Nanometer Contact Physics of Water Ice in Protoplanetary Disks, Breakup, Twisting and Rolling

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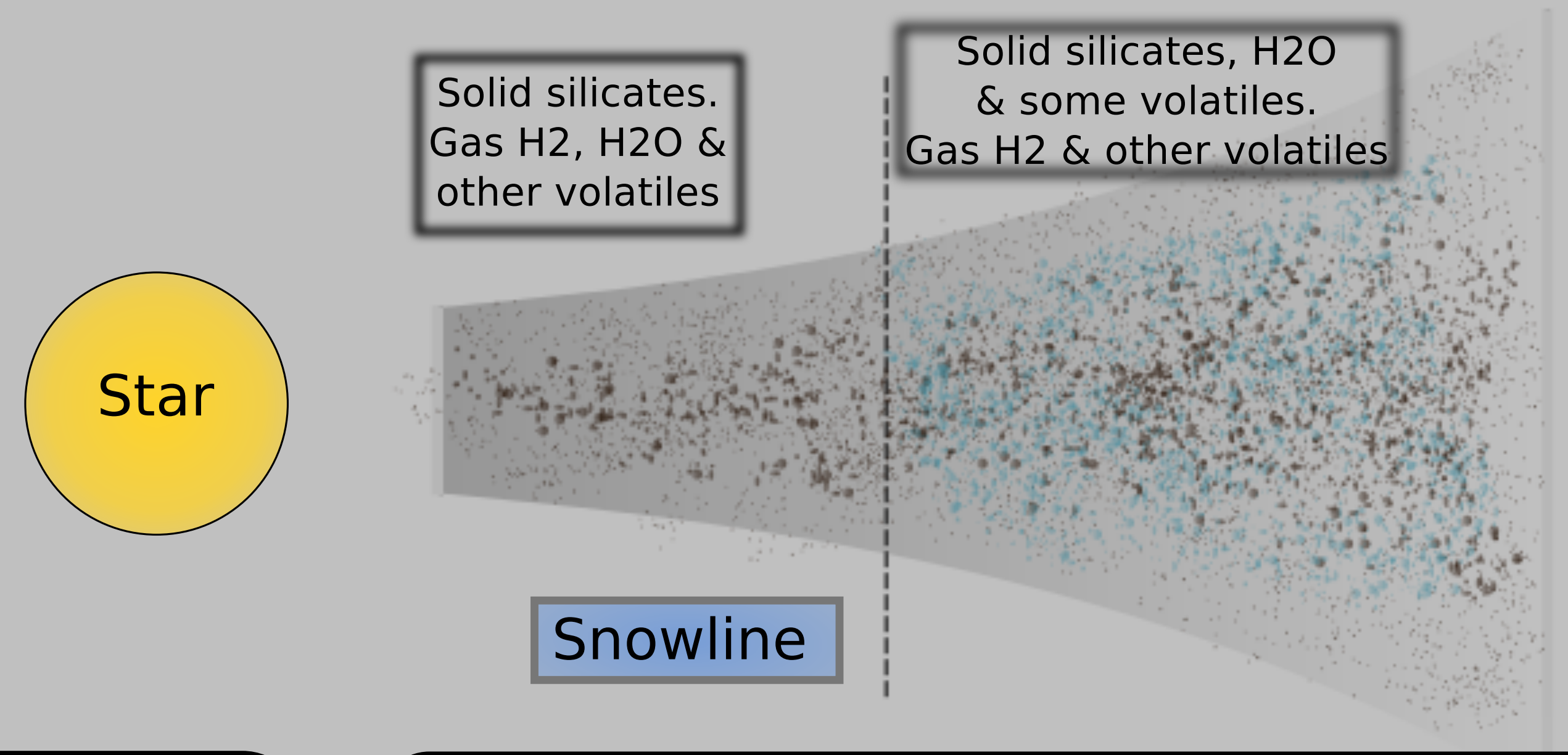
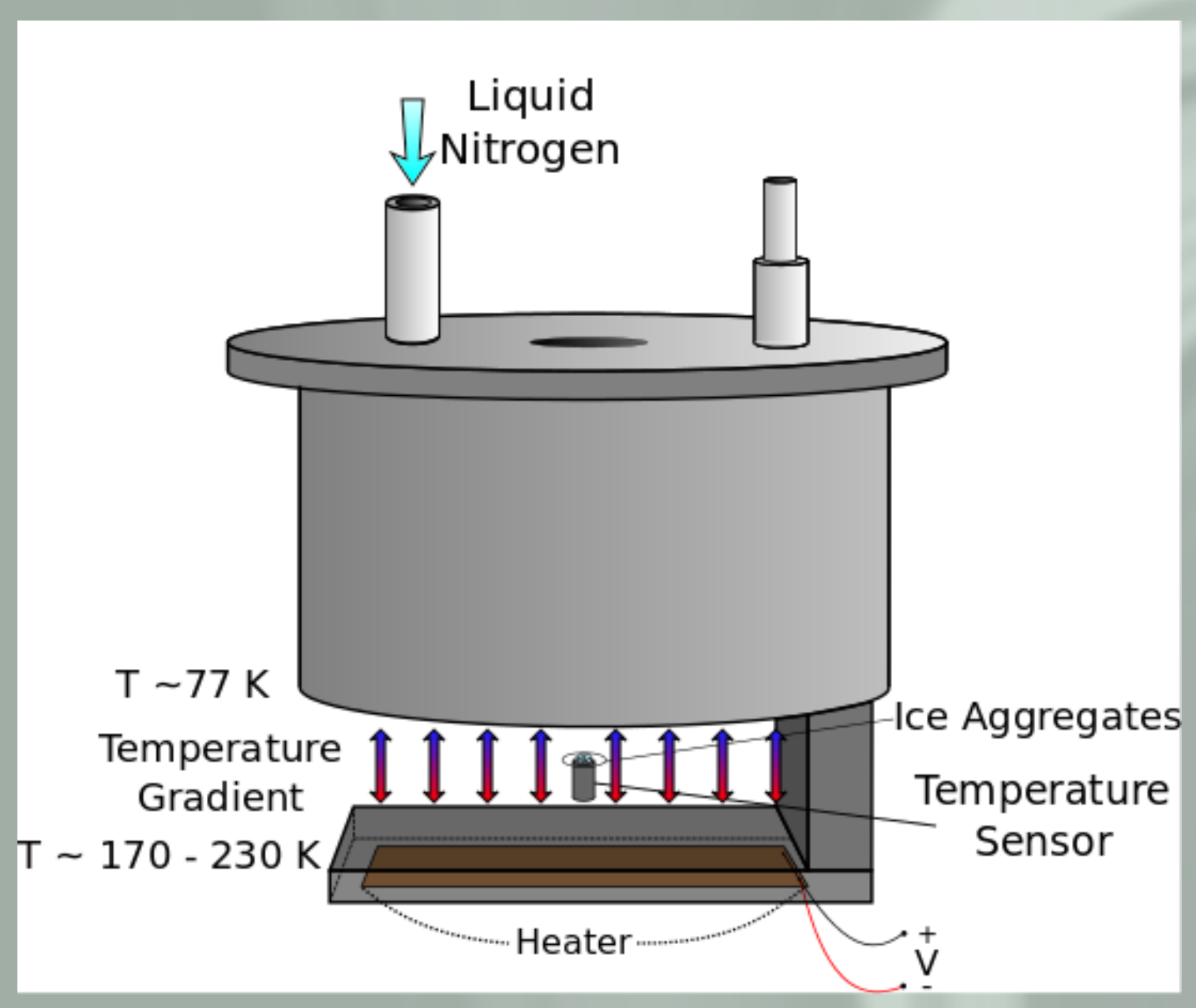
Introduction

