Using Silica Dust to Obtain a Three-Dimensional
Analysis of a Dusty Plasma Part II

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Short Overview

Short Abstract

To this date, the study of the relatively unknown substances termed ‘dusty plasmas’ is limited by the now antiquated method of two-dimensional laser sheet imaging. Our goal is to prove the usefulness of a three-dimensional structural imaging system utilizing dust which fluoresces under ultraviolet light. Ground based studies have shown the method’s potential, and our continued testing for optimization in the laboratory and application in data collection in microgravity environments will allow for strong and conclusive data.

Project Synopsis

The goal of the project was to collect data on dusty plasmas while on board a plane that simulated nearly weightless conditions. The program, NASA’s Microgravity University, took place from June 4th through 12th for us, meaning our experiment had to be completed and shipped to Houston, TX by the beginning of June. The experiment, seen fastened to the plane in Figure 1 below, was built to meet NASA safety requirements while remaining as small and light as possible and still be able to complete all necessary scientific procedures. Easily seen components include our vacuum pump, used to bring our chamber to about 100 mTorr of Argon, our power supply with which we controlled the electrodes, and the touch screen monitor to allow us to view what was happening in the enclosed portion of our experiment and to work with our LabView program.

Figure 1: The DPX II experiment, bolted to the Microgravity University plane.
Figure 2: The Experimental chamber and imaging system, removed from the protective enclosure.

The internal components of the enclosed area are seen in Figure 2. The dusty plasma was formed in the central chamber while the two cameras collected data, one a close view on individual particles and the other a full chamber view to see cloud motion. The laser was used to illuminate the dust so that it could be seen. Due to equipment failures and technical difficulties, we were unable to utilize the fluorescent dust and UV lamp for the experiment this year, but hope to incorporate it next year. Nonetheless, great data was collected of the dust cloud formation, shape, motions, and so forth as functions of gravity and internal pressure, allowing for analysis which was not been done before to better understand the dust clouds. Furthermore, our analysis of this data will better allow us to understand how and where the dust travels while in microgravity, allowing us to design and implement a better camera system which will be able to track or move with the dust cloud.

Short Summary of Status

At current, the project is nearing its completion. We finished all planning, purchasing and construction and our main data collection phase took place on June 9th and 10th through NASA’s Microgravity University program at Johnson Space Center. We were able to collect nearly continuous data from our two flights on the dusty plasmas, watching their motion and changing features as a function of gravity. We utilized a LabView program to display and record data from two cameras, accelerometer data, pressure in the chamber, and time simultaneously for use while running the experiment and later review. Currently we are working on analyzing our data and hope to be nearly finished and working toward being ready to present and hopefully publish our results by the end of August. We are also still continuing our outreach program and are coordinating a presentation at The Liberty Science Center in Jersey City, NJ.
Comprehensive Overview

Abstract

In spite of their relatively unknown nature, dusty plasmas are found very commonly in astrophysical observations, such as planetary rings, as well as inside ground-based devices, including fusion reactors [1-5]. Due largely to greater interest in the effects these dusty plasmas are having inside these ground-based devices, the field of dusty plasmas has been expanding very quickly. In order to learn more about these dusty plasmas, devices are beginning to be frequently brought into microgravity as many experiments can be run and results observed which cannot be recreated with the presence of gravity in the laboratory [6-11]. In spite of advances in many aspects of dusty plasma research, experiments continue to use laser-sheet methods, developed in 1994, to image and gather data on the dust clouds. This method meets limitations with the three-dimensional clouds as it can only get two-dimensional cross sections for analysis [12-16]. Team DPX has been working with other methods of imaging these dusty plasmas, primarily the use of dust which, when exposed to ultraviolet (UV) radiation, will fluoresce. Through making the dust fluoresce, we are able to image the entire three-dimensional structure of the cloud simultaneously and homogeneously in ground-based experiments. This is a vast improvement over the limitations of the laser sheet, and we are working toward gathering sufficient data to prove its usefulness in comparative studies. Microgravity will allow us to test two important aspects of this imaging technique. First, we will be able to move the dust cloud further from the dust tray, simulating an isolated system. This way, any effects from the tray, such as reflections, will be eliminated and the data from the laser sheet method and our UV imaging can be gathered and compared. We will be investigating different intensities of UV radiation as well in order to ascertain the most efficient value, allowing the entire cloud to be illuminated as much as possible, but without affecting the interparticle spacing, the velocities of the particles, or other properties of the cloud. The second task will be a further test of a strange phenomena detected during prior student-directed work on dusty plasmas, wherein the particles gained a rotational velocity while in a direct current (DC)-glow discharge plasma. We will watch to see if this rotational motion can be recreated in the microgravity environment, and if any correlation with the intensity of the UV radiation can be found.

