NOTICE

Final Report

THE RADIATION-INDUCED ROTATION OF COSMIC DUST PARTICLES: A FEASIBILITY STUDY

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INTRODUCTION AND OVERVIEW

The objective of this feasibility study was to learn how solar radiation is able to induce high spin rates in interplanetary dust particles. Of particular interest is to look for evidence of non-statistical spin mechanisms which are capable of causing a body to spin so rapidly that the internal cohesion of the particle will become inadequate to guard against rotational bursting. This bursting into smaller particles affects the size distribution of interplanetary dust particles and so has its influence on a number of interplanetary processes of considerable interest.

In space, apart from the rare collision and random interactions with the solar wind ions, interplanetary dust particles orbit under the influence of solar gravity and solar radiation pressure. Due to the Poynting-Rohertson effect, the solar radiation does exert a dissipative force which will cause particles to spiral into the sun. However, their lifetime against destruction through this mechanism is very long. The possible existence of mechanisms, which would lead to a much shorter lifetime, through radiation-induced rotational bursting, was proposed by Radzievskii in 1954 and Paddack in 1969. Radzievskii pointed out that random albedo variations over the surface of a complex particle should be expected to give a non-zero resultant torque through a radiometric effect. Later, Paddack argued that reflection from the complicated surface geometry of a particle should also be expected to result in a net torque through a "windmill" effect.

In summary, it is suggested that random variations in albedo and geometry will give rise to a non-zero effective torque when one averages the influence of a unidirectional source of radiation (due to the sun) over the surface of an interplanetary dust particle. This non-zero resultant torque is characterized by an asymmetry factor which is the ratio of the effective moment arm to the maximum linear dimension of the body and which has been estimated to be 5×10^{-4}. It is precisely this asymmetry factor, which summarizes the non-statistical response of the particle, that we hope to measure in a future Spacelab experiment.

The orbital characteristics of an interplanetary dust particle reflect the competition between the forces of solar gravity and solar radiation pressure. In the submicron regime there will always be a crossover point at which the radiation pressure becomes dominant and expels very small particles out of the solar system. Thus, the efficiency of particle size reduction through rotational bursting will place a lifetime on the particles before they are removed from the solar nebula.

The optical forces which are exerted on a body are rarely seen under terrestrial conditions due to the competition of other forces whose influence is reduced or isolated in space. Our experimental approach is founded upon the classic studies of laser levitation techniques begun by A. Ashkin and J. M. Dziedzic in 1969 at the Bell Telephone Laboratories in Holmdel, New Jersey. To our knowledge, the laser levitation facility we have established at NASA/GSFC is the only other facility in the United States devoted to the development of these techniques. Experimental detail and our actual accomplishments is expressed later in this final report.

HISTORY OF THE PROJECT

Our feasibility study, "The Radiation-Induced Rotation of Small Celestial Bodies" (Grant NSG-7501) was funded for a 15 month period, 1 August 1978 to 31 October 1979. The Co-Principal Investigators on the project were both affiliated with the Space Astronomy Laboratory (then located in Albany, New York, and presently located in Gainesville, Florida) though the actual experimental work was carried out at the Goddard Space Flight Center in Greenbelt, Maryland, in facilities generously loaned to us by the staff of the GSFC. Our experiment was located in new facilities under construction at the Optical Test Site of the GSFC. Access to this new building and the beginning of assembly of equipment was delayed until December, 1979 when the building was accepted by NASA from the contractor. Central to our experimental facility was the installation of a Spectra Physics 170 CW argon laser.

The high power requirements (5-15 W) of the laser was dictated by the necessity to counter the force of gravity in levitating particles 15-100 microns in diameter by radiation forces. The premature termination of our project was finally caused by the subsequent destruction of that laser which was jointly used with one other Goddard project.

The first four months of the project awaited access to the experimental facility under construction at GSFC. During this period, the Co-Principal Investigators made three trips to the GSFC to meet, brief, and plan with the Goddard staff members who would be responsible for the day-to-day operation of the experiment. Together we traveled to the Bell Telephone Laboratories in Holmdel, New Jersey to visit the experimental facilities of Dr. Arthur Ashkin and Mr. Joseph Dziedzic who pioneered the technique of laser levitation. We must acknowledge their most generous help as it enabled us to progress by drawing upon their unique experience.

We first gained access to our laboratory at GSFC in December, 1978 and achieved our first levitation on 17 January 1979. During the next 8 months, the Co-Principal Investigators made eight extended visits to GSFC. The accomplishments during this period are detailed in the following section of this final report. Highlights of that study were reported in August, 1979 at the IAU Symposium #90 in Ottawa, Canada, and subsequently published. We have enclosed copies of that published report.