The formation of planetary bodies is not yet fully understood. Beyond the snow line in protplanetary disks, volatile components like water condense to solid state. The interaction between these solid particles can cause the formation of larger objects due to aggregation at low velocities, or sometimes -depending on the conditions- their own destruction [1,2] .
Water ice has been detected in protoplanetary disks [3,4] and in order to understand its role in the formation of icy bodies like icy planets, asteroids and comets, we carried out laboratory experiments. Water ice aggregates have been formed from frozen liquid water droplets at ~ 190 K. Droplets are smaller than 20 µm in radius and show a well defined size distribution. At pressure between 0.1 - 1 mbar and temperatures about 200 K, several effects like sublimation, twisting, rolling and breakup have been observed and measured. By the quantification of parameters like mass, acceleration after breakup and aggregate size and structure, the adhesion force that exist in the contact area between the aggregates' monomers, and other parameters, can be determined.



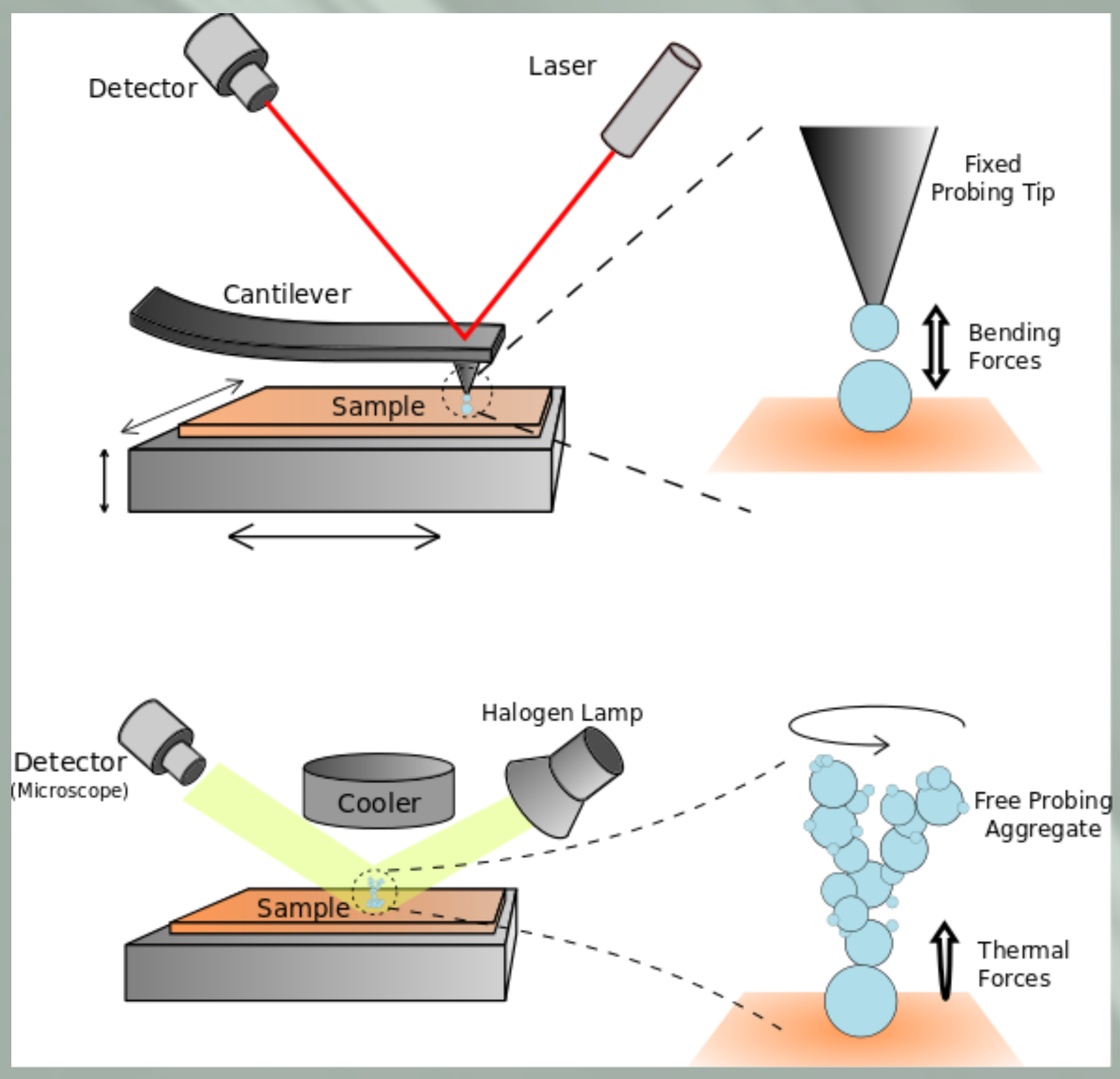
Experimental Setup

A Thermal Gradient Force Microscope



Water ice agregates are formed by hit and stick processes and aggregation in a cooled vacuum chamber. The top part of the chamber is covered by a liquid nitrogen container and a heater is situaded at 4 cm below to create a temperature gradien. A temperature sensor, used as target, is situated between the lower part of the container and the heater. The aggregates formed on the sensor are observed with a high speed camera for later study.

At a local temperature of ~203 K and chamber pressure of ~0.5 mbar, thermophoretic forces, produced by the thermal gradient, are strong enough to move the ice aggregates. Phenomena like rolling, twisting and breakup between aggregates are observed and used to calculate the contact radius between them, i.e. acting as a thermal gradient force microscope. This is possible measuring the displacment after breakup and their rotation in function of time in order to estimate some parameters like the crtical force and rolling and twisting torque.



Observed Interactions:

Breakup, Twisting and Rolling

Using the heating foil we create a temperature gradient between the liquid nitrogen depot (77 K) and the temperature sensor (200 K). With a pressure of ~0.5 mbar, thermoforetic forces are strong enough to move the aggregates and break their contact areas. Sequences of Breakup, Twisting and Rolling are shown in Fig. 5 (a), (b) and (c) respectively.