Introduction

While a relatively unknown substance, dusty plasmas are extraordinarily common in the visible universe, as well as on Earth. In space, we see dusty plasmas in Saturn’s rings, young stellar objects, all kinds of nebulae, comet tails, and stellar ejecta or circumsolar dust. Closer to home, dusty plasmas are seen in natural phenomena like lightning bolts and flames, and in common
objects like fluorescent lights. These dusty plasmas have an industrial importance as well, as they can be unintended creations inside of fusion devices and machines using plasma etching [1-5].

Due to the importance of these substances combined with how little is currently known, many ground-based experiments were begun in more recent years. Unfortunately, on Earth gravity proves a limiting factor on these experiments to understand dusty plasma properties and interactions. As such, a large emphasis has been placed on taking these dusty plasmas and their associated experiments into microgravity environments, where electrostatic and drag forces are the major components [6-8]. These microgravity experiments have taken place through parabolic flight campaigns, on the Mir space station, aboard sounding rockets, and recently have been brought to the International Space Station (ISS) to gain the necessary conditions.

Many new and very important discoveries have come as a result of the microgravity experiment opportunities. In 2002, Annaratone et al. worked aboard the ISS and were able to learn about a new self-structuring mechanism that took place near the outer edge of the dusty plasma void [9]. Another experiment in 2003 by Fortov et al. helped bring a better understanding of the workings of materials on earth by finding properties of different phases in a dusty plasma. New advances are continuously being made in the field as more data is collected and analyzed about these dusty plasmas.

![Figure 3: An example of a laser-sheet. Courtesy of the Max Planck Institute for Extraterrestrial Physics [11.]](image)

However, in spite of the advances in many respects with these dusty plasmas, the main method of imaging and thus collecting data has not changed since 1994. These experiments make use of a laser-sheet which illuminates a two-dimensional slice of the cloud within the dust cloud. Once the particles are able to be seen, the cloud is filmed so that the video can later be analyzed to discover interparticle spacing, found by knowing the distance corresponding to a pixel, and to learn about the dust dynamics [12, 13]. Other properties of the dust cloud which cannot be collected from the video are obtained by using a Langmuir probe [14]. This method works very well to see and
analyze the dust in the path of the laser, “However, this illumination technique limits measurements to a single cross section of the dust cloud. [6]”

When used optimally, lasers allow vertical or horizontal planes to be viewed, but nothing more [15, 16]. At times though, the limitations from the laser plane will prevent any data from being collected, as was seen in an experiment by Nefedov et al. Their attempts to analyze plasma crystals on the MIR space station in 2002 failed “because of a fairly small number of particles in the laser sheet plane, a quantitative analysis of the experimental g(r) function is virtually impossible [17].”

![Figure 4: A schematic from Nefedov et al. [17] depicting the CCD camera and laser sheet technique commonly used in microgravity dusty plasma experiments.](image)

To try and circumvent these limitations, more complex methods have been developed, including the Stereoscopic Particle Image Velocimetry (SPIV). By using a second camera, a three-dimensional analysis of the particles in the laser sheet is possible [18]. In spite of this improvement, it still has a limited field of view at any one time, losing a large amount of data stored in parts of the cloud not illuminated. The set-up itself is also quite difficult, as coordinating cameras and software for SPIV can make for a difficult system.