In the summer of 1979 we designed and operated the first crossed-beam, horizontal optical trap. By using the perfect spheres provided us by high purity silicone oil drops, we were prepared to map out the dynamical dependence of our unique geometry for crossed-beam levitation. However, in September, 1979 our NASA collaborators reported that the glass tube on our Spectra Physics 170 laser had been destroyed. Repair or replacement costs of the tube was estimated by NASA as being $10,000 to $12,000. Only one other laser of similar power was available at GSFC. For a 3-month period (November, 1979 through January, 1980), this laser was released to us between scheduled experiments. Our equipment was reassembled at the location of the replacement laser; however, our Goddard colleagues were unable to make the necessary measurements on the silicone oil drops before the laser had to be relinquished in January, 1980.

Three no-cost-extension approvals to Grant NSG 7501 carried us from 1 November 1979 to 1 September 1981. During this period of time, we explored the interest other GSFC research groups might have in the refurbishing of the broken Spectra Physics 170 laser. NASA decided against this course of action because insufficient interest was expressed to justify the in-house cost of reconstruction of the high power laser. Subsequently, our research space at the Optical Test Site had to be relinquished and our experimental apparatus was disassembled and stored. With that action, we decided against a further request for yet another extension. Thus, we are submitting this final report.

PROJECT ACCOMPLISHMENTS

A. OPTICAL LEVITATION

Our initial successes in the optical levitation of small transparent spheres followed closely the technique first developed by Ashkin and Dziedzic in 1971 at the Bell Telephone Laboratories. The required laser power is dictated by the mass of the confined particle as well as by its optical properties. A 20 μm transparent glass sphere required a 250 mw CW laser (TEM_{00} mode) to achieve levitation. A 400 mw CW laser (TEM^*_{01} mode) was required to levitate 45 μm thin-walled, hollow spheres which simulate high reflectivity. In each case the laser beam was focused to a beam waist comparable in size to that of the sphere.

The confinement of the particle is a stable equilibrium in three dimensions. Any motion of the particle transverse to the beam direction brings the particle into contact with a gradient in the radiation intensity. This in turn induces a force which acts to return the particle to the beam axis. A second beam can be introduced to provide a force transverse to that of the vertical levitating beam. It is found that a laser power in this second beam, half that of the vertical beam, is sufficient to move the particle out of the vertical beam and cause it to fall. In this way we learn that the transverse force exerted on the sphere by the laser is half that of the longitudinal force.

A modification of Ashkin's facility was established at the Optical Research Facility of the Goddard Space Flight Center in Greenbelt, Maryland. We first achieved optical levitation there on January 17, 1979 using transparent spheres of suprasil. We have worked almost exclusively with particles of suprasil and Flexolite which are described later. In addition to single particles, we have levitated clusters of two and three spheres which are stuck together by electrostatic forces. On May 4, 1979, we levitated our

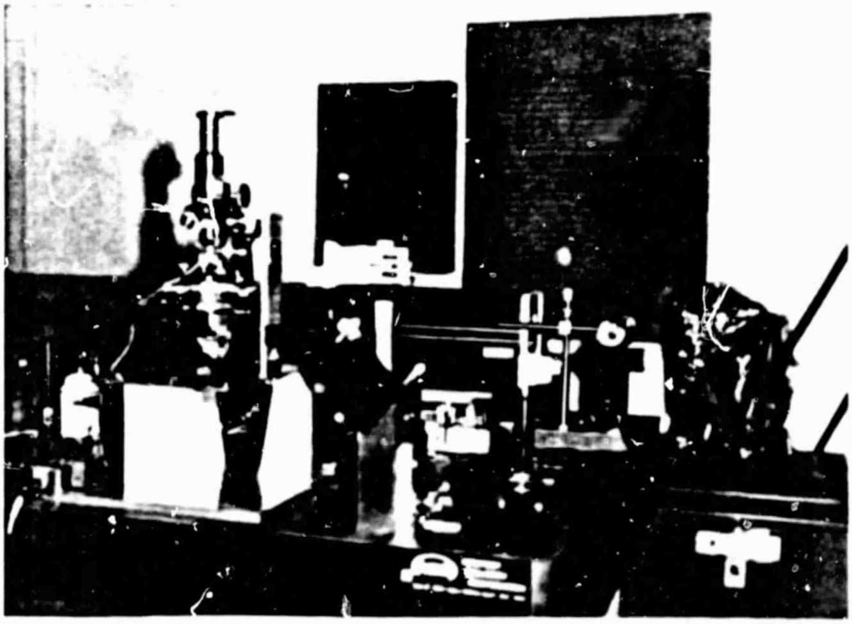


Figure 1. Laser levitation apparatus at Optical Test Facility at GSFC.

most irregular particle (to date) which had a length/width ratio of at least two and numerous flattened surfaces. Our levitated particles have ranged in size from 15 μm to 70 μm and have utilized argon laser beams that range from 350 mw to 5.3 W. We have levitated two 20 μm particles simultaneously in the same beam with a vertical separation of 400 μm.