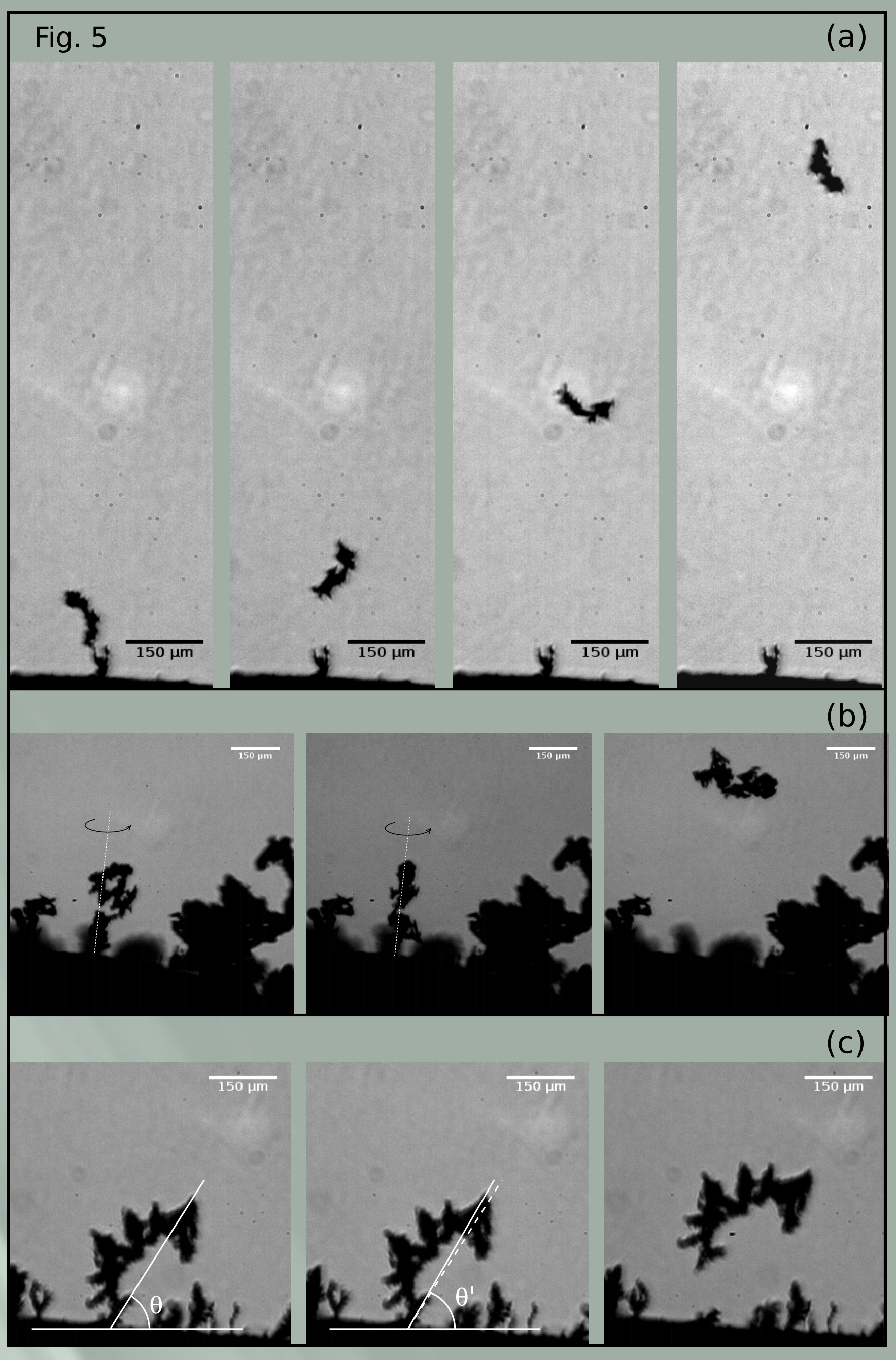
