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Radiation pressure measurements on micron-size individual dust grains

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[1] Measurements of electromagnetic radiation pressure have been made on individual silica (SiO_2) particles levitated in an electrodynamic balance. These measurements were made by inserting single charged particles of known diameter in the 0.2- to 6.82-μm range and irradiating them from above with laser radiation focused to beam widths of ~175–400 μm at ambient pressures $\sim 10^{-3}$–10^{-4} torr. The downward displacement of the particle due to the radiation force is balanced by the electrostatic force indicated by the compensating dc potential applied to the balance electrodes, providing a direct measure of the radiation force on the levitated particle. Theoretical calculations of the radiation pressure with a least-squares fit to the measured data yield the radiation pressure efficiencies of the particles, and comparisons with Mie scattering theory calculations provide the imaginary part of the refractive index of SiO_2 and the corresponding extinction and scattering efficiencies. *INDEX TERMS:* 2129 Interplanetary Physics: Interplanetary dust; 2194 Interplanetary Physics: Instruments and techniques; 6015 Planetology: Comets and Small Bodies: Dust; 5759 Planetology: Fluid Planets: Rings and dust; 6213 Planetology: Solar System Objects: Dust; *KEYWORDS:* cosmic dust, interstellar dust, radiation pressure measurements, electrodynamic for radiation pressure measurements, radiation pressure measurements on individual dust grains

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1. Introduction

[2] Dust grains in astrophysical environments exposed to radiation from nearby sources experience a pressure that is proportional to the radiation intensity, the projected surface area, and the extinction properties of the dust grains. The dynamical evolution and the physical state of dust particles are determined by gravitational and radiation effects. Particles with β = (total radiation force/gravitational force) greater than 1 experience an outward force and move away from the radiation source. For example, small submicron particles of chondritic density, sometimes referred to as β-meteoroids, are believed to be expelled from the solar system by the radiation pressure [e.g., *Spitzer*, 1968; *Dohnanyi*, 1978; *Harwit*, 1998; *Jayaraman and Dermott*, 1996] as indicated by the evidence provided by Pioneer 8 and 9 data analysis [*Berg and Grün*, 1973]. The radiation force may lead to a decrease in the angular momentum of the particle as a result of the absorption and asymmetric reradiation, known as the Poynting-Robertson drag [e.g., *Harwit*, 1998], producing an orbital spiraling of the particles toward the Sun. Radiation pressure has also been considered as a mechanism for an induced "windmill" effect, leading to a possible rotational bursting and an eventual loss mechanism of particles from stellar systems. Fragmentation by collisional processes or possibly by rotational bursting may reduce the particle sizes to critical values when the radiation pressure exceeds the gravitational attraction to drive them out of the solar system [*Paddack*, 1969; *Misconi*, 1993]. Near luminous stars the radiation pressure may be very much larger than the inward gravitational force. For very early phases of massive stars the radiation pressure on the dust grains may be large enough to reverse the dynamical collapse [*Henning*, 1996]. Radiation pressure also plays an important role in the evolution and dynamics of interstellar clouds and the intergalactic medium. Bright galaxies exerting a force on nearby dust grains that exceeds the gravitational force may lose a significant fraction of their metals through the ejected dust to the intergalactic medium, thus possibly leading to the observed loss of a substantial fraction of the metals from the galaxies [*Aguirre et al.*, 2001; *Weingartner and Draine*, 2001].

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[3] Radiation pressure measurements on large objects may be made relatively easy, and the concept is currently being investigated and developed for solar sail technologies for advanced propulsion systems. The concept of dusty plasma solar sails driven by solar electromagnetic radiation pressure on dust grains in a plasma confined in a magnetic balloon is also under theoretical and experimental investigation [*Sheldon et al.*, 2002]. Measurements of radiation pressure and light scattering by laser-levitated micron-size dust grains have been made in recent years by using single-beam or two-beam optical traps, sometimes referred to as "optical tweezers." This optical trapping technique is based on a transverse gradient of light that exerts a force that pushes the particle toward the maximum light intensity in addition to the force directed along the laser beam [*Ashkin*, 1970, 1992; *Ashkin and Dziedzic*, 1971, 1980; *Misconi et al.*, 1990; *Musick et al.*, 1998]. The retrieval of radiation pressure and extinction efficiencies of the particles, however, is based on complex calculations that involve a number of uncertainties.