To eliminate these limitations altogether, Mike Hvasta, a previous Team DPX member, worked under Dr. Andrew Zwicker at the Princeton Plasma Physics Lab with a new method of imaging the three-dimensional structure. This method used fluorescent dust, which would become uniformly illuminated when exposed to UV radiation. With the entire cloud illuminated, rather than the two-dimensional sheet from the laser, the camera could film the full three-dimensions. This allowed all macro-particle dynamics taking place within the experimental chamber to be analyzed, as the only restriction on the number of particles was the depth of field [19,20].

While this imaging technique seemed promising in ground based studies, it would be in microgravity where the laser-sheet and UV fluorescence methods of imaging could be compared for
quality and quantity of data. The first dusty plasma experiment to test this imaging process was run by Team DPX and flew through Microgravity University in the summer of 2007. This experiment was a preliminary step, allowing the team to learn how everything would function in microgravity, what kinds of concerns would be faced in the low gravity environment, and learn about how the dust clouds would react as the gravity continuously changed. The experiment was able to collect good data, primarily from hyper-gravity and the transition periods, and the interparticle interactions and the effects of the microgravity were studied and better understood. The results were presented at a conference by members of the team.

This project presented the next phase of the dusty plasma experiment. It built upon all previous research and findings to produce a much more efficient design that will provide superior data quality and quantity in the microgravity environment. Furthermore, the design was altered for additional structural integrity, a more stable electric field for the dust clouds, and a more independent system which will require less interaction or difficult procedures for the operators in microgravity. The purpose of this experiment was to provide data proving that the data quality of the UV fluorescence method is as good quality, if not better, than the laser-sheet method while providing a much greater quantity of useable results.

Theory

A dusty plasma is, generally speaking, what it sounds like: a plasma with small, suspended ‘dust’ particles. These particles are micron sized, and accompanied by ions, electrons, and neutrals. While dusty plasmas are found naturally and studied by physicists, they are not always intentional or desired. Engineers and industrial scientists sometimes find that dusty plasmas form inside some of their machinery, contaminating the products and causing large losses for the company [12].

For a typical dusty plasma, as seen in the laboratory, the free electrons move much more quickly than do the ions or dust particles. Since the electrons are moving faster, they experience many more collisions and give the dust a net negative charge. Additionally, a charge will accumulate on surfaces inside of the vacuum chamber, creating a sheath. The sheath is one of the major contributors to controlling and confining the dusty plasma into certain areas, as will be shown below [22,23].

Since all of the dust particles will have a net negative charge, they will repulse each other according to the Coulombic law, so long as:

\[ r_d < D < \lambda_d \]

For which \( r_d \) is the average radius of the dust particles, \( D \) the average interparticle spacing, and \( \lambda_d \) is the Debye length. If the interparticle spacing becomes greater than the Debye length, the interactions between the charged particles will be limited by Debye shielding [1,2]. The strength of
These interactions between the various dust particles can be calculated through use of the coupling parameter:

\[ \Gamma = \frac{\text{Potential Energy}}{\text{Kinetic Energy}} = \frac{(Z_d e^-)^2}{D(K_B)T_d} \]

For which \( Z_d \) is the number of charge carries on each particle, \( e^- \) is the charge for a single electron, \( K_B \) is the Boltzmann constant, and \( T_d \) is the temperature of the dust. The coupling parameter is directly proportional to the strength of interactions between the particles, meaning a larger parameter means stronger interactions. To understand this value a little better, \( K_B \) and \( e^- \) are constants, \( T_d \) tends to be a small number in eV, ranging from 2-6, and \( Z_d \) changes greatly as a result of many factors (e.g. photoionization, particle work function or plasma temperature) and can be anywhere between \( 10^4 \) and \( 10^6 \) e\(^-\) [17,21, 24]

This coupling parameter also determines the phase of the dusty plasma, similar to how the strength of inter-atomic forces will determine the phase of other, everyday materials. While \( \Gamma \ll 1 \), the particles freely move about in a gaseous phase. As the \( \Gamma \) value is increased, the phase becomes increasingly more liquid and then solid, finally becoming constant and consistent at \( \Gamma \geq 170 \) when plasma crystals are formed. Experiments are done investigating all different phases, taking advantage of the different circumstances in which to study the particle interactions, which is leading to a better understanding in material science about these particles [1,8,21].

