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PHOTOPHORESIS ON WATER-ICE PARTICLES INDUCED BY THERMAL RADIATION IN PROTOPLANETARY DISCS

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Abstract. It is widely believed that planets form in accretion discs by the growth of small dust and ice grains. To verify the scenarios of protoplanetary disc processes including the transport of material in vertical as well as in radial direction, it is crucial to understand the interaction of small dust and ice particles with their surroundings, *i.e.*, with the gas, star light, and other ice and dust particles. In first laboratory experiments, we observe trapped irregular-shaped water-ice particles which levitate up to half an hour in a vacuum chamber at a pressure of about 2 mbar due to photophoresis and thermophoresis. While they are firmly levitating, they rotate preferentially about their vertical axis. The physics leading to the levitation is explained and the results of an analysis of the particle rotation are presented.

1 Introduction

To understand the interplay between small dust and ice particles with their surroundings, it would be favourable if free particles were observed and available for manipulation in laboratory experiments. A technique to trap particles was recently developed by Kelling *et al.* (2011). They show that micron-sized irregular-shaped water-ice particles levitate under the Earth's gravity due to photophoresis and thermophoresis. Both phoretic forces are induced by a temperature gradient. In the first case, the temperature gradient exists across the particle, while the gaseous environment is at a constant temperature and, in the latter case, the temperature gradient exists in the gaseous environment. At the height where the particles are levitating, the phoretic forces and the opposing forces of gravity and gas drag cancel each other out and the particles are trapped in stable positions.

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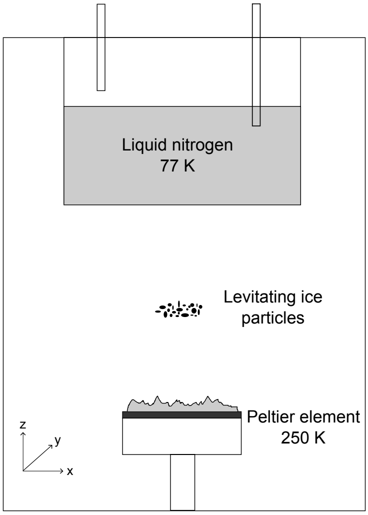

Fig. 1. Experimental setup (van Eymeren & Wurm 2012).

2 Experimental setup

Ice particles are dropped onto a Peltier element cooled down to 250 K which is situated in a vacuum chamber at room temperature (Fig. 1). A reservoir of liquid nitrogen at 77 K is placed above the Peltier element at a height of 28 mm. The chamber is evacuated to roughly 2 mbar. As soon as the pressure decreases to below 10 mbar, single ice particles begin to rise from the surface of the snow layer due to a combined effect of thermophoresis and photophoresis. While the thermophoretic force directly depends on the temperature gradient between the Peltier element and the reservoir of liquid nitrogen, the photophoretic force is induced by the thermal radiation of the Peltier element and – once rising – of the surrounding warm chamber. Depending on the properties of the particles and the gas pressure, the particles either fall back, continuously rise or are trapped halfway up. We here concentrate on the levitating particles. Typically, the formation of groups of up to a few dozens of particles is observed. While they are firmly trapped at a fixed height, they still rotate.

To resolve the rotation, we obtained video sequences at 502 frames per second of the levitating ice particles (an example is shown in Fig. 2). Our sample contains about 100 ice particles of different sizes and shapes. Within the resolution limit, this includes almost spherical particles as well as cylindrical particles, but mostly very irregular-shaped particles. The particles vary in size between 20 μm up to a few hundred μm.