It has been our experience that in air the complex particles, irregulars or clusters of spheres, are more stable than many of the nearly spherical particles. Clearly, the equilibrium position of a particle is achieved when it intercepts and refracts just enough light from the diverging vertical beam to overcome its weight. Thus, the equilibrium position may vary very rapidly with the orientation of a particle in the beam if that particle is very rough. Under these conditions we would expect that a rough particle will come to rest with an orientation which corresponds to an equilibrium position closest to the vertical focus. However, we have seen many cases in which the irregular particles may be induced to undergo a sudden rotation of 90° or 180° to a new stable orientation. Thus, these particles may often settle into orientations which are stable but are only local minima in the potential energy as a function of orientation.

In contrast, the simpler, nearly spherical particles are frequently very active. Rotation rates of 1-10 HZ are common.

Slightly less common are vertical oscillations during rotation. But, these are occasionally violent with the particles moving as much as 20 particle diameters in vertical displacement. Later, we will see that our Flexolite spheres frequently have small micron size crystals growing out of the otherwise smooth spherical surface. Such small scale irregularities will in turn cause local irregularities in the dispersion of the light emerging from the otherwise spherical surface. Such local concentrations (or rarifications) of the light will give rise to local hot (or cold) spots on the particle surface. The ambient atmosphere can react to these thermal gradients and drive the particles in the manner described above. Since these particles are close to spherical, their equilibrium position varies very little with orientation, and these thermal forces can more easily overcome small differences in orientation and drive these particles in a quasi-continuous manner.

We should stress that the above-mentioned rotation is not the result of one of the spin mechanisms that we wish to eventually study. The viscous drag of the air is most effective in damping out either rotational or translational kinetic energy of our particles. Indeed, the Paddack or Radzievskii effects would never be seen under conditions of atmospheric pressure. But, the thermal effects we cite above depend upon the air for their operation. In fact, we see that these effects increase in strength as we begin to reduce the pressure and peak at about 1 Torr. They disappear at lower pressures.

The force exerted by a diverging laser beam on a particle depends on both, the amount of light intercepting the particle and the angle through which the light is bent. Indeed, as the power of the vertical beam is varied, the particles will move many particle diameters along the beam axis relative to the focal point. As the focal length of the lens intercepting the vertical laser beam is shortened, the opening angle of that beam increases and the equilibrium position of the particle will move closer to the focal point so that it intercepts the necessary amount of light. Simultaneously, the larger opening angle means a smaller intensity gradient as we move transverse to the beam axis and, therefore, weaker transverse confinement. A sufficiently small beam divergence is thus necessary both for levitation and confinement of the particle. We found it useful to work with lenses between 48 mm to 80 mm in focal length which guaranteed an angle of divergence of less than 1°.

The angle through which the light is bent depends upon the curvature of the entering and exiting surfaces of the particle. The radiation force exerted on a sphere is almost maximal because of the high curvature of every part of the surface. Indeed, this is why clusters of spheres are so easy to work with. Most irregular particles which are created by crushing have some flattened surfaces, and these give rise to reduced radiation forces. Indeed, we find that platlet-type particles are virtually impossible to confine and levitate. There is reason to believe that the confinement problem for such particles will be easier with the anti-parallel configuration described in the next section.

B. CROSSED-BEAM CONFINEMENT

The sun provides interplanetary dust particles with a unique, unidirectional source of light. The challenge of our eventual Spacelab experiment will be to predict the response of these particles to this light source through their geometrical and albedo irregularities, i.e., the Paddack and Radzievskii spin mechanism. We note these effects may be distinguished from each other in that the spin axis from the Paddack mechanism should be expected to be predominantly aligned with the direction of the incident radiation, while that from the Radzievskii mechanism should be normal to the incident radiation.

The facts argue that in the design of a Spacelab experiment, the particles should be exposed to a unique radiation direction. Furthermore, this light which is responsible for the angular acceleration of the particles must also be responsible for their confinement to a localized region of space.

These seemingly conflicting requirements can be simultaneously realized by creating an "optical bottle" out of the region of space between the foci of a pair of anti-parallel laser beams. If the particle is located between the two foci, then there is an axial restoring force that serves to trap the particle between the foci. If the pair of beams is identical, then the symmetry point P is in fact a point of 3-dimensional equilibrium for the sphere. In order for this to be a stable equilibrium, the beam axis must be a local maximum for highly transparent particles. For highly reflective particles the beam axis should be a local minimum. The beam axis maximum may be achieved by a laser operated in TEM_{00} (gaussian) mode while the beam axis minimum is achieved by a laser operated in TEM^*_{01} (donut) mode.