[4] The feasibility of making radiation pressure measurements in an electrodynamic balance has been shown by *Davis et al.* [1990]. This technique presents a straightforward method of making radiation pressure measurements on individual micron-size particles in an electrodynamic balance that permits levitation of small charged particles in simulated space environments. The radiation force exerted on the particle is directly measured by balancing it with an electrostatic force. A brief summary of the experimental technique, the basic equations, and some measurements on SiO_2 particles is given in the following sections.

2. Experimental Setup for Radiation Pressure Measurements

[5] The experimental apparatus employed here for radiation pressure measurements is based on an electrodynamic balance that has been described in detail in previous publications [e.g., *Davis*, 1985; *Spann et al.*, 2001; *Abbas et al.*, 2002a, 2002b]. The electrodynamic balance or quadrupole trap employed in the existing apparatus consists of a top and bottom cap electrode and a central ring electrode of hemispherical and cylindrical configurations, respectively. With the top and bottom electrodes kept at opposite dc potentials and the ring electrode at an ac potential, a null potential is produced at the geometric center of the electrodes. An individually charged particle inserted into this configuration is stably trapped under appropriate conditions and may be subjected to a wide variety of experiments simulating space environments. A schematic of the experimental apparatus employed for radiation pressure measurements is shown in Figure 1.

[6] The dust particles are inserted into the balance with a particle generator that utilizes a pressure pulse to form a liquid stream containing insoluble particles through a 15- to 20-μm orifice. A dust particle in the stream is charged inductively as it enters the region of a high static electric field, with the liquid evaporating and leaving the particle charged positively or negatively.

[7] The levitated particles are illuminated with the laser light from above or alternatively with a low-power (15 mW) He-Ne laser from the side and imaged on a monitor with a CCTV camera using a zoom lens. The particle position is adjusted to a fixed point on the screen, representing the null point of the balance by varying V_{dc} manually. A detailed description of the experimental setup of the electrodynamic balance employed in the measurements discussed in this paper has been given by *Spann et al.* [2001] and *Abbas et al.* [2002a, 2002b].

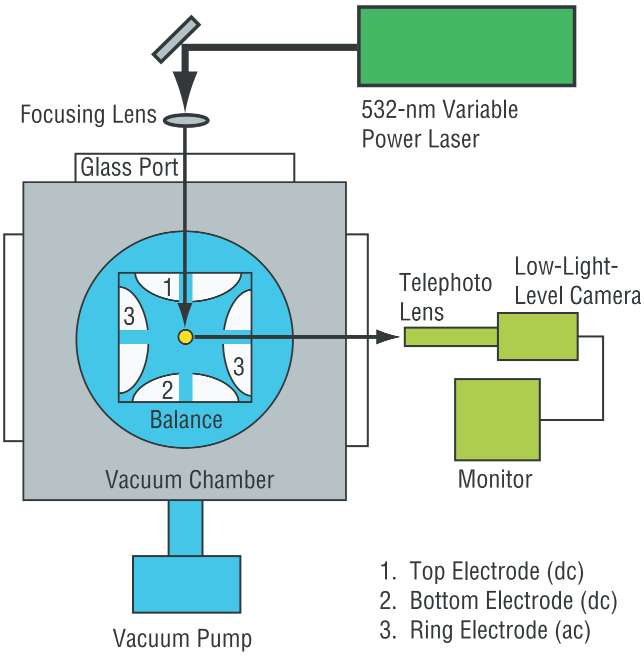

Figure 1. Schematic of the experimental setup for radiation pressure measurements on an electrodynamic balance.