While this is a complex system with a number of interacting forces, only those parts from gravitational and electrical are important, as the ion and neutral drag forces are actually orders of magnitude smaller than the first two forces and will make no noticeable difference. Clearly, the dust cloud will float or stop at the point where the electrical and gravitational forces cancel out, allowing the cloud to stay at rest:

\[ \sum F = E Z_d e^- - mg = 0 \]

In this equation, \( E \) is the magnitude of the electric field, \( m \) is the average mass of the dust particles, and \( g \) is of course the acceleration due to gravity. As the particles come to this zero point, they begin to interact with each other, and this mutual repulsion allows for a formation or order to be created, making structure of plasma crystals. In figures 5 and 6, depictions of these crystal structures, also called the dust clouds, are shows and produced by Hvasta [25].
Figure 5: Three cone shaped clouds form just above the dust tray. These small three-dimensional clouds are approx. 2-4 mm in diameter.

Figure 6: A close up of a dusty plasma structure created at PPPL. The particles are balanced against gravity via mutual repulsion and the electric force provided by the electrodes. The width of this three-dimensional cloud is approx. 12 mm.

In the three-dimensional structures of Figure 5 and Figure 6, the dust particles have a size limitation which determines the interactions, based on the gravitational conditions. Since the charge on the dust is gained by collisions with the electrons, the charge will be located on the surface, meaning that the charge is proportional to the surface area [1,2]. By starting with the equation for the surface area:

and accounting for the mass of the particle:

—
where $\rho$ is the mass density of the dust. Clearly, the mass will increase with radius faster than the surface area will, leaving an upper cut-off value at which point the dust particles could not remain suspended. Work by Hvasta has shown this limit to be around 0.12 mm [26]. Once in microgravity, this should no longer be a concern though, as there will be very little influence from the gravitational force and thus little importance placed on the mass. The dust particles will be able to remain in the bulk plasma, and the structure’s shape will only depend on the shape and size of the chamber it is in, as the repulsive forces between the particles will be counteracted by the sheath effect near the chamber walls and the influence of the electrodes [22,23]. Conversely, in the hyper-gravity sections, the upper limit of particles will likely become smaller, limiting the number of dust particles further and condensing the structure.

These changes in the microgravity environment provide two primary advantages. First, with the increased cloud size, there will be a larger number of particles from which data will be collected. This will allow for the creation of more accurate and real models of bulk plasmas and their interactions with normal materials [10,11,27]. Second, with no restriction on the particle size in the microgravity case, larger particles can be observed and analyzed to achieve a better understanding of the dynamics related to them. These larger particles are important, as it will allow for more accurate representations of macro-particles and their interactions on an even larger scale, such as from comet tails and inside planetary rings [1,4,17].

**Project Timeline and Execution**

The project itself was a continuation from a previous years work, but we went in to it knowing that we needed to totally start from scratch with the experiment platform and construction, regardless of whether or not we were selected for NASA’s Microgravity University. We began working in the fall of 2008, and sent in our application for the program on October 24th. The announcement of team selections was supposed to be made at the beginning of December, but due to some issues on NASA’s end, we were not told until early February that we would be flying in the beginning of June, giving us a four month deadline to the project. Once we were accepted to the program, we were able to begin working on more ways to finance our project and started working much harder to be ready with a more difficult project, since it had to not only work on the ground, but in the microgravity environment and with meeting NASA’s very strict requirements. Our proposal was sixty pages long, and our safety analysis document, due in mid April, was significantly longer, more difficult, and required many revisions before it fully satisfied everything NASA needed. With a strict deadline, every member put in many hours every week, working up until the last moment possible before we had to ship our experiment.