Optical confinement in air and vacuum by such an anti-parallel beam configuration had never been demonstrated and was a central thrust of our current research. Our attack on this problem has been through the use of the experimental setups (shown in Figure 2) which incorporate both, optical levitation and crossed-beam confinement. In brief, a particle is levitated in the vertical beam and is then raised to the point of intersection with the horizontal beams by a vertical displacement of lens L_1. The variable neutral density mirror (NDM1) is then rotated to transfer power from the vertical beam to the horizontal beams. When sufficient power is in the horizontal beams, the particle will be supported vertically by the transverse component of the force exerted by the horizontal beams and the vertical beam can then be eliminated.

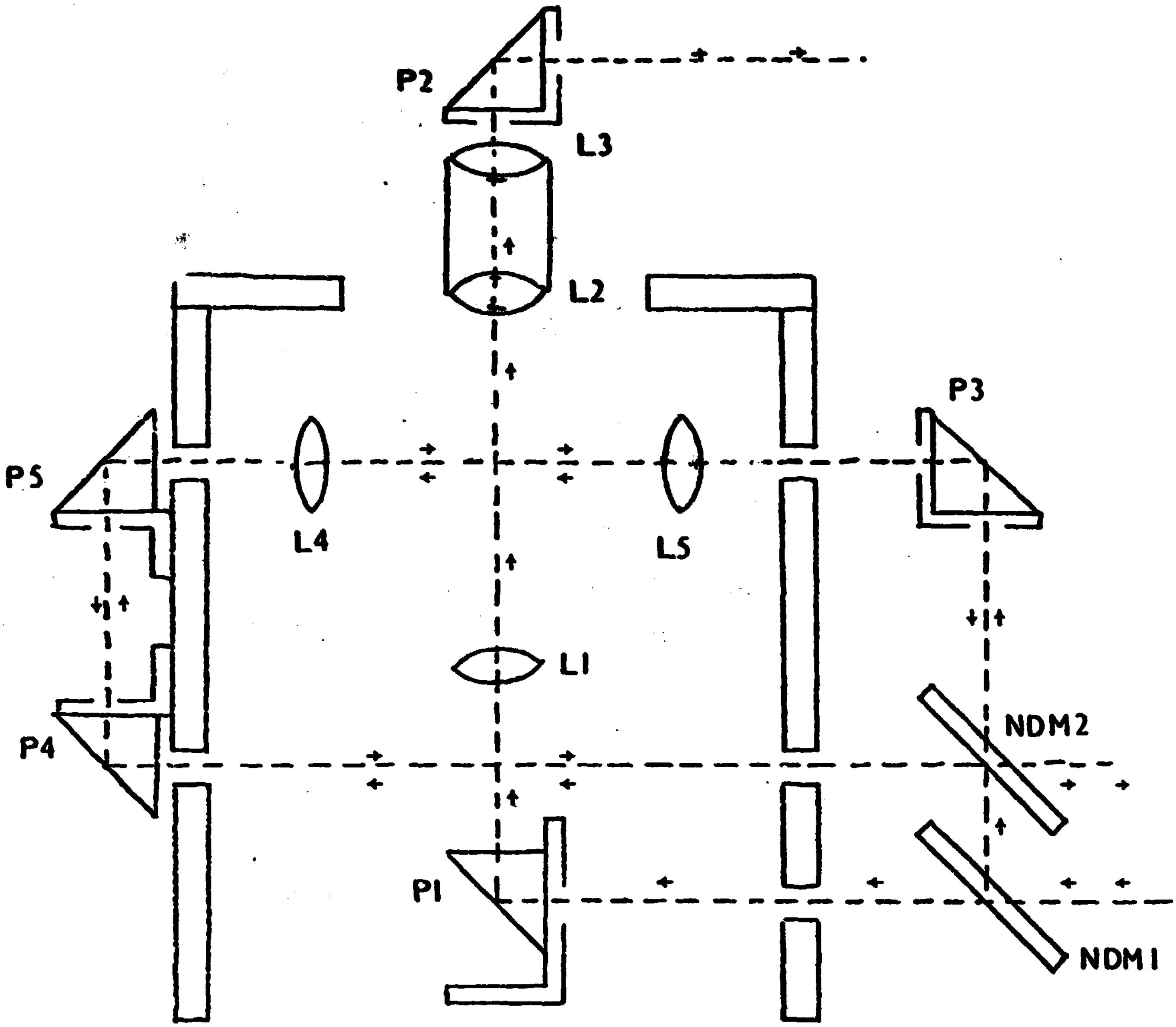


Figure 2. Schematic design of the beam system used in our experiment for optical levitation and crossed-beam confinement. Shown are the lenses (L_1-L_5), prisms (P1-P5), and neutral density mirrors (NDM1,2) which are used as beam splitters.

