Dynamic and Optical Characterization of Dusty Plasmas for Use as Solar Sails

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Abstract

Solar sails presently have mass loadings about 5 gm/m^2, which when including the support structure and payload, could easily average to > 10 gm/m^2. For realizable spacecraft, the critical parameter is the total mass / total area, which when combined with the reflectivity, directly give the true acceleration. We propose that dusty plasmas trapped in a "mini-magnetosphere" (Winglee et al. JGR 2000) can produce a solar sail with a total mass loading < 0.01 gm/m^2, and reflectivities of $\sim$1%. This configuration provides an acceleration equivalent to a standard sail of 95% reflectivity with $< 1\text{gm/m}^2$. Thus, dusty plasma sails represent a potential replacement for thin film technology.

However, the physics of dusty plasma sails is not mature. Several important questions need to be resolved in the laboratory before a large scale effort is warranted. Foremost among these questions are, what is the largest force a dusty plasma can sustain before it demagnetizes and separates from the binding magnetic field? What are the charging properties of dust under solar UV conditions? What is the light scattering cross section for the dust? What is the optimum dust grain size for magnetization and scattering? What are the optimum dust grain materials?

In this paper we outline what we know about dusty plasmas, and what we are hoping to learn from two existing dusty plasma experiments at the National Space Science and Technology Center (NSSTC) and at Auburn University. In the Dusty Plasma Lab at NSSTC, we have a force balance or Paul trap to suspend a single dust grain either in air or in vacuum. With this arrangement, we determine the forces on a dust grain illuminated by a laser, and measure directly the ratio of light pressure to grain size and composition. At Auburn University, and now also in the Spinning Terrella Lab at NSSTC, we can observe the collective properties of a dusty plasma, and study whether we can suspend a "Saturn's ring" of dust around a rare-earth magnet.

1 Introduction

The concept of a sail is so ancient as to defy attribution, yet so modern that it is constantly re-engineered and redefined. For example, the parasail is a relatively new invention that remakes the simple sail into an airfoil, and thereby spawned a whole new sport. If we are permitted to broaden the scope of a sail to include any device that couples momentum from the atmosphere, we might be able to include sailplanes and autogyros. In exactly the same way, if the definition of solar sails were broadened to include any device that couples spacecraft momentum to sunlight, we would be able to include magnetic balloons and plasma sails, which may do for solar sailing what parasails did for parachutes.

The first recorded occasion when mankind could the ground and took to the air might be considered when the Montgolfier brothers sent a sheep up in a hot air balloon in the 1783.

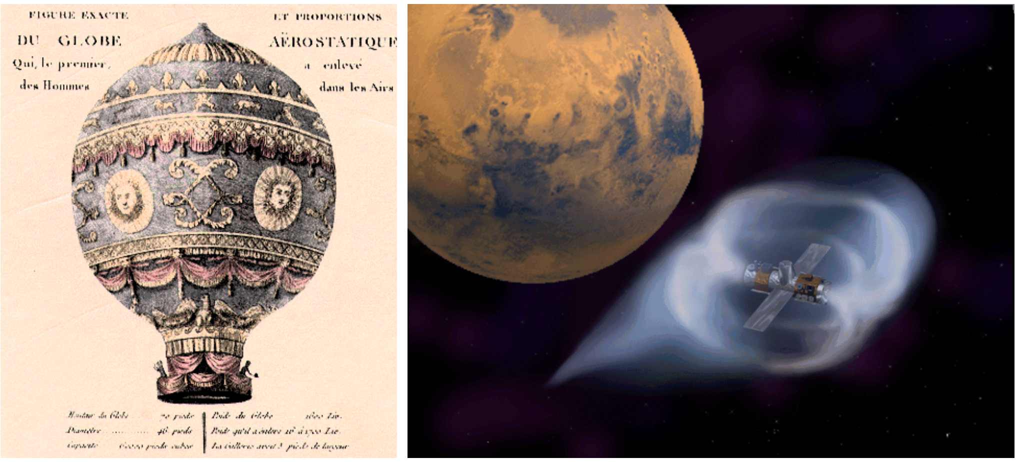

Figure 1: Left: Engraving of Montgolfier balloon; Right: An artists conception of a magnetic balloon with a plasma sail *en route* to Mars.