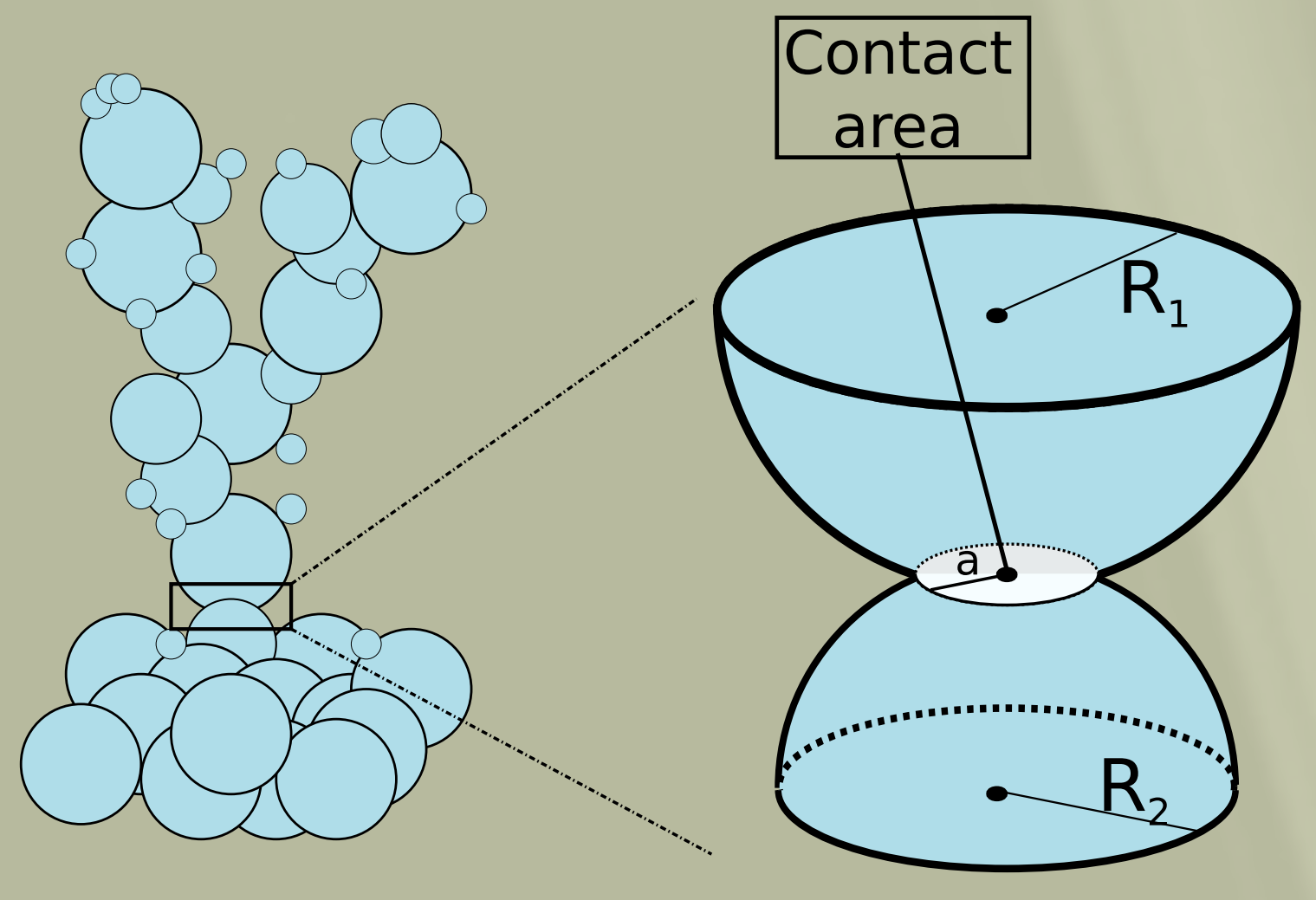