3. Basic Equations of an Electrodynamic Balance

[8] A brief summary of the basic theory and the equations employed in the radiation pressure measurements presented in this paper is given here for convenience. The electrodynamic balance consists of a top and a bottom hemispherical electrode with dc potentials, $\pm V_{dc}$, and a central ring cylindrical electrode with an alternating potential, $V_{ac} \cos \Omega t$ of angular frequency $\Omega = 2\pi f$. The applied potentials in this configuration produce a null electric field at the center of the balance cavity at a distance, z_0, from the top or the bottom electrode. A charged particle injected by suitable means discussed in the references is stably trapped in the cavity for a range of variables, referred to as "field strength" and "drag" parameters, determined by the particle characteristics and the electrical parameters and defined, respectively, as

$$\beta = \frac{2g}{C_0 z_0 \Omega^2} \frac{V_{ac}}{V_{dc}} \tag{1}$$

$$\xi = \frac{18\eta}{\rho \Omega D^2}, \tag{2}$$

with

$$\frac{q}{m} = \frac{g z_0}{C_0 V_{dc}}, \tag{3}$$

where η is viscosity of air, ρ is mass density of the particle, C_0 is a geometric constant experimentally determined to be = 1.1, z = 0.750 cm, and g is the gravitational acceleration. The quantities V_{ac}, V_{dc}, and $\Omega = 2\pi f$ in equations (1) and (2) and the charge-to-mass ratio (q/m) in equation (3) are directly measurable quantities for a trapped particle. Detailed discussions of the basic equations and the stability conditions have been given elsewhere in several publications [e.g, *Davis*, 1985; *Spann et al.*, 2001; *Abbas et al.*, 2002a, 2002b].

3.1. Basic Equations for Radiation Pressure Measurements

[9] The radiation pressure measurements using an electrodynamic balance are based on its capability to provide direct evaluation of the charge-to-mass ratio of the levitated particles with the dc voltage required to balance the gravitational force, $F_g = mg$. In the absence of any radiation pressure on the particle, the charge-to-mass ratio is given by equation (3). However, if the dust particle is subjected to an additional downward force from above in the form of radiation force, F_{rad}, an adjustment in the dc voltage is required to bring the particle position back to the balance center. Equation (3) may then be written in a modified form as

$$\frac{q}{m} = \frac{gz_0}{C_0 V_{dc}} + \frac{(F_{rad}/m)z_0}{C_0 V_{dc}}, \quad (4)$$

or simplified to

$$\frac{q}{m} = \frac{z_0}{C_0 V_{dc}}(g + g'), \quad (5)$$

with $g' = F_{rad}/m$.

[10] The radiation force, F_{rad}, on the dust particle may thus be determined experimentally by making measurements of V_{dc} with and without the radiation on the particle and solving for F_{rad} with

$$F_{rad} = F_g \frac{\Delta V_{dc}}{V_{dc_0}}. \quad (6)$$

[11] The radiation force may also be calculated from the measured values of the total laser radiation power, the beam width, and the particle diameter with the expression

$$F_{rad} = \frac{E}{c} A_d Q_{pr}, \quad (7)$$

where $E = P/(\pi D_{beam}^2/4)$ is the radiation intensity with P as the laser power and D_{beam} as the beam width, c is the velocity of light, A_d is the projected surface area of the particle, and Q_{pr} is the radiation pressure efficiency. Substituting the numerical values, we have

$$F_{rad} = 3.33 \times 10^{-12} P_{mw} \frac{D_d^2}{D_{beam}^2} Q_{pr} \quad (N), \quad (8)$$

where P_{mw} represents the laser power in milliwatts and D_d is the particle diameter. Radiation pressure measurements on the basis of equation (4) were made on the balance on SiO_2 particles and are discussed in section 4.

4. Measurements

[12] The measurements of electromagnetic radiation pressure discussed in this paper were made on spherical SiO_2 particles of predetermined diameters in the 0.2- to 6.82-μm range, obtained from Bangs Laboratories, Fishers, Indiana. Negatively charged individual particles were inserted and brought to a stable levitation in the balance center by adjustment of the magnitude of the ac and dc potential and frequency of the ac potential. An evacuation procedure is started to achieve the particle chamber pressure on the order of 10^{-3}–10^{-4} torr, and the particle position is readjusted to the balance center. Radiation from a Spectra-Physics Millennia II*s* laser at a wavelength of ~5320 Å directed from above was focused to experimentally determined beam widths of ~400–175 μm at the levitated particles. The laser was turned on and off with the power adjusted to provide successively higher radiation intensities incident at the particle. The incident laser radiation exerts a downward force, F_{rad}, on the particle, causing a downward drift of the particle. The dc potential, V_{dc}, is adjusted to compensate for the change in the position of the particle and the radiation force is calculated by using equation (6). Since the work function of SiO_2 is higher than the photon energy of the incident radiation, no change in the particle charge is expected when the laser is turned on, as verified by checking the initial conditions for each laser power. The range of radiation flux over which the measurements can be made in the current setup is limited on the lower side by the minimum measurable force in the current configuration of the balance and the sensitivity of the dc voltage measurements and on the upper side by the temperature of the particle at which physical changes begin to take place due to the absorbed radiation power.