Balloons played an important role in warfare 100 years before aircraft, being used by both sides in the Civil War as forward observation posts. Even today, ambitious entrepreneurs are attempting to fly dirigibles equipped with cell phone antennas 10 miles above a metropolitan area and thereby cover 10,000 square miles with one "tower". So we see that balloons fill two roles: they are often the first steps into conquering new territory, and they occupy some specialized niches much more effectively than the more versatile, higher technology aircraft.

These are the same two roles that magnetic ballooning fills with respect to solar sails. Solar sails are undoubtedly high technology. Materials that are incredibly thin and light have to be deployed over square kilometers of area and stretched to mirror smoothness. While great strides have been made in materials the long term survival of such fragile films, and the deployment of a large sail are still areas needing work. Knowledgable estimates suggest 5-10 years for the deployment of a 100 meter sail that will act as a testbed for future work. In light of the real technological hurdles facing solar sails, is there an easier way to harness the promise of infinite Isp solar propulsion? Yes, if one is willing to accept some limitations that come with the great simplification of ballooning.

Robert Winglee of the University of Washington has proposed and recieved funding from the NIAC to develop the concept of magnetic ballooning, which he prefers to call "M2P2" for mini-magnetospheric plasma propulsion (Winglee, JGR 2000). Winglee used a computer code for plasmas that he had developed over the past decade to show that a magnetic field can be inflated by a plasma to many times its original size. Then when this inflated magnetic field is placed in the supersonic solar wind, the wind transfers momentum to the magnetic field which accelerates at a constant rate until it approaches the speed of the solar wind, about 400 km/s. One convenient feature of his balloon is that it expands as it gets further from the sun, much like a weather balloon expands as it rises through the atmosphere, so that unlike a solar sail, a balloon experiences a constant force at all distances from the sun. This theoretical model has been tested with a scale model placed in a 30 ft vacuum chamber at MSFC, providing the first demonstration of the inflation of a balloon, and the deflection caused by hitting the balloon with a simulated solar wind. In figure 1 we show an artist's rendition of such a satellite employing a dusty plasma sail to rendezvous with Mars.

The principle of ballooning is simple, but involves some tradeoffs that require some quantitative discussion. The strength of sunlight at the Earth's orbit is about 1.4 kW/m^2. Einstein demonstrated that light is a particle and therefore has a momentum given by $p = E/c$. This means that the intensity of sunlight given above can be converted into a pressure (=force/area) by dividing by the speed of light, c. Working in SI units, that would be 4 μPa of pressure generated by light on a black sail. But in addition to sunlight, the sun is evaporating, sending out heated hydrogen and helium in a supersonic radial flow known as the solar wind. The solar wind, like the Earth's wind, varies in speed from 300-1000 km/s, but on average is about 400 km/s. The density is quite low, however, between 1-10 atoms/cc, which has an average around 3/cc. So if we have a square meter of area intercepting this flow, the pressure exerted by the solar wind would be the momentum of all the particles in a volume 1m^2 x 400 km, or 1.2x10^{12} proton x 1.67x10^{-27} kg/proton x 400 km/s = 0.8 nPa. Since the solar wind is about 5% Helium, it adds about 25% to the mass density, which makes this a convenient round number of 1 nPa for the pressure exerted by the solar wind. The result of this calculation is that solar wind is about 4000 times less effective than sunlight in pushing a sail.

This calculation is why the solar sail calculations rarely add the forces due to the particles. A magnetic balloon, on the other hand, intercepts most of the solar wind pressure and very little of the sunlight pressure. So why would anyone prefer a magnetic balloon? Well, when calculating the acceleration of a spacecraft, it isn't the pressure that is needed, it is the total force divided by the total mass. If a solar sail is 1000 times heavier than a balloon of the same size, then even if it does experience more pressure, its acceleration is less. Worse than that, as the sail leaves the sun, its acceleration drops with decreasing light intensity whereas a balloon keeps a constant acceleration (theoretically at least out to the heliopause, which is beyond the orbit of Pluto).

