor as for the correlated difference in evaporation rate.

Fig. 9 suggests that the breakup rate is not dependent on the aggregate size. We would like to caution though that the breakup

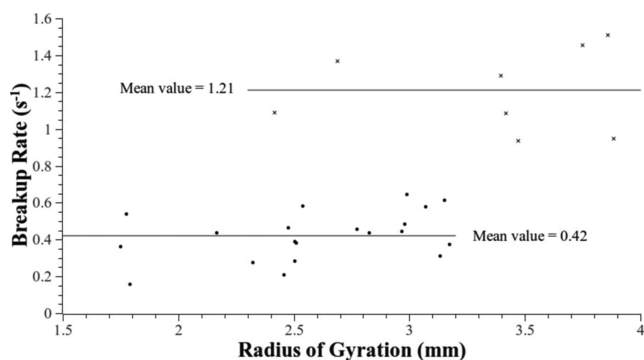


Figure 9. The breakup rate for ice particles with different initial size. Upper and lower values are correlated to the difference in sublimation rate. Each data point corresponds to a different experimental run. Solid lines mark average rates.

constancy is not a universal feature in detail. As described above, aggregates form during the preparation of the ice particles. Individual grains have a size distribution between several up to a few tens of microns, though the latter might already be small aggregates (Fig. 5). This size distribution directly translates to a distribution in contact areas or necks between neighbouring grains. We cannot spatially resolve these contact areas. For aggregates with a distribution of neck sizes, the breakups proceed continuously in time with some statistical variations. Besides this, the neck size distribution determines the breakup rate in detail. It is the inability to quantify this distribution that the breakup rate of *all experiments* is approximated by one average value. We note though that average breakup rates in *individual experiments* with similar initial size might differ by a factor of 3 (see Fig. 9)! More complex breakup rate dependencies on size or even for a given size would certainly be possible within the uncertainties of the data. However, these simplifications allow us to specify a total number of breakups for a given size and scale this to much larger aggregates in protoplanetary discs.

3 DISCUSSION

The experiments give direct evidence that sublimating ice aggregates frequently breakup as has been proposed by Saito & Sirono (2011) and – including sintering – by Sirono (2011). This will generate a number of smaller aggregates which eventually reduce to aggregates of embedded silicate (dust) particles. This is an interesting novel idea on the road to explain the formation of planetesimals. Our laboratory experiments support this, showing that breakup is indeed a viable mechanism to increase the density of smaller particles in the vicinity of the snowline. We consider the ice in our experiments as suitable analogue to cluster–cluster aggregates in protoplanetary discs. It is likely that some initial difference in ice structure and morphology is responsible for the two different sublimation rates observed. For each of the two existing sublimation branches, we assign an average breakup rate, n . The total number of breakups, N , is therefore NT , where T is the total sublimation time. The given average surface sublimation rate (on each of the two branches) $a = dA/dt$ gives a linear total time T with aggregate surface, $T = A/|a|$. In terms of size this translates to a $T = br^2/|a|$. The total number of breakups then is

$$N = \frac{nbr^2}{|a|} = \chi r^2. \quad (3)$$

As n scales with a factor of 3 in the experiments correlated to the same scaling factor for a , the actual sublimation rate is not important and we combine all empirical factors in a single constant parameter $\chi \simeq 2 \text{ mm}^{-2}$ in equation (3). It had to be expected that the total number of breakups does not depend on time or any time-dependent breakup rates or total sublimation rates. So the result that the total number of breakups only depends on the size is consistent with these expectations.

The laboratory situation is effectively a 2D scenario where the 2D projection covered by ice is proportional to the square of the size. Ice aggregates in 3D have the same projected area if they have a fractal dimension of 2. This corresponds to aggregates which grow via cluster–cluster aggregation (CCAs), where aggregates of the same size hit and rigidly stick to each other at the first contact point. This growth process initially occurs in protoplanetary discs (Blum & Wurm 2008). For fractal dimension 2, the projected surface essentially also scales with dimension 2. That means that the

size of protoplanetary ice aggregates correlates well with the size of aggregates in our experiments. Therefore, our results can directly be applied to large aggregates in protoplanetary discs, and equation (3) gives the number of breakups for a CCA cluster of given 3D size r .