[13] Selected plots of the measured values of the radiation force (equation (6)) exerted on 0.2- to 6.82-μm-size SiO_2 particles as a function of the radiation intensity incident on the particle are shown in Figures 2a–2f by the dots, indicating a linear relationship between the two quantities as expected. The solid line shows a plot of the theoretical radiation force obtained by using equation (8) with a radiation pressure efficiency, Q_{pr}, provided by a least-squares fit to the measured data. The value of Q_{pr} inferred for each particle size is shown in Figures 2a–2f. The average radiation pressure efficiencies are seen to increase from ~0.22 ± 0.01 for particles of ~0.25-μm size to 1.14 ± 0.07 for particles of 6.82-μm size. A summary plot of the calculated and measured radiation force for all particles of D = 0.25 to 6.82 μm is shown for comparison in Figure 3. The error bars shown on the plots are based on the estimated uncertainties in the directly measured quantities, such as V_{dc}, the laser beam width, and the laser power. Uncertainties in the particle diameters and the effects of any departure from the assumed spherical shapes of the particles as indicated by Bangs Laboratories have not been included. The effects of departures from nonspherical shapes of the particles may be inves-

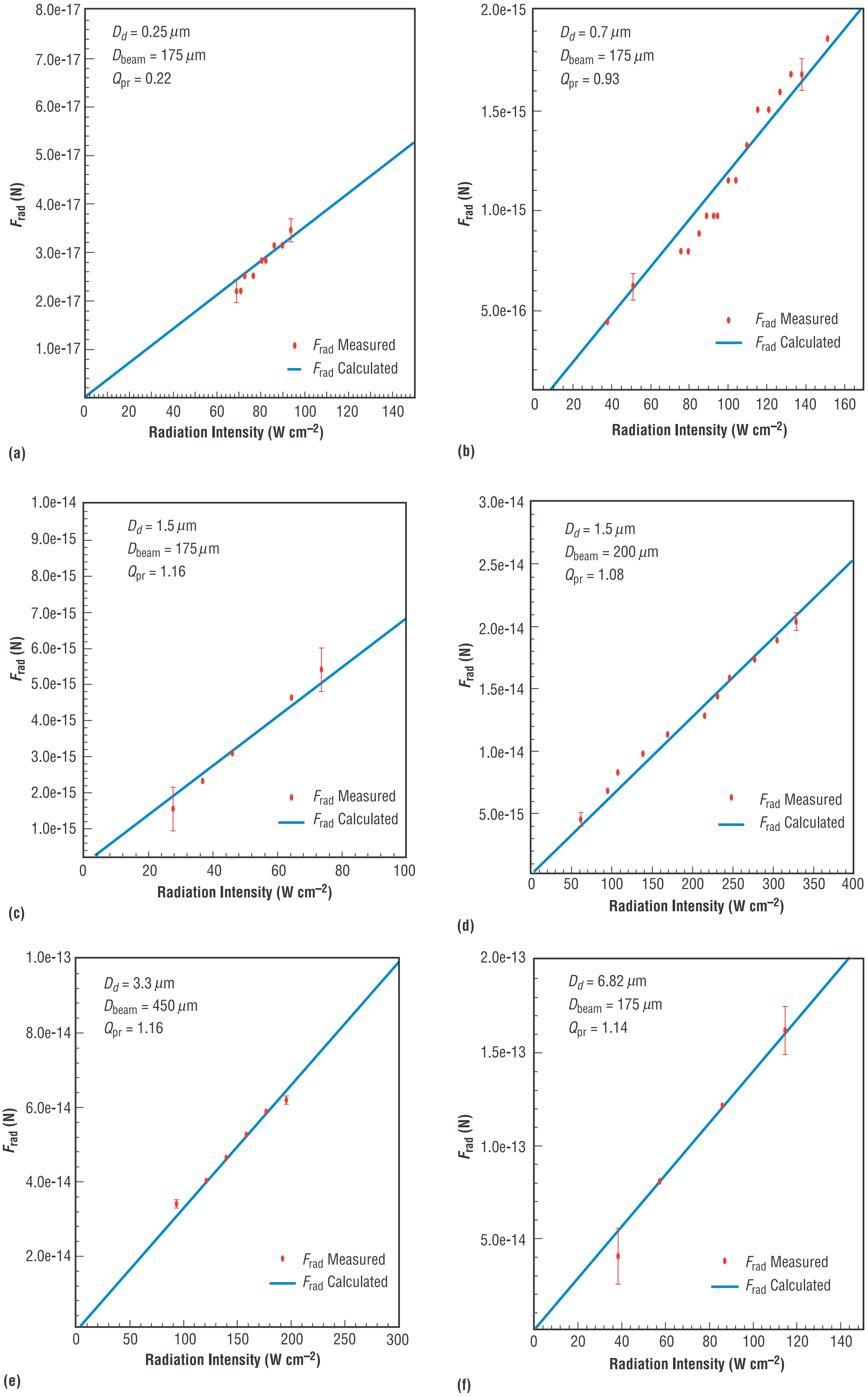

Figure 2. Measured and calculated radiation force as a function of the radiation intensity, exerted on individual SiO_2 particles of D = 0.2- to 6.82-μm size irradiated with a laser radiation at a wavelength of 0.5320 μm focused to beam widths of D_{beam}. The radiation pressure efficiency, Q_{pr}, required to provide a least-squares fit to the measured values with the calculated radiation force is indicated.

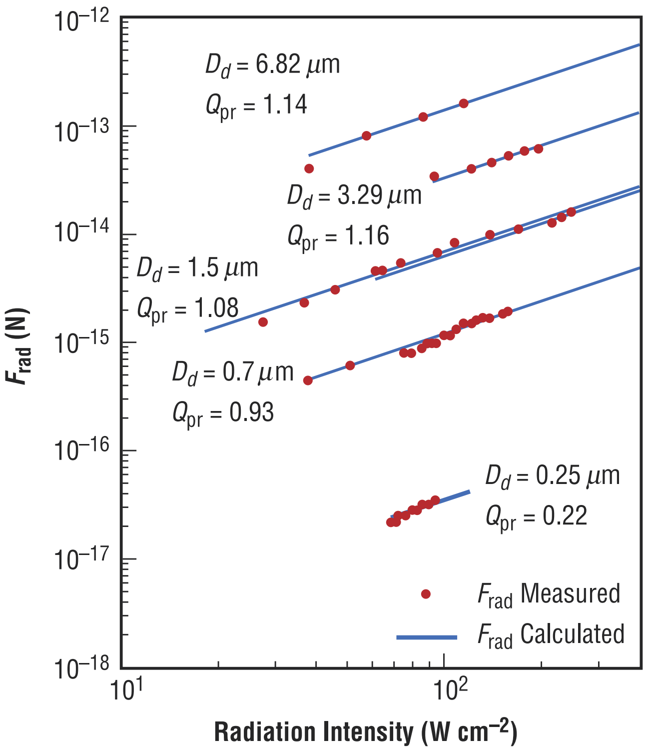

Figure 3. A summary plot of the calculated and measured radiation force for all particles of D = 0.25- to 6.82- μm shown for comparison.

