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Citation: AIP Conference Proceedings **1925**, 020005 (2018);
View online: https://doi.org/10.1063/1.5020393
View Table of Contents: http://aip.scitation.org/toc/apc/1925/1
Published by the American Institute of Physics

Particle Velocity Distribution in a Three-Dimensional Dusty Plasma under Microgravity Conditions

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Abstract. The velocity distribution function of dust particles immersed in a plasma was investigated under microgravity conditions. A three-dimensional (3D) cloud of polymer microspheres was suspended in a neon plasma, in the PK-4 instrument onboard the International Space Station (ISS). These dust particles were tracked using video microscopy in a cross section of the 3D dust cloud. The velocity distribution function (VDF) is found to have a non-Maxwellian shape with high-energy tails; it is fit well by a combination of low-energy Maxwellian core and a high-energy non-Gaussian Kappa-distribution halo. Similar non-Maxwellian VDFs are typically observed in space plasmas.

INTRODUCTION

A dusty plasma consists of electrons, ions, electrically-charged micron-size dust particles, and neutral gas atoms. Experiments with dusty plasmas are generally dissipative nonequilibrium systems driven by an external source, which results in electric fields and ion flows that can introduce energy into the collection of dust particles. In a two-dimensional dusty plasma levitated in a plasma sheath, a non-Gaussian high-energy tail was observed in the probability distribution function of particle displacement, and this feature was linked to superdiffusion of particles [1,2].

For the velocity distribution function, non-Gaussian distribution features, especially with energetic tails, are found in a wide range of plasmas, including low-collisionality plasmas such as the solar wind [3,4]. It is commonly found that the velocity distribution in the solar wind has high-energy tails, and it is often fit to the Kappa distribution [5,6].

$$f_\kappa(v) \propto \frac{1}{\left(1 + v^2 / \kappa v_0^2\right)^{\kappa+1}}, \tag{1}$$

where $v_0 = [(2\kappa - 3)k_B T_p / \kappa m_p]^{1/2}$ is a characteristic speed, and T_p is the temperature of the particle with mass m_p. The parameter κ characterizes how far the system is from thermal equilibrium. When $\kappa \to \infty$, the Kappa distribution approaches a Maxwellian, but when κ is finite, it has high-energy tails, with more high velocity particles than for a Maxwellian. We note that the mathematical expression for a Kappa distribution can be rewritten in another form, called a Tsallis distribution, which is widely used in a statistical framework called non-extensive statistical mechanics [7,8].

Here we study the statistics in a three-dimensional (3D) dusty plasma under microgravity. Using microgravity conditions allows suspending the dust particles in a region where the electric field is weaker and therefore the

Diverse World of Dusty Plasmas
AIP Conf. Proc. 1925, 020005-1–020005-4; https://doi.org/10.1063/1.5020393
Published by AIP Publishing. 978-0-7354-1617-8/$30.00

nonequilibrium conditions can be less extreme. Laboratory experiments under 1-g conditions, in comparison, require a strong vertical electric field to levitate the dust particles, and this results in strong ion flows that can impart significant kinetic energy to a dust cloud. By using microgravity conditions, we are able to observe dust particle motion in the central plasma region instead of in the sheath, so that the dust particles are exposed to a weaker ion flow.

EXPERIMENT

The experiment was performed using the Joint ESA-Roscosmos facility called "Experiment Plasmakristall-4" (PK-4) onboard the International Space Station (ISS) [9]. Figure 1 is a sketch of the main features used in this experiment. A U-shaped glass tube was evacuated and filled with neon gas at a low pressure of 100 Pa. A plasma was initiated by applying a DC high voltage between the active and passive electrodes. The RF coil was then powered at 81.36 MHz with 0.4 W power. This RF coil sustained the plasma while the DC voltage to the electrodes was turned off. Dust particles, which were melamine-formaldehyde microspheres of diameter 3.38 μm, were introduced by agitating a shake dispenser. These dust particles were electrically trapped by the RF plasma. Under these conditions, we observed an absence of self-excited dust-acoustic waves.

A thin sheet of laser light illuminated a cross section within the dust cloud, which was imaged at 90° by the particle-observation video cameras. The images had a resolution of 13.9 μm per pixel and a field-of-view of $22.1 \times 16.6\ mm^2$. The cameras recorded particle images at a frame rate of 35 Hz. An example image is shown in Fig. 2(a).