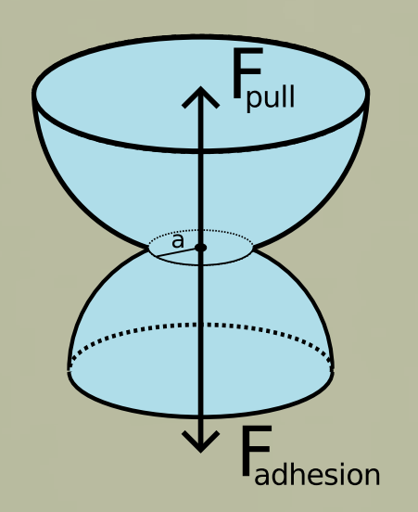
Fig. 5

Model's description

In this figure a sketch of an ice aggregate and its contact area with the rest of an ice sample is shown. R_1 and R_2 are the radius of the monomers that are in contact forming a contact area with radius a.



Breakup



In order to breakup the contact, an applied pulling force F_C must be greater than [2]:

$$F_c = 3\pi\gamma R$$

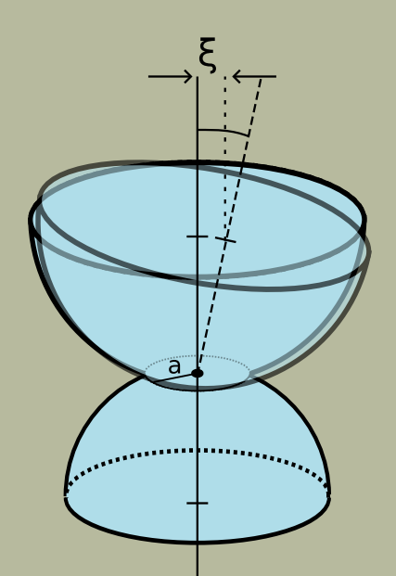
where R is the reduced radius of the two grains in contact and γ is the surface energy. If the force is not enough to break up the contact, the radius of the area will be modified as:

$$a = \left(\frac{3R}{4E^\star}\left(F + 6\pi\gamma R + \sqrt{(6\pi\gamma R)^2 + 12\pi\gamma RF}\right)\right)^{1/3}$$

Here, E^* is the Young modulus of the material. If no force is acting on the contact area, then its radius a will be:

$$a_0 = \left(\frac{9\pi\gamma R^2}{E^\star}\right)^{1/3}$$

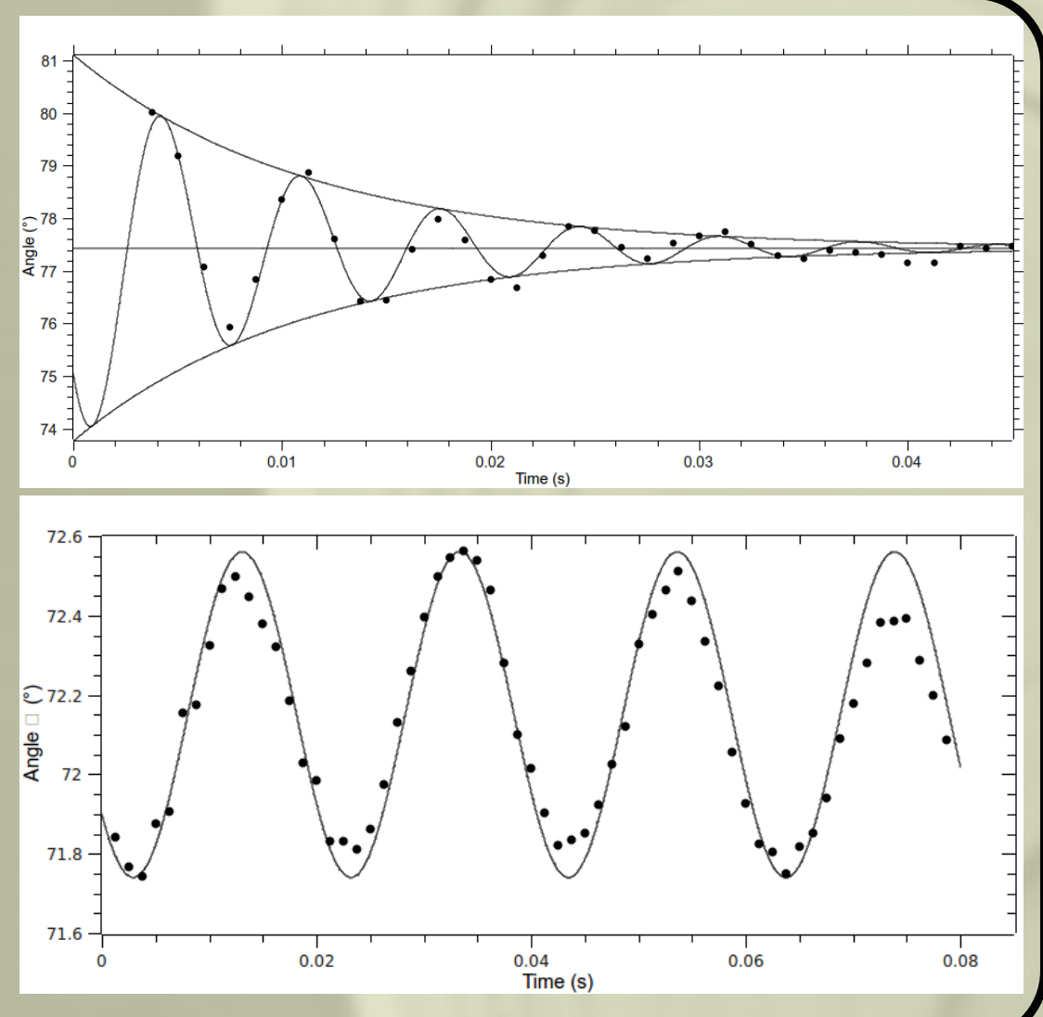
Rolling



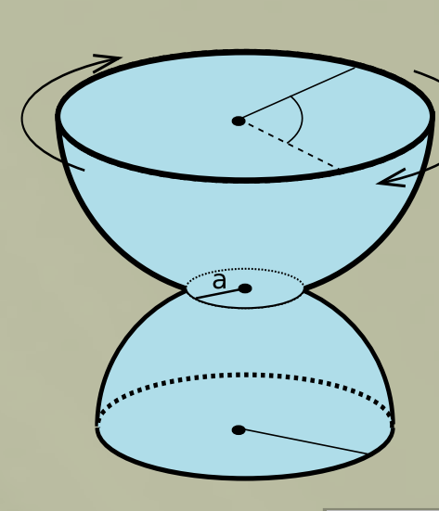
The oscillation of aggregates in the perpendicular direction of the pulling force has been often seen. The torque produced by rolling in the aggregates can be estimated theoretically and experimentally as:

$$M_r = 4F_c\left(\frac{a}{a_0}\right)^{3/2}\xi_c \qquad M = I \times \alpha$$

respectively. I is the aggregate moment of inertia and α the angular acceleration. In some cases, the amplitude does not remain constant in time presenting a damped oscillation, but their amplitude is too large to be caused just by elastic torque at the contact, assuming that gas drag plays the main role on oscillation and damping. The oscillation frequencies for all the aggregates goes from ~25 to ~150 Hz, in agreement with gas-grain coupling regime at considered pressure, temperature and aggregates' grain size.