The beam waist of each of the three beams is about 50 μm at focus. At this point, the alignment of the system is delicate. Crude alignment and separation of the horizontal foci is first achieved by filling the particle glass scattering chamber with smoke to make the beams visible. Both horizontal beams make complete roundtrips and emerge on their return from NDM2. When these beam images are made to coincide, then the horizontal beams are guaranteed to be superimposed between lenses L_4 and L_5. The residue of the smoke must be carefully cleaned from the walls of the chamber. Final alignment is achieved by levitating a particle and raising it, (using L_1) to the point of intersection where lenses L_4 and L_5 record an image of the particle as well as of the horizontal beams. A superposition of these four images completes the alignment.

When the variable neutral density mirror (NDM2) is rotated, this changes the ratio of the power incident upon the particle from the left and the right. An oscillation of this mirror then displaces the particle back and forth in the vertical beam. The effect of the horizontal beams is also seen in the non-linear response of the particle to vertical displacements of L_1. As L_1 is raised, the particle initially remains at the intersection point until the displacement of L_1 is sufficient enough to induce a sudden jump some two or three particle diameters above the horizontal beam of the particle. After reversing the motion of L_1, the particle reverses its discontinuous behavior and jumps suddenly into the point of intersection.

The procedure outlined on the previous page succeeds in a proper intersection of the beams; however, the real effort is the one necessary to insure conjunction of the optical trap. To achieve this we created a triangular glass scattering chamber as shown in Figure 3. The particle P is suspended in a vertical beam (coming out of the page in Figure 3). The 90° scattering of the vertical beam results in beams