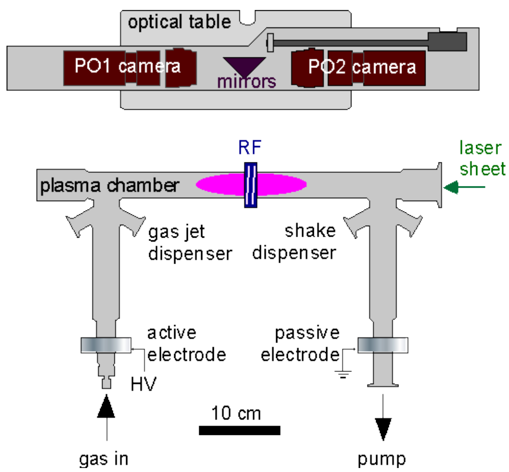

FIGURE 1. Sketch of the Joint ESA-Roscosmos "Experiment Plasmakristall-4" (PK-4) onboard the ISS. For the experiment reported here, the RF coil was powered, trapping a dust cloud near the center of the glass tube plasma chamber, where a cross section was imaged by a particle observation (PO) camera in combination with an illuminating laser sheet.

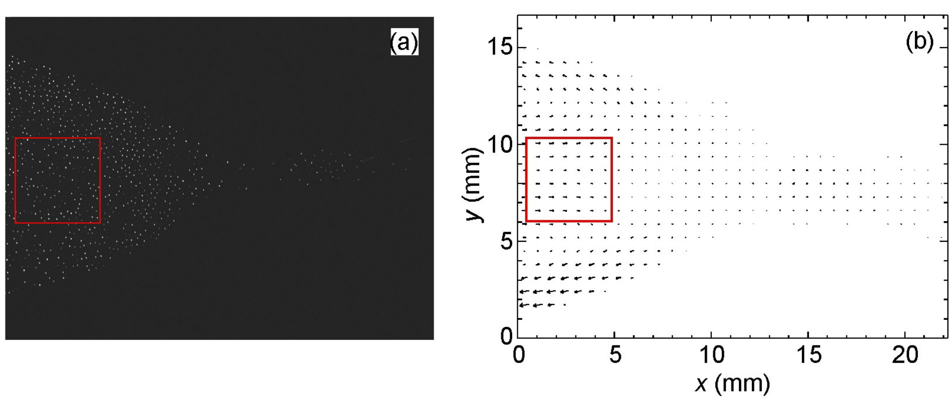

FIGURE 2. (a) Image of a cross section of particles in a 3D dust cloud. We tracked individual particles everywhere in the image, yielding the velocity vectors of particles. Averaging these particle velocities within a grid cell yields the flow pattern (b). We selected the region identified by the box for further analysis because of its low flow velocity, as compared to the edge of the dust cloud.

We analyzed the image data, yielding measurements of particle position and velocity, which we repeated for 1000 consecutive video frames. We measured particle positions using the moment method of Ref. [10], yielding two dimensional (2D) positions (*x, y*) with sub-pixel accuracy. To obtain particle velocities, we subtracted the positions of particles in two consecutive frames. We used the particle velocities for two purposes: we prepared a velocity distribution function (VDF) as the histogram of the velocities of individual particles, and we also prepared a map of the flow pattern. The flow pattern, which was obtained by averaging all the particle velocities within a square grid at intervals of about 1 mm, is shown in Fig. 2(b). We subtracted this local flow velocity from the particle velocities, when we prepared the histograms for the VDF.

To minimize the effects of flows and boundaries, we chose to analyze a region near the center of the cloud. The selected region is marked by a box in Fig. 2.

RESULTS

We verified that the microscopic positions of dust particles had a typical liquid structure, as indicated by the pair correlation function *g*(r). The three-dimensional *g*(r), shown in Fig. 3, was obtained from the 2D particle positions using the method of Ref. [11]. Using the first peak of *g*(r) with the method of Ref. [11], we find that the 3D number density of our dust cloud was $8.8 \cdot 10^4$ cm^{-3}.

Our result for the velocity distribution function (VDF) is shown in Fig. 4. This velocity distribution was prepared as a histogram of the dust particle velocities in the *y* direction. We find that the VDF in Fig. 4 is non-Maxwellian, with superthermal tails, i.e., high-energy tails.

Neither a pure Maxwellian nor a pure Kappa distribution captures all features in the entire experimental distribution. A pure Maxwellian distribution fits well the low-energy core of the experimental distribution, but it fits the data poorly at high velocities. The high-energy tails are reproduced by a Kappa distribution, although the Kappa distribution overestimates the number of low-velocity dust particles. These two fits are shown as dotted and dashed lines in Fig. 4.