Can we estimate the size/mass ratio of a balloon? This is the calculation Winglee has done. He argues that a simple magnetic field, say, from a permanent magnet, doesn't make much of a balloon. However, when plasma is injected into that magnetic field, much the way Jupiter fills its magnetic field with plasma, then the size of the balloon is increased 10 or 100 times. (A magnetic field filled with plasma was called a "magnetosphere" when it was discovered around the Earth 40 years ago, which accounts for Winglee's terminology). For example, if we could see Jupiter's magnetosphere from Earth, it would be larger than the full moon, being about 100 times larger than Jupiter itself. Therefore, Winglee argues, we can build a spacecraft that inflates a magnetic balloon much larger than the spacecraft itself. Winglee estimates that a 30 km wide balloon can be inflated with "commercial off-the-shelf" (COTS) components on a 1-meter sized spacecraft that weighs about 500 kg. In solar sail terminology, that is <0.001 gm/m^2, which is a very low mass-loading. Even with the 1/4000 times weaker solar wind pressure, the resultant acceleration is still equivalent to a 10 gm/m^2 solar sail/spacecraft.

Are balloons then, destined to be surpassed by solar sails when sails can finally be made with mass loading < 10 gm/m^2? Not necessarily, for if magnetic balloons can tap, if ever so slightly, into the sunlight pressure, they can increase their exfficiency up to 4000 times, in essence, becoming a solar sail. Imagine for a moment, that there exists a gas that is bright yellow when it is ionized. If the magnetic balloon were inflated with this yellow plasma, then it would not only deflect solar wind, it would deflect sunlight. Perhaps not all of the sunlight, but even 1% of the sunlight would be a factor of 40 more acceleration for the balloon. That is, a 1% opaque plasma filling a 500 kg balloon to a diameter of 30km would have an equivalent mass loading of 0.1 gm/m^2. Not only does this surpass the expectations of the AO, but such a plasma sail would be easily deployed, resistant to tearing, compactly stored, and radiation hard. This then, is the purpose of this paper: to investigate the potential for magnetic balloon materials that are opaque to sunlight, which we refer to as "plasma sails".

2 Plasma Sails

It is well known that if a solar sail can specularly reflect sunlight, it not only gains a factor of 2 in momentum, but it gains the ability to "tack", or generate thrust at an angle from the radial. Despite this advantage, one of the more promising solar sail candidates at the present is the black carbon-fiber sail, that can only absorb sunlight, and therefore cannot "tack" efficiently. It is promising because of its robust performance with respect to heat, tearing, deployment and mass-loading. It is instructive to examine microscopically how a carbon-fiber sail accomplishes this feat. It replaces a 2-D film with a 3-D mesh of carbon fibers which have on average, a smaller diameter than the thickness of the 2-D film. Yet it is remarkably robust, primarily because of its 3-D structure. Somehow an open mesh of mostly empty space can be stronger than a 2-D solid structure of the same weight.

In the same way, we view a plasma sail as an open mesh of mostly empty space, held together by long-range electrostatic and electromagnetic forces, rather than chemical bonds. In this sense, a plasma sail is just the extrapolation of a carbon sail to infinitesimal fibers. The components of a plasma are an even mixture of ions and electrons that form an electrically neutral fluid. The ions can be simple atoms that have lost a few electrons, or they can be massive particles with a net charge of many hundreds of electrons, or an admixture of both. The response of the plasma to a force depends on its magnetization as well as ion's mass. The properties of a plasma, then, are crucial in determining whether a plasma sail can withstand the pressure of sunlight and solar wind without ripping it to the shreds we see in comet tails.

The simplest plasma sail one can imagine is an atom that when ionized, still absorbs or scatters sunlight. All ions that are not fully stripped, that is, having at least one electron left, possess this property. Since the solar wind is composed of mostly fully stripped H^+ and He^{++} it remains invisible. But we could use for example, Ba^+, or Li^+ ions that scatter some characteristic frequency of light, which are the principle means for coloring fireworks. The trouble with using a colored ion for the plasma, is that it absorbs such a narrow part of the solar spectrum, resulting in a small efficiency increase. Ideally, one would like a "black" ion, one that absorbs all the sunlight. A viable alternative is to use molecules or clusters that form charged dust grains, or dusty plasmas. These plasmas occur naturally around comets or within Jupiter's magnetosphere, where they can be observed with telescopes. The field of dusty plasmas is brand new and many questions have yet to be answered, but we can still draw some conclusions from observations of comets.

