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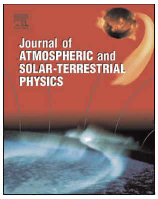

Study on morphology and growth of water–ice grains spontaneously generated in a laboratory plasma

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ABSTRACT

An apparatus has been developed to study the nucleation, growth, and morphology of water–ice grains spontaneously generated in a weakly ionized plasma having very cold neutral particles. Nucleation of water–ice grains in the laboratory experiment occurs only when plasma exists but the plasma density is not too high. Nonspherical, fast growth occurs when the mean free path of water molecules exceeds the screening length for the ice grain in which case molecules incident on the ice grain can be considered to have collisionless trajectories. High water vapor pressure enhances this nonspherical, fast growth provided the collisionless condition is satisfied. Magnetic field impedes nonspherical growth by reducing the charge residing on water–ice grains if the field is sufficiently strong to make the electron gyro radius smaller than the ice grain screening length.

1. Introduction

Water–ice dusty plasmas are composed of electrons, ions, neutrals, and water–ice grains. These plasmas exist in many natural contexts, most notable examples being terrestrial polar mesospheric clouds, certain of Saturn's rings, and astrophysical molecular clouds. The water–ice grains constituting terrestrial polar mesospheric clouds have 10–100 nm nominal size (Havnes et al., 1996) and exist during the summer at ~85 km altitude and polar latitudes in the mesopause. Because of the high altitude of these clouds, they are visible at night and so are also called noctilucent clouds. The water–ice grains are negatively charged with a few elementary charges. Occasionally positively charged grains are observed and it is presumed that this positive charging occurs by the photoelectric effect (Havnes et al., 1996). Strong reflection of 50 MHz–1.3 GHz radar has long been observed from these clouds (Ecklund and Balsley, 1981) and Bragg reflection by electrons is thought to be responsible for the radar echo (Rapp and Lubken, 2004). However, sounding rocket measurements sometimes show radar echoes occur from bite-out regions where most of the electrons reside on the water dust grains so there are no free electrons in the plasma (Havnes et al., 2001; Rapp et al., 2003). The reason for this remains controversial; Bellan (2010) suggested that elongated morphology of water–ice grains might explain this bite-out mystery.

Saturn's E-, F-, and G-rings are also water–ice dusty plasmas and are composed of micron size water–ice grains (Goertz, 1989). Since the number density of water–ice grains is quite high in the F-ring, a large fraction of the negative charge resides on the dust grains and collective behaviors of the ice grains such as waves are observed (Goertz, 1989; Murray et al., 2008). On the other hand, the number densities of water–ice grains in E- and G-rings are so small that most electrons are free in the plasmas and the dust grains do not have strong mutual interactions. Saturn's E-ring and Enceladus have attracted much recent attention because Cassini spacecraft images reveal that Enceladus emits water vapor and water–ice grains into the E-ring (Porco et al., 2006).

In astrophysical molecular clouds, water–ice grains play several important roles including forming planetesimals, cooling the cloud, and storing oxygen molecules. These astrophysical water–ice grains have been observed indirectly via infrared spectroscopy, and their density structure has been used to estimate the evolution stage of molecular clouds (McClure et al., 2012).

Probably for reasons of mathematical convenience, it has generally been assumed that water–ice grains are spherical in all the contexts mentioned above. However there is no strong evidence that this is so. We believe that non-spherical geometry is more likely in many situations because water molecules have a

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large dipole moment and because water–ice grains in a plasma environment become electrically charged. Furthermore, it has been reported that if water–ice grains were non-spherical, certain observed features might be better explained (Baumgarten and Fricke, 2002; Rapp et al., 2007; Bellan, 2010). In order to investigate the possibility of non-spherical ice grains, we built a laboratory apparatus and used this apparatus to investigate the morphology of water–ice grains in a plasma. Initial results show that water–ice grains are spontaneously generated in a plasma environment and grow nonspherically if the neutral pressure of the background weakly ionized plasma is low (Chai and Bellan, 2013). We report in this paper measurements made to provide an improved understanding of the underlying physics of nonspherical growth. Besides morphology, we also investigated the nucleation and the growth rate of water–ice grains.

2. Experimental setup

Fig. 1 shows a photo of the water–ice dusty plasma; a detailed description is given elsewhere (Chai and Bellan, 2013). The apparatus incorporates design features of a previously existing experiment at the Max-Planck-Institute for Extraterrestrial Physics (Shimizu et al., 2010) but differs in two important aspects: the inter-electrode separation is adjustable and water vapor is directly injected into an argon plasma instead of forming water molecules in a plasma created from a fill of D_2 and O_2. Adjustable electrodes provide a wider range of pressures for plasma breakdown and direct injection of water vapor into a pre-existing argon plasma provides independent means for controlling and measuring the water vapor pressure. The plasma is created in the space between two 6 cm diameter aluminum electrodes in the vacuum chamber. The electrodes are thermally connected via cold fingers to containers holding liquid nitrogen.