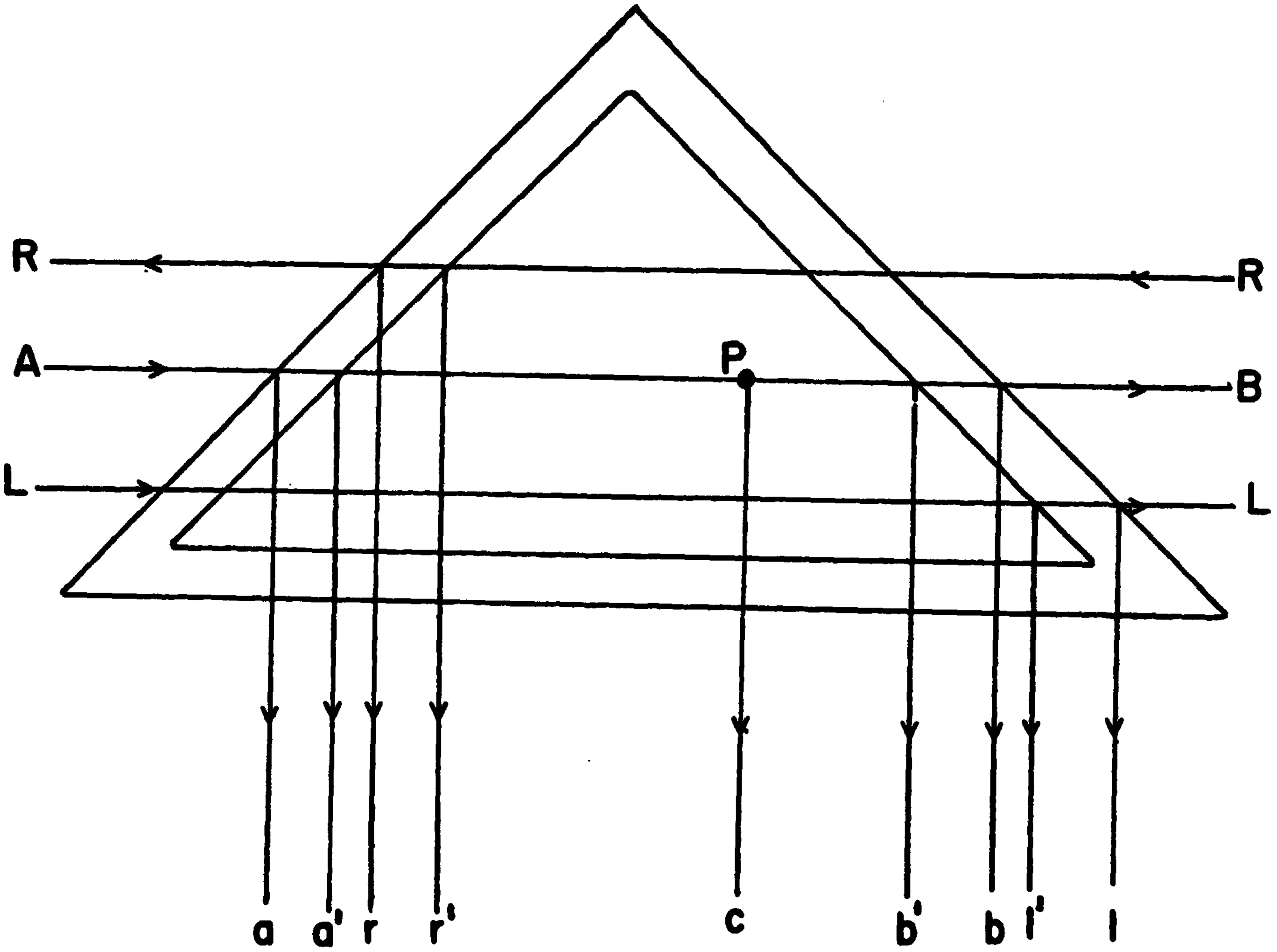


Figure 3. The triangular scattering chamber used for final alignment of the beams.

A, B, and C. Beams A and B are each reflected 90° at air-glass interfaces. Each of these reflected images carries 4% of the incident radiation. Thus, a total of five images of the levitated particle pass through the hypotenuse of the scattering chamber where they are observed with a microscope. The horizontal Beams L and R approach the particle from the left and right sides, respectively. The images of these horizontal beams likewise produce images through the hypotenuse by means of the 4% reflected intensity. We denote these image pairs by r,r' and L,L'. As pictured in Figure 3, the side beams R and L are imagined to be close, but not coincident with the particle. Thus, the reflected beam images would appear as bright, empty spots. When the side beams R and L are translated to intersect particle P, success will be registered by the coincidence of beam images r,r', L,L' with particle images a,a', b,b', respectively.

As the lenses responsible for the foci of beams R and L are moved back and forth, the size of the beam waist from R and L at the location of particle P will change. This change is easily seen in the five particle images we monitor. Minimizing the beam image size around the particle image pairs a,a' and b,b', thus locates the foci of R and L, respectively, at the particle. Backing off the side lenses a given amount then creates the horizontal optical trap with particle P reliably located between the foci of R and L. This method proved to be the most reliable and quickest of any other scheme that we developed and investigated for locating a particle in a horizontal trap.

The particle in the optical trap can then be used to test the properties of that trap. By rotating the beam splitter NDM2 (Figure 2), the particle can be displaced to the left or right within the trap. Rotation of beam splitter NDM1 transfers power from the vertical to the horizontal beam and would finally permit pure crossed beam confinement and levitation.

It should be mentioned that this is the point in the development of our experiment at which the glass tube of the laser was cracked — which subsequently proved to be a permanent loss. Simultaneously, we had built the drift tube, injector, and exit channel necessary to use silicone oil drops in the chamber described above. Silicone oil drops are free from surface irregularities and, therefore, give a particle response to the intensity gradients of the laser beam which depends *only* on particle position but not on particle orientation. As such, the silicone oil drops are ideal for mapping out the dynamical structure of the crossed-beam trap. In these measurements, the vertical beam is used as a probe to push the particle with the application of a known force through the side of the cylindrically symmetric horizontal trap. Our experiment ended at this very crucial point. If in the future we are given the opportunity to continue these investigations, it is to this point that we must immediately return.

C. THE INJECTION OF PARTICLES

The problem of injection is that of placing a free particle at rest within the optical trap which will be responsible for its subsequent spatial confinement. The injection problem has two aspects. The first is the freeing of the particle by its release from some support surface. The surfaces of the particle and support are held together by Van der Waals forces which are short-range forces arising from induced electric dipole moments. For particles, which are tens of microns in size, this electromagnetic force is some four orders of magnitude greater in strength than the gravitational force. Thus, for example, there is no way that a laser beam, of the power necessary for levitation, is by itself capable of supplying a force adequate to free the particle from its support.

The second aspect of the injection problem is removing energy from the particle so that it will remain confined by the optical trap. If the particle appraoches the optical trap from the outside, it will merely be scattered by the optical trap and will only be captured providing that energy can be removed while in the trap. Below we discuss our approaches to this problem.

1. The Acoustical Shaker

This method was first used by Ashkin and Dziedzic and it remains the principal method which we have used in our work. The particles are placed on a glass plate to which is attached a piezo-electric crystal in the form of a ring. The crystal will vibrate in response to an electric potential applied across the ring. In our experiment we sweep the applied voltage from 100 kHZ to 1MHZ five times each second. At the appropriate frequency, the particle looses contact with the glass plate, is caught in the laser beam, and is transported at rest to the desired equilibrium position by manipulation of the lens of the supporting beam.