We started with testing previous ground based experiments, gaining familiarity and skills we would need to use with our own experiment, and deciding what we needed to keep and what to
change for our microgravity experiment. We then moved in to the research phase, finding components we would need, making drawings, and gathering equipment. From there we broke in to two groups for a while, with three members focusing on design, construction and safety analysis while the other four members focusing on testing the equipment, the formation of dust clouds and determining optimal pressures, voltages and dust composition for our chamber. It is through this testing that we came to realize limitations with our design in working with the fluorescent dust and were unable to form any dusty plasmas with their combination. We are still investigating why this did not work, if the fluorescent dust was contaminated in some way or if there is a problem with our electrodes, but due to the imminent deadline for shipping, we chose to utilize normal silicate dust which we knew worked very well with our experiment design and formed very strong and easily imaged clouds.

We have also continued with our outreach program. On campus, we held talks and presentations of our research, the work we are doing, and about the Microgravity University program itself, encourage others to talk part in this in similar programs and to get involved. We also ran ‘Women in Science’ panel, putting together a group of female scientists to speak about their experiences as researchers, especially in male dominated fields, and encourage female science majors to go out and achieve, in spite of any adversity they may feel. We have also each held a presentation at our own high schools or middle schools showing where we came from, as students where they were, to where we are now and the amazing opportunities we have received. The main premise and goal of these presentations was to encourage the students to go into science professions and majors in college and to realize the amazing things that are out there. In concluding our program for this year, we will be holding a presentation at the Liberty Science Center in Jersey City, New Jersey later this summer. We had done a similar presentation last year after completing our project and had the opportunity to give two separate talks and reach out to a varied audience beyond our normal scope, and hope to have a similar impact and number of people attend this year.

**Final Construction**

In its final form, the experiment measured 58”x24”x23” and weighed 290 lbs. It was mounted along the direction of the plane and connected to a K-bottle of argon. The frame was made of 80/20 extrusions and padded with pipe foam to protect people floating in the vicinity of our experiment. PVC paneling was used to enclose the main chamber to protect all in the cabin from the laser light, the possible danger of over pressurization of the chamber leading to the chamber shattering, and from the future use of UV light. The rest of the frame was left unenclosed to allow easy access to all components, whether from the side or from above, whichever was easier in the microgravity environment. Team members can be seen operating the experiment in the figure below.
Data Collection

Prior to flight, our setup was taken to its initial conditions, which included the following: depressurizing the chamber, backfilling with argon gas to the desired pressure, applying a voltage of approximately 480 volts to create a stable plasma, increasing voltage to approximately 600 volts to excite dust particles, reducing this voltage again to maintain a stable plasma, and bringing the system to desired pressure and voltage conditions to create an optimum dust cloud.

During the course of the experiment, only two parameters were manipulated: the position of the fine-view camera and the pressure. There was one wide angle camera to locate the cloud inside the chamber, and one zoomed in camera to visualize the cloud up close. We were recording from both cameras. Synchronization issues were taken care of by utilizing a LabView program designed to gather and process analog video inputs, accelerometer data, and pressure readings. The laser sheet was made from a modified laser-pointer and a diverging lens.

Our first day of flight ran into issues with not being able to find the dust cloud. The close view camera collected no data while the team worked frantically to figure out if a cloud was even being formed. Fortunately, in reviewing data from the wide-view camera later that night, we were able to see that a cloud was present but only seen in the microgravity portions due to a misalignment and incorrect positioning of the laser. This problem was easily rectified and the second day of flight proved incredibly fruitful, with continuous data caught in both cameras.
Results and Analysis

To the point at which this report is being submitted, there are not yet any reportable results. The analysis is currently being done, lead by sophomore physics major Aliya Merali working at the Princeton Plasma Physics Laboratory. She is primarily focusing on breaking down and categorizing the usable data at current. She will soon be analyzing the images using the known pixel to cm ratio for each of the two cameras in the system to learn about the cloud dynamics, both on the macroscopic and microscopic scale. The goal is to note individual particle spacing and motions as a factor of the different pressures and variable gravity. We also hope to map out the electric field inside of our chamber by following the dust clouds path on the large scale, and watch for any changes from parabola to parabola or if the entire system fully repeats.
## Budget

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### Income

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Bibliography


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