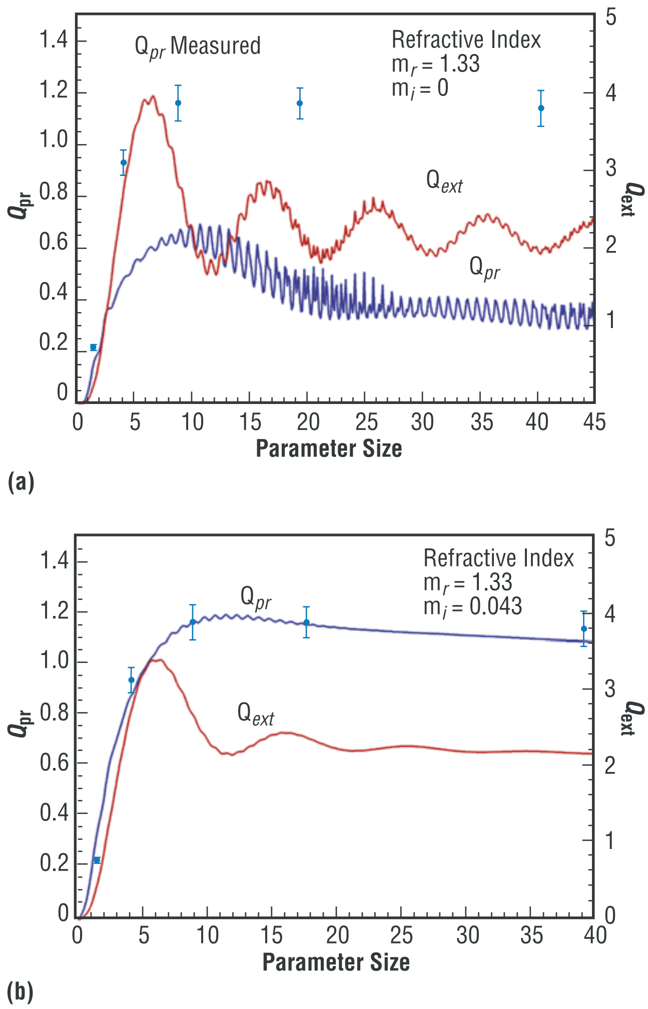

Figure 4. (a) Plots of the radiation pressure and extinction efficiencies, Q_{pr} and Q_{ext}, as a function of the size parameter, $x = 2\pi r/\lambda$ for m_r = 1.33 and m_i = 0. The experimentally determined values of Q_{pr} for the SiO_2 particles are shown for comparison. The Mie theory resonance structure seen in this plot should be measurable by this technique for particles with high m_r but small m_i. (b) Same as in Figure 4a except with an inferred m_i = 0.043 to provide a least-squares fit to the Mie scattering theory calculations. The resonance structure for this case appears to have smoothed out.

tigated with availability of suitable particles for such investigations.

4.1. Comparison With Theoretical Calculations

[14] When a beam of light is incident on a particle, a part of the light proportional to the cross section C_{abs} is absorbed and a part proportional to the cross section C_{sca} is scattered in all directions. The total attenuation in intensity or the part that is removed from the beam in the forward direction is proportional to the extinction cross section, $C_{ext} = C_{abs} + C_{sca}$. The cross sections per unit areas are referred to as the absorption, scattering, and extinction efficiencies, defined respectively as $Q_{abs} = C_{abs}/\pi r^2$, $Q_{sca} = C_{sca}/\pi r^2$, and $Q_{ext} = C_{ext}/\pi r^2$, where r is the radius of the particle. The incident radiation or photons exert a force or radiation pressure on the particle that depends on the absorption and scattering properties of the particle. The radiation pressure efficiency, Q_{pr}, expresses the efficiency of momentum transfer from the radiation to the particle and may be written in a simple form as $Q_{pr} = Q_{ext} - \langle\cos\theta\rangle Q_{sca}$ where $\langle\cos\theta\rangle$ is referred to as the "asymmetric factor" and represents the average cosine of the scattering angle. The Mie scattering theory, however, provides a rigorous means of calculating the extinction, scattering, and radiation pressure efficiencies [e.g., *Van de Hulst*, 1957; *Kerker*, 1969; *Wiscombe*, 1979; *Bohren and Huffman*, 1983]. We have used the numerical program of *Wiscombe* [1979] for calculations discussed in this paper,

Table 1. Comparison of Mie Scattering Theory Calculations of Radiation Pressure Efficiencies of SiO_2 Particles With the Known Value of m_r = 1.33, the Experimentally Determined Value of m_i = 0.0425, and the Measured Radiation Pressure Efficiencies on the Electrodynamic Balance

Particle Diameter, μm	Size Parameter, x	Calculated Extinction Efficiency, Qext	Calculated Scattering Efficiency, Qsca	Calculated Radiation Pressure Efficiency, Qpr	Measured Radiation Pressure Efficiency, Qpr
0.25	1.47	0.33	0.16	0.28	0.22
0.70	4.10	2.75	2.12	0.94	0.93
1.50	8.80	2.66	1.66	1.21	1.12
3.29	19.35	2.36	1.24	1.18	1.16
6.82	40.12	2.17	1.11	1.09	1.14

with the definitions of the efficiencies as given in the references and as discussed above.