Comets have two tails, a dust tail and a plasma tail. The dust tail somewhat follows the orbit of the comet, whereas the plasma tail is stretched radially in the direction of the solar wind. Indeed, these observations were the first indication of the existence of the solar wind. But this indicates that the dust does not stick to the plasma, it is not contained by the draped magnetic fields of the comet. If we are going to make a "black" magnetic balloon out of dusty plasma, we must find a way to get the dust to stick.

These then form the two prongs of an experimental approach towards developing second generation plasma sail materials: an investigation of "sticky" dusty plasmas, and an investigation

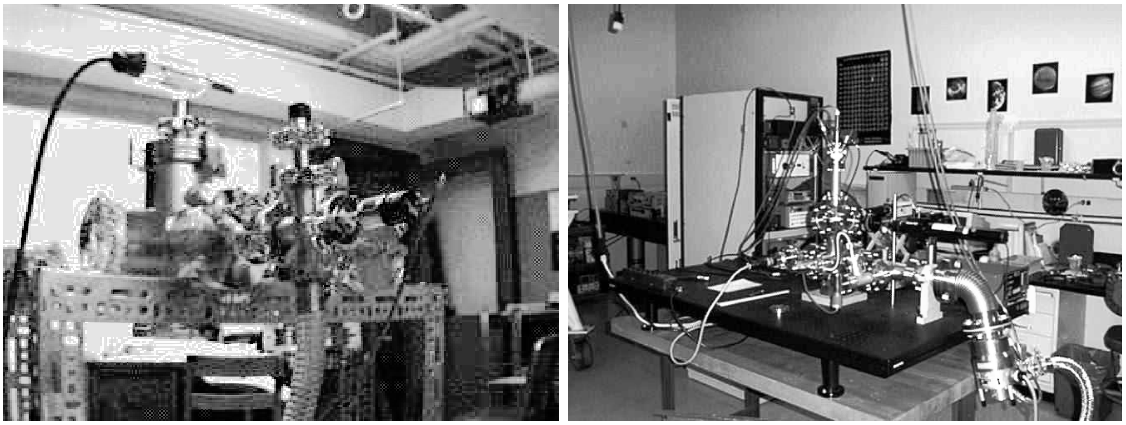

Figure 2: Left Panel: The dusty plasma experiment (DPX) at Auburn University. Right Panel: Dusty Plasma Lab at NSSTC.

of "black" plasma materials. The first problem, of maintaining the integrity of a dusty plasma against an external force, is very similar to the problem of dusty plasma levitation against the pull of gravity, an experiment that has been addressed by Edward Thomas Jr at Auburn University. The second problem, of quantifying the scattering coefficients of a dusty plasma, has been addressed by Jim Spann and Mian Abbas of NASA/MSFC, albeit for selected dust types. In figure 2 we show the experimental setups of both groups. We propose to augment both experiments to measure candidate dust types for a plasma sail, measuring the radiative transfer functions for individual dust grains at MSFC, while examining their collective behavior at Auburn University.

3 "Sticky" Dusty Plasma Theory

In a dusty plasma, the usual plasma (ionized gas) environment of ions, electrons, and neutral particles is modified by the presence of a fourth species - charged particulates; i.e., the dust particles. The dust particles can range in size from hundreds of nanometers through hundreds of microns. Because the dust particles are charged, they fully interact electrostatically with the other charged species in the surrounding plasma. The presence of the charged dust grains in the plasma modifies many of the properties of the plasma, e.g., charge distributions and potential profiles, and introduces entirely new dust-plasma phenomena, such as the levitation of dust observed in panel one of figure 3.