Twisting



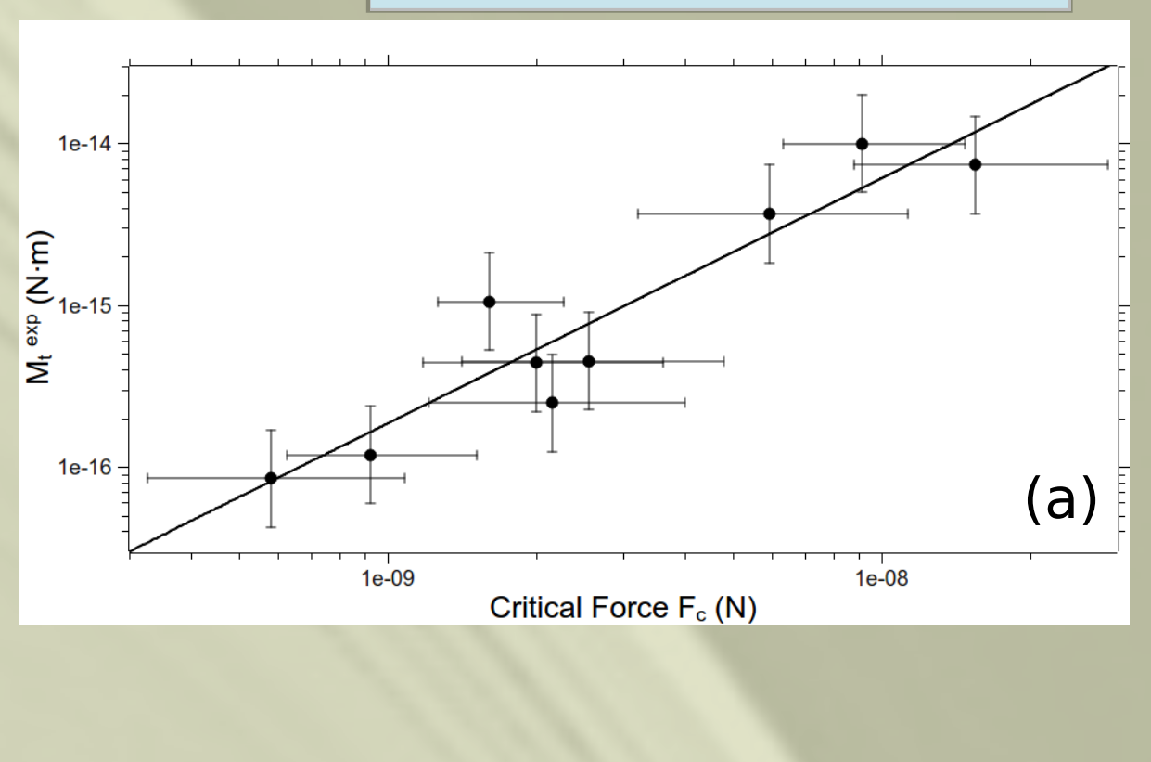
Rotation of aggregates around the perpendicular axis to the contact area plane have been observed several times. In these cases, a torque M_t between the two contacting monomers may be estimated from

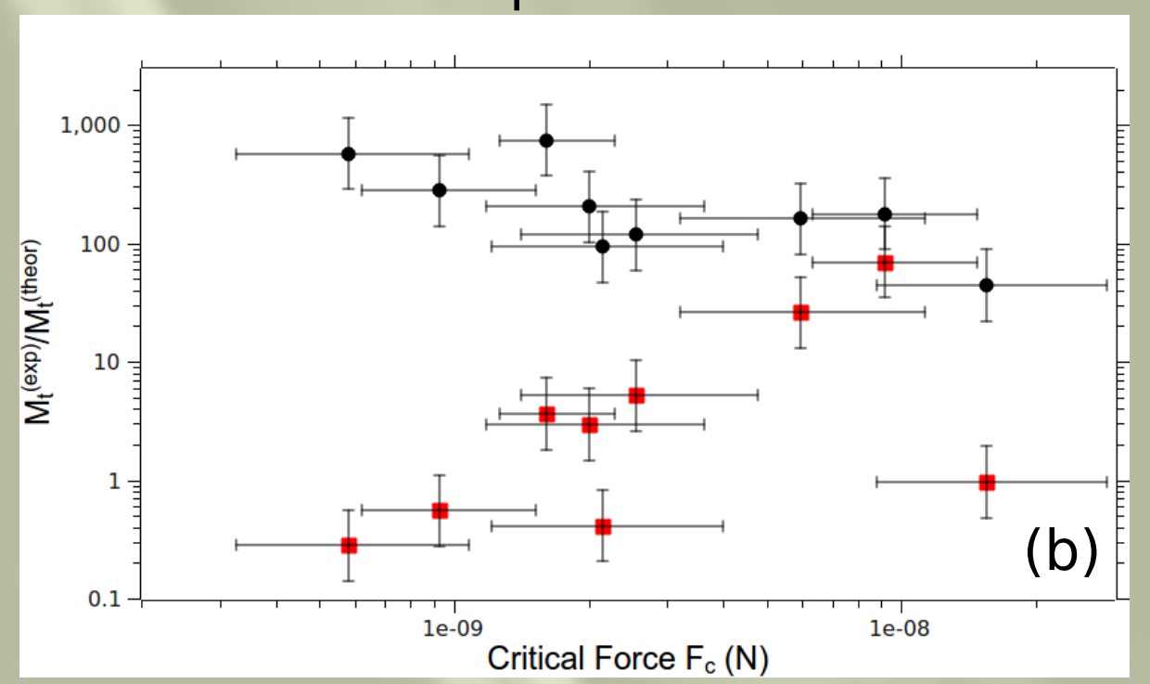
$$M_t = \frac{Ga^3}{3\pi} + \frac{\pi}{3}F_c a_0\left(\frac{3}{4}\left(\frac{a}{a_0}\right)^4 - \left(\frac{a}{a_0}\right)^{5/2}\right) - \frac{2}{9}\pi a^3 p_c$$