In normal operation, the electrodes are cooled by first pouring liquid nitrogen into the containers. We then wait 45 min to obtain suitably low equilibrium temperature in the chamber. The vacuum chamber is then filled with 100–600 mTorr Ar gas (13–80 Pa) and a plasma is ignited with 0.5–2 W of 13.56 MHz rf power applied across the electrodes. Immediately after 0.5–2 mTorr (0.07–0.27 Pa) water vapor has been introduced into the plasma, water–ice grains form spontaneously and levitate between the electrodes. Sufficient cooling time and plasma are necessary for formation of the water–ice grains—if there is not enough cooling time or no plasma, water–ice forms only on the surface of the electrodes.

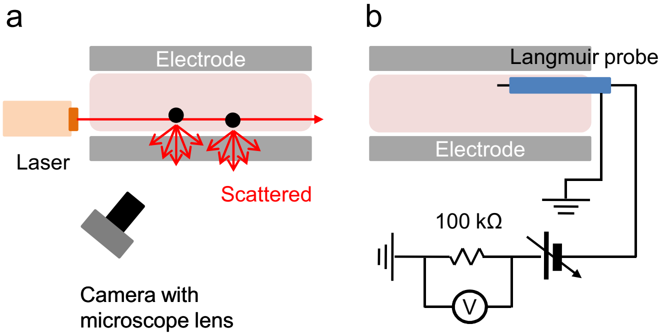

Fig. 2. Schematic sketches of (a) laser-aided long distance microscope camera and (b) Langmuir probe.

The water–ice grain size and shape are measured using the method shown in Fig. 2(a). In this method, relatively large water–ice grains levitating near the bottom electrode are illuminated by a 5 mW, 632.8 nm He–Ne laser with 0.5 mm beam diameter (focused by a lens). Magnified images of ice grains are then obtained by a long distance microscope lens (Questar QM-100) mounted on a digital SLR camera (Nikon D5300); the lens and camera view at a right angle to the laser beam. The distance between the water–ice grains and the entrance of the long distance microscope is about 20 cm. The magnification of this microscope-camera system is 16 and the depth of field is 30 μm. This imaging system shows the water–ice grain size and shape directly provided the water–ice grain dimension exceeds the resolution threshold of a few microns. This imaging system also enables measuring the water–ice grain number density by simply counting how many water–ice grains exist in the laser beam path.

A Langmuir probe is used to measure ion density as shown in Fig. 2(b). The Langmuir probe is biased with a large negative voltage (−30 V) and the ion saturation current flowing through a 100 kΩ resistor is measured. Ion density is calculated from the measured ion saturation current, using the relation $n_i = I_{is}/(\alpha e A_p u_s)$

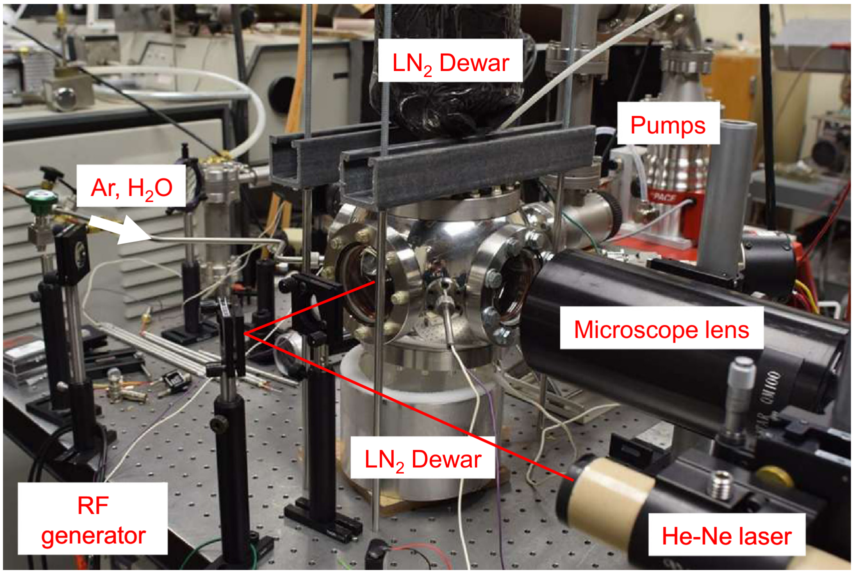

Fig. 1. Photo of Caltech water–ice dusty plasma apparatus. Two parallel, cold fingered electrodes are used to ignite and cool down the plasma. Ar gas is used for making background plasma and water vapor is used to form water–ice grains. Laser-aided long distance microscope camera and single Langmuir probe are shown at the bottom right.