In this proposed application of dusty plasmas as solar sails, several key questions must be addressed. First, can the mass loading of the dust be sufficiently low to compete effectively against current solar sail technologies? Second, can the dust particles remain sufficiently well-confined within the magnetic balloon and, for sufficient duration, to ensure continuous acceleration? Third, is the reflectivity of the dust particles sufficient to gain the added benefits of a "black" plasma? While some preliminary studies have been performed to examine this application of dusty plasma, it is important to note that the focus of this proposed investigation will be to fully assess the feasibility of this idea.

There are two scale lengths that are critical to assessing the feasibility of the dusty plasma solar sail: a, the radius of the dust particles and R, the radius of the magnetic balloon. If the dust particles are spherical then the mass of an individual particle will scale as a^3 and the charge per grain will scale as a. The total mass of the system will depend upon the density of the dust grains within the magnetic balloon and will scale as R^3. Furthermore, the condition for confinement of the dust particles within the dust cloud will be set by a particle gyroradius less than R. In order to resolve these various scaling arguments, it is first necessary to make an estimate of the total charge that accumulates on the dust grain surface.

3.1 Charge per Grain

The charging of the dust in the magnetic balloon will be due to the contribution of three effects: the collection of ions and electrons from the expanded plasma and photoionization due to UV radiation [Goertz, 1989]. The ion and electron contributions are given by their flux to the surface of the dust particles. Under the assumption of a Maxwellian plasma, these fluxes will be given by:

$$I_e = 4\pi a^2 \left(\frac{en_e}{4}\right)\left(\frac{8kT_e}{\pi m_e}\right)^{1/2} \exp\left(\frac{eU}{kT_e}\right) \tag{1}$$

$$I_i = 4\pi a^2 \left(\frac{en_i}{4}\right)\left(\frac{8kT_i}{\pi m_i}\right)^{1/2} \left(1 - \frac{eU}{kT_i}\right) \tag{2}$$

where: e is the electron charge, n_i and n_e are the ion and electron densities, T_i and T_e are the ion and electron temperatures, m_i and m_e are the ion and electron masses, and U is the potential difference between the dust grain and the surrounding plasma. The photoelectric current is given by:

$$I_\nu = \pi a^3 K e^{-eU/kT_p} \tag{3}$$

where: K is the photoelectron flux, $K = \eta(2.5 \times 10^{14})D^{-2}$, η is the photoemission efficiency ($\eta \sim 1$ metals and $\eta \sim 0.1$ dielectrics), and D is the distance from the sun in astronomical units (AU). T_p is the temperature of the photoelectron and is assumed $T_p \sim 1$ eV.

3.2 Estimated Mass

The dust grain charge Q_d is computed from the capacitance of the dust particles,

$$Q_d = 4\pi\epsilon_0 aU. \tag{4}$$

Assume that the dust is composed of 1 micron diameter solid spherical silica particles with a mass density of 1500 kg/m^3. The mass of an individual particle will be $m_d \sim 7.85 \times 10^{-16}$ kg. The balance of the charging equations

$$I_e = I_I + I_\nu \tag{5}$$

under the constraint that the total charge in the plasma is conserved

$$en_i = en_e + Q_d n_d \tag{6}$$

allows an estimate of the average charge on the dust grains to be made. This calculation is made using plasma parameters for a hydrogen plasma generated by a spacecraft that is located at D