The role of atmospheric pressure is central to the success of this injection mechanism. The particle leaves the plate with a high velocity. However, the viscosity of the surrounding medium effectively removes this kinetic energy and the particle quickly comes to rest in the laser beam. The viscosity of the air remains effective to about 1 Torr. Below this pressure, the particle merely scatters from the optical trap.

2. The Atomizer for Liquid Drops

The second proven technique is the simplest of all but is limited in use to liquid drops. In this case, we construct a double chamber which is separated by a moveable plate with a hole in it. We spray a mist from an ordinary drug store atomizer into the upper chamber. The drops quickly reach terminal velocity and some pass through the temporarily open hole into the lower chamber where they are caught in the laser beam. Our most commonly used liquid is silicone oil.

This is chosen due to its very low absorptivity and the fact that it evaporates very slowly in vacuum.

3. The Sublimating Solid Technique

The attempt here is to develop a method in which the dust particle can be released with negligible velocity under vacuum conditions. The idea is to embed the particle in a solid which will sublimate in vacuum — thus, freeing the particle. We were particularly interested in biphenyl ($C_6H_5C_6H_5$) which has been previously used in space. We ran tests of the sublimation rate of biphenyl using an Ainsworth balance under the supervision of Jim Wall of GSFC. Our first concern was to assess whether the act of sublimation might impart too great a velocity to the embedded particle. The second concern was to ensure that the microcrystals of the biphynyl were sufficiently small to permit accurate spatial location of the embedded dust particle so that they are released at a known position. Conclusions as to the usefulness of this technique must await the future continuation of this project.

D. THE OBSERVATION AND ANALYSIS OF ROTATION

1. Three Optical Signals

The information obtained about particles confined in optical traps is contained in the light which is scattered by the particles. We have found three signals to be particularly useful.

(i). Near Field Forward Scattering

The lens system, L_2-L_3 in Figure 2, constitutes a microscope which is focused on the levitated particle and thus records the near field image of the particle in the forward direction (0° scattering) with respect to the vertical beam responsible for levitation. An example of this pattern for a doublet is shown in Figure 4.

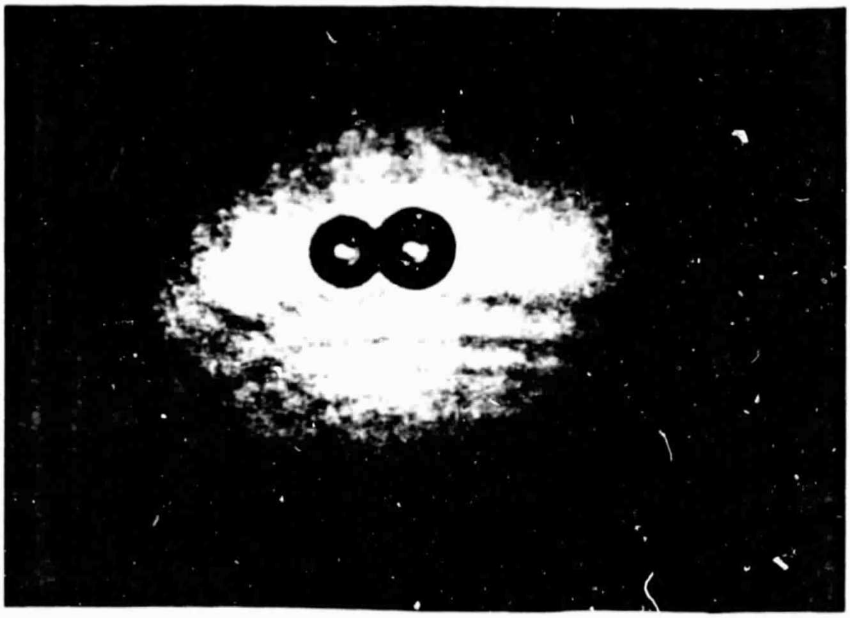
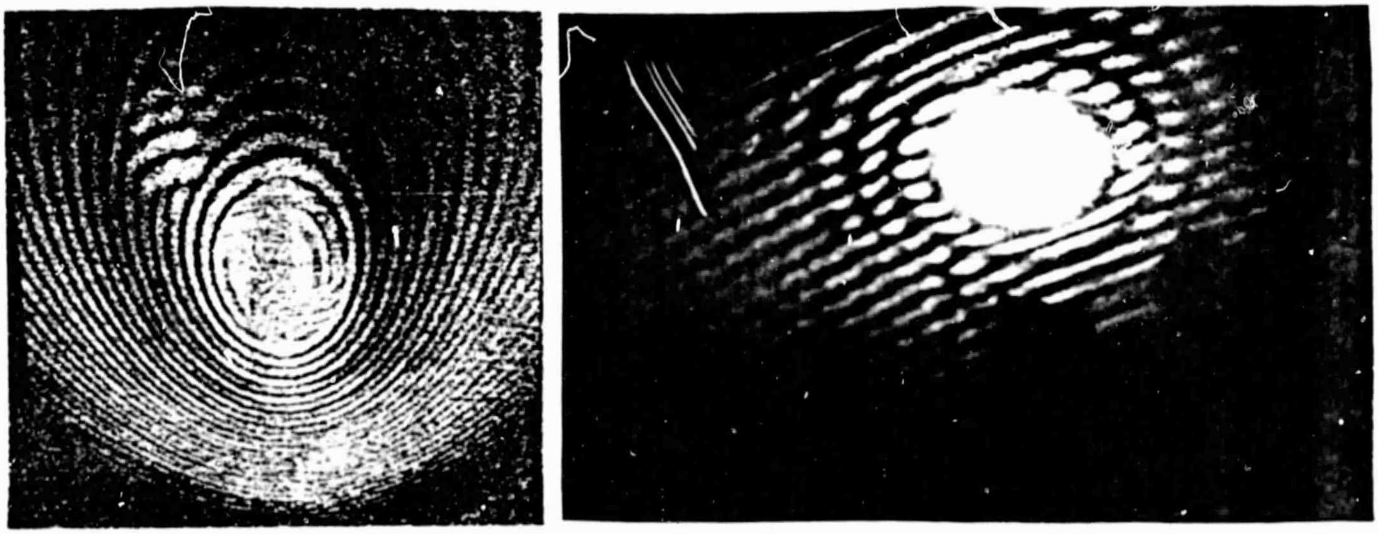