[15] Mie scattering theory calculations were carried out for comparison with the experimentally determined values for the SiO_2 particles of known diameters of 0.2- to 6.82-μm size and known real part of refractive index as $m_r = 1.33$ (measured by Bangs Laboratories). Since the imaginary part of refractive index $m = m_r - im_i$ of SiO_2 at 0.5320 μm is not known, we carried out scattering calculations for each particle for a number of values of m_i in the range of 0 to 0.1. This simple procedure permits us to infer a value of $m_i = 0.0425 \pm 0.005$ with which Mie scattering theory calculations of radiation pressure provide the best least-squares fit to the experimentally determined radiation pressure efficiencies. A tabulation of the Mie theory calculations of the extinction, scattering, and radiation pressure efficiencies with the inferred value of imaginary refractive index, $m_i = 0.0425$, along with the experimentally determined values of the radiation pressure efficiencies for the SiO_2 particles, is given in Table 1. The measured Q_{pr} shown for the 1.5-μm particle in Table 1 indicates the average of the two particles represented in Figure 2.

[16] The calculated radiation pressure efficiencies for all particles of diameters in the 0.20- to 6.82-μm range (with the corresponding size parameters $x = 2\pi r/\lambda$ varying from ∼1.5 to ∼40) indicate a good fit with the measured values for an inferred imaginary refractive index, $m_i = 0.0425 \pm 0.005$, with the corresponding extinction and scattering efficiencies shown in Table 1. Table 1 shows the consistency of the radiation pressure measurements on the electrodynamic balance over a wide range of the size parameter, and indicates the technique employed here as an alternative means for retrieving extinction and scattering efficiencies of individual micron-size dust grains in astrophysical environments.

[17] Two plots based on calculations of the radiation pressure efficiency as a function of the size parameter for SiO_2 particles for two cases with the imaginary refractive index, $m_i = 0$ and $m_i = 0.0425$, are shown in Figures 4a–4b along with the experimentally determined values. Figure 4a with $m_i = 0$ shows a large discrepancy between the calculated and the experimental values while Figure 4b shows a generally good agreement over the entire range of the size parameter. The calculated values in Figure 4a exhibit a ripple or resonance structure indicated by the Mie scattering theory [e.g., *Van de Hulst*, 1957; *Kerker*, 1969]. The resonances are believed to be due to the interference between the diffracted wave and surface waves on the dielectric spheres and have been observed in the laboratory on optically levitated dielectric particles and oil droplets with refractive indices ∼1.2–2.0 [e.g., *Ashkin and Dziedzic*, 1977, 1981; *Chylek et al.*, 1983; *Chylek*, 1990]. Experimental determinations of the interspacing of resonance locations are the subject of investigations as an accurate means for determining the particle size and for studies of the surface physics of dielectric spheres. The resonance structure is damped out by absorptions with a high imaginary refractive index of the material, as in Figure 4b, with $m_i = 0.0425$.

[18] The resonance structure for materials with lower values of m_i could be observed with the measurement technique presented here by varying the size parameter by changing the wavelength with sufficiently high resolution and covering a few peaks of the resonance structure.

5. Conclusions

[19] The experimental data presented in this paper demonstrate the usefulness of the electrodynamic balance for making direct radiation pressure measurements on individual micron-size dust particles of astrophysical interest in simulated space environments. The method employed is inherently simple and is based on direct measurement of the radiation force on a levitated particle by balancing it with the measurable electrostatic force on the particle. Mie scattering theory calculations of the radiation pressure on a number of SiO_2 particles with known real part of refractive index, $m_r = 1.33$, and unknown imaginary refractive index, m_i, and with size parameters in the range ∼1.5 to 40 provide a good fit with the measured values for a retrieved value of $m_i = 0.0425$. Radiation pressure measurements on an electrodynamic balance thus provide an alternative means of inferring extinction and scattering efficiencies of individual micron-size dust grains in astrophysical environments.

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