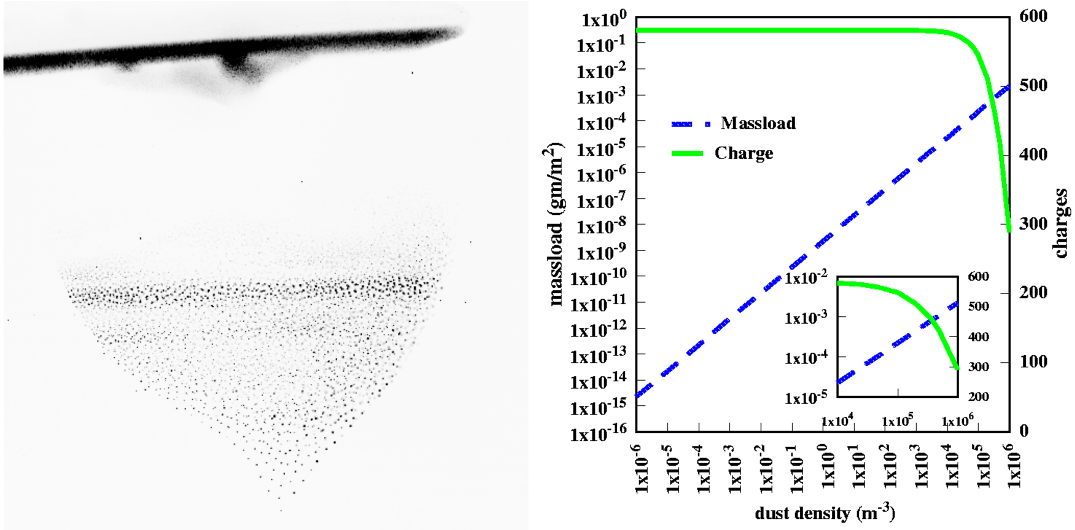

Figure 3: Left panel: Inverted gray-scale photograph of 3 micron diameter dust particles suspended beneath the anode of the Auburn University Dusty Plasma Experiment. Right Panel: Theoretical charge per dust grain as a function of dust grain density.

= 1 AU, temperatures, $T = T_e = T_i \sim 1$ eV, and T_d (dust temperature) ~ 0.5 eV, densities, $n_e = n_I \sim 10^7 m^{-3}$, and dust densities in the magnetic balloon of $n_d \sim 10^5 m^{-3}$. Under these assumptions, the dust grain charge will be negative, $Q_d \sim 5.4 \times 10^{-17} C$ or $Z_d = (Q_d/e) = 336$ electronic charges. The total mass of dust contained in a 20 km diameter magnetic balloon is $M_{\text{total}} \sim 330$ kg. Finally, this gives a mass loading for the sail and a 500 kg payload (as computed from the ratio of total mass to projected circular surface area of a spherical magnetic balloon) of 0.0026 gm/m^2.

Figure 3 shows the total dust mass and dust grain charge as a function of the dust density. Note that decreasing the dust grain charge has the effect of increasing the gyro-orbit of the dust particles about the magnetic field, thereby reducing their confinement.

3.3 Advanced Dusty Sail Concepts

Of course, changing the size and makeup (i.e., mass density) of the dust grains, or changing the dust grain density in the magnetic balloon, can have a major impact on the mass loading. One of the critical parameters in this calculation is the dust density. High dust densities ($n_d > 10^5 m^{-3}$) are needed to ensure efficient light scattering to enhance the acceleration of the magnetic balloon. However, at these high densities, the mutual screening between the dust particles reduces the total charge that can be accumulated upon each grain. This competes against the fact that a relatively high grain charge is required to confine the dust within the balloon.

The scaling of the mass of the dust particles in the balloon and the effective charge on the grains is shown in figure 3. The figure indicates that even for the highest dust densities, the mass loading remains well below the target value of 1 gm/m^2. To address the issue of confinement, it may be possible to use non-spherical dust (e.g., cylindrical or conical) in order to promote strong coupling effects between the dust particles, thereby reducing the need toward larger dust grain charges. Additionally, the use of magnetic materials for the dust particle may sufficiently increase the magnetic field within the balloon to allow the dust particles to be confined, even with the lower charge.

Yet another scaling comes into play when the laboratory dusty cloud is scaled to 30 km, which is the fact that the mass grows as the cube, whereas the area grows only as the square. However, if Saturn is able to confine its dust rings into a plane, it may be possible in the presence of a large dipole magnetic field, to confine the dust into the equatorial plane of the magnet. This thin dust plane would then have a mass that scaled with the square so that the mass loading becomes a constant independent of size. To explore this further, we have modified the Spinning Terrella Experiment at NSSTC to study the dust trapping behavior of a dipole magnet.