3 Results

The analysis of the ice particle rotation reveals that about 95% of all the particles spin about their vertical axis. We do not find particles rotating about their

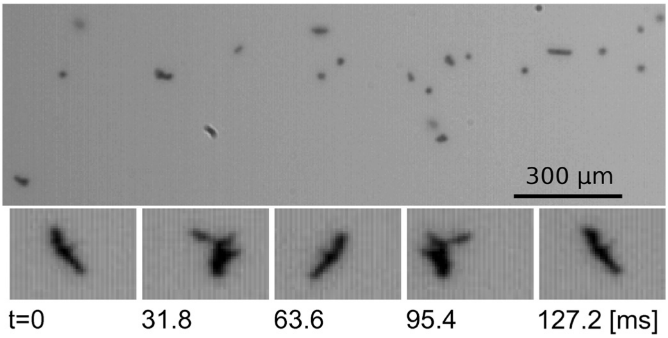

Fig. 2. *Top*: levitating ice particles as observed in the experiment; *bottom*: the rotation of a single ice aggregate, the image section is 230 μm × 160 μm (van Eymeren & Wurm 2012).

horizontal axis. The remaining 5% of the particles show either no resolvable rotation (they appear to be frozen between the Peltier element and the reservoir of liquid nitrogen) or they have an additional velocity component along the z-axis (they are moving up or down and generally show more complex trajectories). The particles rotating about their vertical axis can be divided into two classes: about half of the rotating particles show bound rotation, the other half does not have an additional horizontal movement, which might be a resolution effect if the particle is small.

We measure the rotation frequency of the levitating ice particles. As a measure of the particle size, we choose the horizontal, maximum extent of the ice particles. The frequency plotted over the particle size is shown in Figure 3. Small symbols represent all particles which show resolvable bound rotation. Large symbols represent all particles where a horizontal orbit cannot be resolved. There is no clear trend visible. However, there seems to be an offset in frequency of particles with and without noticeable bound rotation. While particles without bound rotation cover a range of frequencies from roughly 10 Hz to 100 Hz, particles with bound rotation need more time for one full turn and spin with a few up to 50 Hz. As photophoresis relies on a temperature gradient across the particle, we now compare the time a particle needs for a full rotation with the time that is needed for conductive heat transfer in the particle. According to Wurm & Krauss (2005), the time-scale is given by

$$\tau_{\text{heat}} = \frac{\rho c a^2}{k_{\text{th}}} \tag{3.1}$$

where ρ is the ice density, c is the heat capacity of the ice particles, and k_{th} the thermal conductivity. For a typical particle radius a of 10 μm with a density of 1000 kg m^{-3}, and a thermal conductivity of about 1 W/m/K, this characteristic time is 10^{-4} s or 10 000 Hz. This is sufficiently short to maintain a temperature gradient across the rotating ice particle.

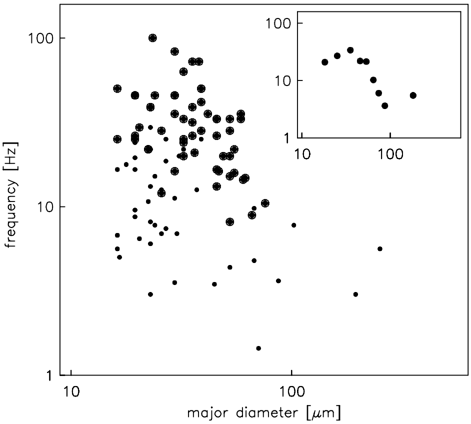

Fig. 3. The frequency of rotation of the ice particles is plotted *vs.* their maximum horizontal extent, here called major diameter (both on logarithmic scales). Small symbols: bound rotation; large symbols: no additional (resolvable) horizontal movement. Small panel: mean values of the frequency of rotation calculated for different ranges of the major diameter, *i.e.*, $10-20\,\mu$m, $20-30\,\mu$m, ..., $100-260\,\mu$m (van Eymeren & Wurm 2012).

4 Conclusion

Our experimental results can be applied to protoplanetary discs by using equations for photophoresis, substituting particle parameters by the experimental values, and scaling the gas parameters like pressure, temperature, and gravity to disc properties (Loesche & Wurm 2012). This is a numerical task of its own. However, the capability of levitating particles against the Earth's gravity suggests that particles can stay aloft at the surface of a disc even in the cooler outer parts due to photophoresis induced by thermal radiation of the disc. Due to the vertical alignment of the rotation axis, rotation is not decreasing the vertical strength of photophoresis. This supports the concept of photophoretic transport of levitating particles over the surface of protoplanetary discs (Wurm & Haack 2009).

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