The best fit to the experimental VDF is a combination of a Maxwellian core and a Kappa function halo,

$$f_{M+\kappa}(v) = Ae^{-v^2/v_{th}^2} + \frac{B}{\left(1+v^2/\kappa v_{th}^2\right)^{\kappa}}, \qquad (2)$$

shown as a solid curve in Fig. 4. The fitting parameters are: $A = 10823$, $v_{\rm th} = 0.27$ mm s^{-1}, $B = 991$, and $\kappa = 1.72$. The same characteristic speed $v_{\rm th}$ was used in both the core term and the halo term of Eq. (2). In energy units, the fit value for $v_{\rm th}$ corresponds to $m_p v_{\rm th}^2/k_{\rm B} = 161$ K, where particle mass $m_p = 3.1 \cdot 10^{-14}$ kg.

The small κ value for the Kappa-distribution halo indicates the VDF tail has a substantial deviation from Gaussian statistics. Recall that a Gaussian would be characterized by $\kappa \to \infty$. For comparison, we can also express $\kappa = 1.72$ as $q = 1.58$, where q is the fit parameter for the Tsallis distribution, which would have a value $q = 1$ for a Gaussian.

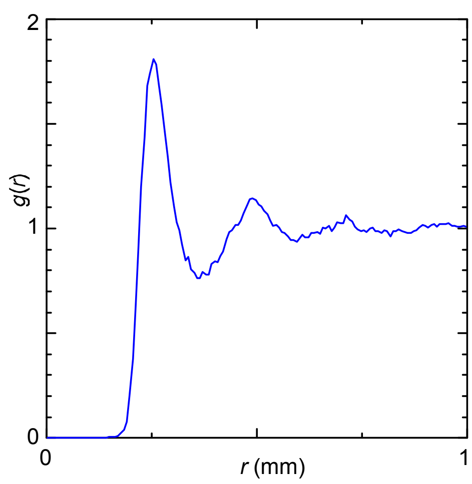

FIGURE 3. Pair correlation function, for three-dimensions. The shape of this function indicates a liquid-like microscopic structure.

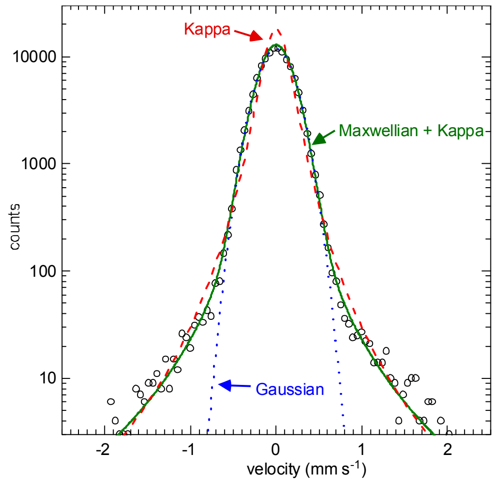

FIGURE 4. Velocity distribution function, for particle motion in the *y* direction. The experimental data (circles) is obtained from an analysis of a time series of the duration of about 28 s. We fit the data to: Maxwellian (dotted), Kappa (dashed), and a combination of Maxwellian and Kappa functions (solid curve). In preparing this histogram, we subtracted the local flow velocity from the particle velocity, so that the distribution is shown centered at zero.

A combination of a Maxwellian core and a Kappa function halo like the one we report has been observed previously in the solar wind [3,4]. The solar wind is nonequilibrium, although for different reasons than our dusty plasma. The solar wind is mostly collisionless, and it is strongly affected by magnetic fields. The dust particles in our plasma, on the other hand, are highly collisional among themselves, and electric fields generally provide the energy source.

SUMMARY

An analysis of particle motion in a 3D dusty plasma under microgravity conditions reveals a velocity distribution function (VDF) that is non-Maxwellian. This non-Maxwellian VDF is fit well by a combination of a Maxwellian core and a Kappa function that has high-energy tails, similar to observations of the solar wind.

ACKNOWLEDGMENTS

All authors acknowledge the joint ESA/Roscosmos "Experiment Plasmakristall-4" onboard the International Space Station. This work was partially supported by DLR Grant Nos. 50WM1441 and 50WM1442.

Work at Iowa was supported by NASA.

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