While the dust-filled magnetic balloon initially appears to satisfy the mass loading criterion of $< 1gm/m^2$, numerous basic physics and engineering issues must be addressed in order to demonstrate the feasibility of these ideas. Some of the most critical areas for investigation will be laboratory investigations of the confinement and density distribution of dust within the magnetic balloon and optimization of the choice of dust material (size, mass, coating, magnetic properties, etc.). Nonetheless, the initial calculations suggest that the addition of dust to the magnetic balloon can be a viable technique.

4 Black Plasma Materials

Ions that absorb a great deal of the solar spectrum are ideal for plasma sails. Part of the quiet acceptance of fluorescent lighting has been the improvement in spectral color caused by innovative rare earth phosphors that coat the inside of the tubes. These phosphors absorb the mercury light and reradiate it efficiently at all wavelengths. If the same rare earth materials can be incorporated into a dust particle, they may provide a large improvement in solar spectrum opacity. Another possibility are Polycyclic Aromatic Hydrocarbons (PAHs) which are thought to occur naturally in nebulae and produce wide band absorption features. These, and other advanced dust materials must be tested to quantify their various strengths and weaknesses.

For this purpose, an experimental facility based on an innovative technique referred to as electrodynamic balance has been under development for a few years at the Marshall Space Flight Center. The objectives are to carry out some basic experiments for understanding the microphysics involved in the formation, charging, growth, and destruction of cosmic dust grains and to determine their extinction coefficients (absorption and scattering characteristics) in various astrophysical or planetary environments. The current work focuses on various charging process of dust particles, and some preliminary results been obtained and presented in various international meetings (e.g., Spann et al., 2000). Plans are under consideration for supplementing the existing apparatus with optical and cryogenic facilities for measuring the optical characteristics of levitated single dust grains of known composition under controlled pressure/temperature environments. The developing laboratory facility will be employed for measurements of extinction coefficients and scattering characteristics of dust grains considered to be suitable for development of the proposed propulsion systems employing magnetic balloon concepts. The experimentally determined data of optical characteristics of dust grains of desired composition, size, and shape will permit radiative transfer modeling of the solar radiation for accurate estimation of the total thrust on the magnetic balloon in varying space environments.

A pictorial view of the laboratory facility at MSFC shown in the second panel of figure 2, employs an innovative experimental technique that permits suspension of single test particles in an electrodynamic cavity (e.g., Davis, 1985; Spann, 1985). The experimental apparatus is divided into three functional groups: the particle generator, the particle container, and the radiation source and detector. The particle generator utilizes inductive charging to produce a charged particle. A solution of the particle to be studied is placed in a tube, sealed at one end with a metal plate containing an orifice and injected at the other with a piston. The particle container is known as an electrodynamic balance or a quadrupole trap (Davis, 1985). An alternating electric field is applied between a ring electrode and two cap electrodes as shown schematically below. For a charged particle in the trap volume, the time-averaged electric field, coupled with the particle's inertia, causes it to be confined to a null point of lowest potential. For experiments requiring vacuum, the particle generator is removed and the trap is evacuated to $p < 10^{-5}$ torr. Once the particle is trapped, it is balanced at the null point of the trap by adjusting the potential between the top and bottom electrode. Measurements of the parameters required for balancing and suspension of the dust particle permits calculation of the charge, mass and size of the particle.

Polarized tunable laser light sources detectors, combined with a tungsten lamp blackbody light source will be used to measure the optical characteristics of test dust particles in the visible and infrared spectral range. Comparison of the measured scattered light as a function of angle to that computed from Mie theory will be used to determine the index of refraction and particle size. The Mie scattering program of Wiscombe (1979) will be used to perform the data inversion in order to determine the optical properties and size of the particle. The computations of the intensity functions employing Mie theory, with measurements of the scattered intensities as a function of angle, permit calculations of the scattering phase matrix and the Stokes parameters providing information about the angular distribution of radiation scattered by the dust grain and the polarization characteristics.

5 Conclusions

It is still too early to judge whether a dusty plasma sail can survive the rigors of space. Yet without a doubt, dusty plasmas push the technology of mass loading into heretofore unexplored regimes of low mass loading. If we are able to master the technology, we will have found a new material that may someday power the fleets of interplanetary spacecraft in the solar system.

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