Assuming that the largest ice aggregate in the form of a CCA would be about 10 cm in a protoplanetary disc, the aggregate would fragment into $\sim 2 \times 10^4$ pieces, a 1-cm CCA would fragment into ~ 200 pieces, releasing a large number of small dust aggregates, eventually. More compact ice aggregates will certainly fragment as well but the number of total breakups might vary.

The laboratory experiments are closely resembling drifting particles in protoplanetary discs. Certainly, in detail the total number of breakups might differ from the laboratory value. Nevertheless, equation (3) might be a suitable approximation from the experimental side. Clearly, not all dust particles embedded in an ice aggregate will leave as single particles as the shrinking ice aggregate only forms a limited number of smaller ice aggregates. We assume (not the result of this study) that every ice fragment with silicate cores will eventually be reduced to an aggregate of its silicate cores with the same morphology, i.e. a CCA ice aggregate results in a CCA silicate aggregate.

The principle idea behind the proposals by Saito & Sirono (2011) and Sirono (2011) is that the released silicate particles drift slower. Actually, for CCAs the overall aggregate size does not change the gas–grain coupling time (Blum & Wurm 2008). As the gas–grain coupling time determines the drift velocity, such CCAs would always drift with the same speed. This is due to the fact that the gas–grain coupling time is proportional to M/A , where M is the aggregate mass and A is the aggregate cross-section or surface. For CCAs consisting of the same individual grains, M/A is constant. However, the individual grain size of the cores is – per definition – smaller than the size of the individual ice grains. Also, the density of silicates is about twice or three times as high as the density of water ice. This decreases the M/A ratio by a certain factor. Therefore, these final dust aggregates couple better to the gas of the disc, and their radial drift velocity is indeed reduced.

For compact aggregates (not subject to this study), breakup might also occur. If final silicate aggregates are compact, the mass scales with $M \sim r^3$ and M/A depends linearly on the overall size of the aggregates. Any smaller fragment then drifts slower than the original large ice aggregate.

Therefore, while the details depend on the initial ice aggregate morphology and the details of the breakup including silicate cores, the breakup of ice aggregates due to sublimation at the snowline will occur and it almost inevitably leads to a density enhancement of silicates.

4 CONCLUSION

Saito & Sirono (2011) and Sirono (2011) proposed that ice aggregates drifting inwards and sublimating at the snowline leave behind a large number of smaller silicate or dust grains with much smaller radial drift velocity. This leads to a dust density enhancement close to the snowline and subsequently an increased likelihood for planetesimal formation. Planetesimal formation might be due to more frequent sticking collisions and growth or due to gravitational instabilities. The proposal by Saito & Sirono (2011) was based on the mere assumption that ice aggregates breakup upon sublimation and release silicate particles. We verified these ideas of ice aggregate breakup upon sublimation in laboratory experiments. Indeed, we find that ice aggregates breakup in a large number of smaller aggregates. Scaled to protoplanetary discs, a 10-cm CCA aggregate would fragment into $\sim 2 \times 10^4$ pieces. We only observed the fragmentation of pure ice aggregates. We currently assume that all silicate particles that would be embedded in one ice fragment would end up as one aggregated particle after total sublimation, i.e. a 10-cm CCA ice aggregate would result in $\sim 2 \times 10^4$ silicate aggregates. If the presence of silicate cores would influence the sublimation process or what the morphology of the silicate aggregates looks like is subject to future studies. However, the observed breakup into smaller fragments supports the idea that sublimation of ice aggregates close to the snowline might promote the local formation of planetesimals by providing a reservoir of silicate particles that drift slower.

ACKNOWLEDGMENTS

GA is supported by the European Community’s Seventh Framework Programme (FP7/2007-2013 under grant agreement No. 238258). We appreciate the valuable comments from the reviewer.

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