OPTICAL LEVITATION OF OPAQUE PARTICLES IN A LASER BEAM: ZERO-GRAVITY EXPERIMENT

by

John Painter

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Advisor/Thesis Coordinator:

Justin Peatross

Signature: ______________________

Department Chair: Scott Sommerfeldt

Signature: ______________________

Abstract

Opaque microscopic particles are levitated in the focus of a single laser beam with a Gaussian intensity profile. Evidence is presented that rules out the hypothesis that particles are trapped in low-intensity pockets of the laser. We design a chamber, in which particles are trapped, that can be dropped to test whether trapping is possible in the absence of gravity. The results show that particles stay trapped during freefall. This suggests that convection currents (i.e. hot air rising) are not the mechanism responsible for trapping. An explanation of Crooke's radiometer is included, since the trapping mechanism may be related.

Acknowledgments

I would like to acknowledge Nathan Powers and Eric Christensen for providing computer training and machining assistance. My lab partner, Adam Hendrickson, for helping develop experimental designs and software programs. My advisor, Justin Peatross, for his motivation and training. My wife, Deborah, for her love and patience.

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CHAPTER 1. BACKGROUND

1.1 Motivating Observations

Early after the development of lasers, Eric G. Rawson and A. D. May observed dust particles executing interesting motions in the beam inside of their He-Ne laser cavity [1]. Two predominant particle motions were observed: particles traveling parallel to the beam path, called runners, and particles traveling perpendicular to the beam path called bouncers. They hypothesized that photophoresis was responsible for the behavior of the particles. "Photophoresis is the net transfer of momentum to a particle with a temperature gradient due to gas molecules rebounding from the hotter side with greater momentum than from the colder side. The 'photo' prefix implies that the temperature gradient is due to absorbed radiation."

1.2 Development Of Transparent Particle Levitation

A few years later Arthur Ashkin attended a conference in which Rawson and May reported their findings [2]. Ashkin later recalled, "When I came home, I did a calculation and realized, given the size of the beam and the particles, it couldn't be radiation pressure. More likely, I thought, [it was heating] that led to the crazy behavior. This made me think of radiation pressure again." Arthur Ashkin spent many years in the field of optical trapping and many consider him the father of the field. Using radiation pressure, Ashkin conjectured that it was possible to accelerate and trap transparent micron sized particles in a continuous TEM_{00} mode laser beam, which he confirmed subsequently by experiment [3]. Ashkin explained that when a transparent particle leaves the beam laterally, it acts as a lens, deflecting the laser light, which produces a restoring force that brings the particle back into the laser focus. The force arises from the change in momentum of deflected light. For the transparent particle to be pulled into the beam, it must have a higher index of refraction than the surrounding medium. This was experimentally verified by observing the behavior of an air bubble ($n = 1$) in water ($n = 1.33$). Repeatedly, the bubble was pushed out of the beam.

Ashkin developed the first optical trap which allowed 3-dimensional manipulation of transparent particles, known today as optical tweezers [4]. Optical tweezers rely on the laser beam having a sharp focus with a wide divergence angle. When the particle moves axially from the focus, the exiting light cone narrows, resulting in a change in the light momentum and the reactive force generated gives a kick to the particle in the direction of the focus.

Since Ashkin's pioneering work, optical tweezers have become an indispensable tool for manipulating small particles without mechanical contact. Optical tweezers are used in a wide range of biological applications. One of the more common uses for optical tweezers is in characterizing protein binding strength. Proteins are glued to transparent spheres with a resin. The spheres are trapped by the optical tweezer and the protein is pulled apart [5]. The force, at which the protein splits, is then derived from the strength of the optical tweezer. Optical tweezers are also used in connection with laser scalpels to perform in vitro fertilization. First, a laser scalpel cuts off the tail of a sperm cell and then etches a hole in an egg. An optical tweezer is next used to capture the translucent sperm cell and manually insert it into the egg [6].

1.3 Opaque Particle Levitation Due to Photophoresis

As mentioned above, optical tweezers that rely on radiation pressure require that the particles be transparent; opaque particles are pushed out of the focus by radiation pressure. However, in 1981 Lewittes et al. discovered stable trapping of opaque particles in the focus of their laser beam [7].

They believed it was necessary to have an intensity minimum in the middle of the beam that was sought out by the particle. In explaining the need for a lateral intensity minimum, Lewittes wrote, "If the particle moves laterally from the intensity minimum it will experience increased heating on the side to which it moves. The corresponding increase in radiometric pressure on this side will drive the particle back toward the intensity minimum." [7]

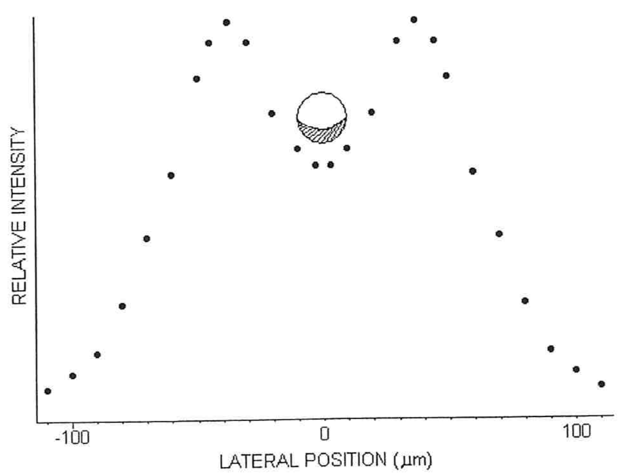

Fig. 1.1 TEM^*_{01} (doughnut) mode profile [7].

They suggested that radiometric recoil is the major mechanism responsible for particle levitation. Lewittes et al. were apparently unaware of the earlier work by

Rawson and May (which showed particles interacting with the laser, but not stable trapping), but their explanation of the phenomenon was similar, gas molecules rebounding from the particles that were heated more on one side than or the other.