Figure 4. The near field forward scattering image of a doublet consisting of 20 µm and 30 µm spheres of suprasil photographed in the green light of an argon laser at GSFC.

The bright spots in the center of the spheres represent rays of the incident light which enter the sphere at near normal incidence and which are therefore not bent away from the forward direction. The darkness of the remainder of the sphere arised from rays of light which are refracted away from the forward direction. Irregular particles show the expected sharp irregular image characteristic of their surface profile. The image is filled in by bright and dark areas. The more platlet-like the particle, the brighter will be its image in the forward direction because most of the light will be undeviated in direction. It is quite easy to follow the rotations of the particle in this image as well as translations normal to the beam axis.

(ii). Mie Scattering

The far field scattering pattern (known as Mie scattering) reveals the expected set of interference fringes which fill the laboratory when a particle is levitated. In Figure 5 we show an example of the Mie pattern for a levitated doublet. This is the forward scattering obtained by removing the microscope above the levitated particle. Rotations of the particle are very easily followed



A. B.

Figure 5. The forward Mie scattering pattern of a perfect shape (A) and of the doublet (B) seen in Figure 4.

in the Mie pattern even when the particle is very close to being spherical. The doublet pattern in Figure 5 shows very characteristic differences from that of the simple concentric rings expected for a single sphere. However, we find that the Mie pattern for single particles does not easily reflect the shape of the particle.

(iii). 90° Near Field Scattering

This pattern arises by focusing on the particles with a microscope but in a direction perpendicular to the beam axis. For a nearly spherical particle the image consists of two bright spots which arise from reflected and refracted rays as shown in Figure 6. In addition, we see a fainter image of the surface of the particle which appears as a circle connecting the bright spots. Irregularities

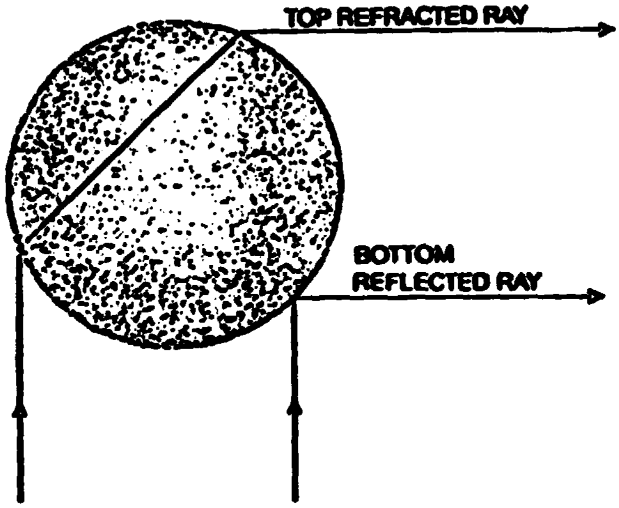


Figure 6. The rays responsible for the pair of bright spots seen in the 90° scattering pattern.