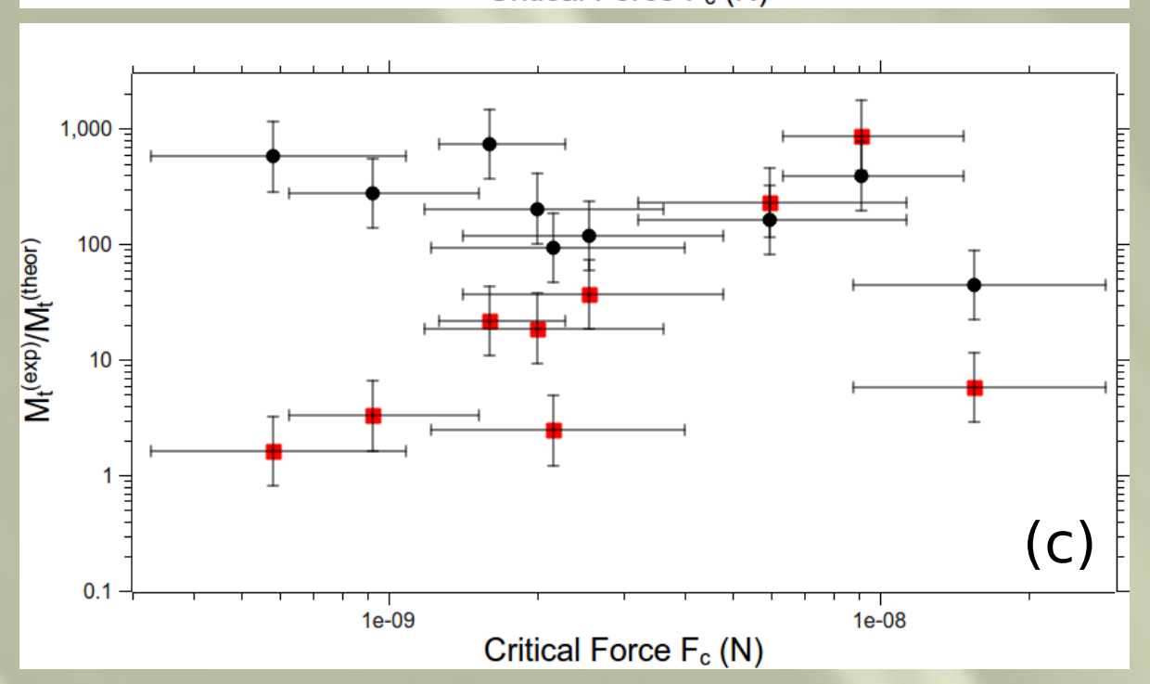
where

$$p_c = \frac{2.67b^3}{\pi\sigma^3}G - \frac{24.72b^4}{\pi\sigma^5}\gamma$$

G is the shear modulus of the material, b and σ are material parameters.







In plot (a) the dependence of the experimental twisting torque M_t measures with the critical force for different aggregates is shown. M_t grows for higher critical forces and, therefore, for larger contact areas a as it would be expected.

In plot (b) the ratios between experimental M_t over their theoretical counterparts for γ=0.37 J/m^2 are shown. The black dots correspond to measured values with no sublimation rate correction. Red squares are values with this correction applied. In plot (c) can be seen the results for the same aggregates but for γ=0.10 J/m2. The presence for ratios up to 1000 in some cases may be due to quantum effects that are no considered by the current theory.

Discussion and conclusions

**Experiments with water ice aggregates show some specific effects like twisting, rolling, breakup and sliding between their grains. These phenomena occur when the aggregates are embedded in a ~ 0.5 mbar and ~ 200 K atmosphere and can be applied to the first steps of icy bodies formation in protoplanetary disks.

**The measurement of some parameters like rotation frequency, acceleration after breakup and 3D structure of the aggregates applied on theoretical contact physics equations [2], were used to measure the contact area acting as a thermal gradient force microscope.

**Comparing the expected theoretical calculations and the direct experimental observations, a difference of factor up to 1000 is observed for M_t. Since experimental measurements yields to nanoscale contact area ranges, the physics of these phenomena cannot be ruled by classical mechanics anymore and quantum effects should be considered.

**Unfortunately, a theory of contact physics at that sacale is still not yet developed and is not possible to find a reliable model to explain satisfactorily the results presented here.

Acknowledgments

This project is supported by the University of Duisburg-Essen, the University of Münster and by LASSIE thanks to the European Commission's Seventh Framework Programme (FP7/2007-2013 under grant agreement No. 238258).

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