For weakly absorbing particles, the radiometric force is negative because the light focuses near the backside of the particle where it experiences greater heating. This allows for inverse radiometric levitation (i.e. the laser beam directed downward). When experimentally verifying the trapping of weakly absorbing particles, in a downward directed beam, they observed that a much higher laser intensity was needed to trap.

As will be shown in this thesis, the conjecture by Lewittes et al., that the laser beam should have a large dip, is not accurate.

1.4 Hypothesis of Low-Intensity Pockets in Laser Beam

A year after the publication by Lewittes et al., Antonio Pluchino reported simultaneous trapping of multiple carbon particles with a laser operating in the TEM_{00} mode [8]. When he sprayed multiple particles into the cell, many became trapped both above and below the focal plane (at odds with the explanation of Lewittes et al.). Pluchino was able to trap with the beam orientated in any direction. He wrote, "It seems, therefore, that gravity and convection are not necessary influences for the levitation of particles."

In an effort to explain how opaque particles remain trapped, Pluchino calculated the electromagnetic diffraction of a focusing Gaussian beam, truncated with an aperture at the lens. His calculations show an energy density that exhibits maxima and minima on both sides of the focal plane (Fig. 1.2). Furthermore, he believed that the Poynting vector, adjacent to the down-stream side of these pockets, was directed against the propagation of the main beam. This fantastic notion of how the Poynting vector behaves near diffraction features might help explain how stable trapping occurs (if it were true, which it is not).

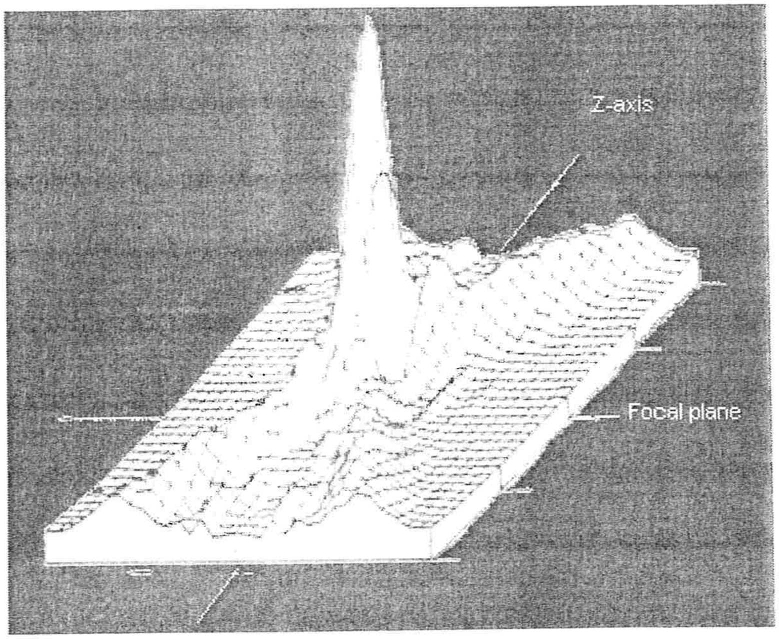

Fig. 1.2 Energy density plot near laser focus [8]

Pluchino explicitly stated that neither convection, radiation pressure, nor photophoresis are responsible mechanisms for particle levitation, but rather particle levitation is, "due to the particle being surrounded by regions of higher energy density and swirling energy flow."

1.5 Thermal Creep

Huisken and Stelzer, in 2002, levitated metal particles surrounded by air with a upwords directed laser beam, anti-parallel to gravity [9]. They wrote, "Because of the distribution of the incident light's intensity, the particle's surface is unevenly heated by its orientation in the laser beam. The heating of the surface is followed by corresponding heating of the medium close to the surface, which decreases the gas density in the hot parts such that gas molecules diffuse in the direction of increasing temperature (thermal creep)." Huisken and Stelzer incorrectly insist that Maxwellian thermal creep is distinct from photophoresis. According to the International Union of Pure and Applied Chemistry [10], photophoresis means "the motion of particles due to the influence of light." Photophoresis, therefore, encompasses two subclasses, radiation pressure and thermophoresis, the latter involving particle heating and subsequent interaction with the surrounding medium.

Maxwellian thermal creep is the type of thermophoresis that explains a Crooke's radiometer (see Fig. 1.3). In this case, gas molecules (at low pressure) interact with the non-uniformly heated vanes of the instrument, giving rise to radiometric pressure (not to be confused with radiation pressure) which pushes on the vanes.

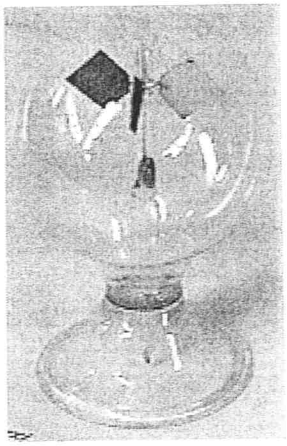

Fig. 1.3 Crooke's Radiometer enclosed in an evacuated bulb.

Huisken and Stelzer claim that the correct explanation for particle trapping forces is similar to that which describes the forces that act on the vanes of Crooke's radiometer.

However, their description only explains particle levitation above the focal plane when the beam is directed upward. Other orientations of the laser beam (which they did not try) under their description would not allow the diffusing gas molecules to counteract the force due to gravity. The paper of Huisken and Stelzer contributes very little to the understanding of this problem. They did nothing new other than to use metal particles. They resorted to the explanation presented by Lewittes while their experimental observations were similar to those presented by Pluchino.

1.6 Crooke's Radiometer

Part of the work for this thesis was to experiment with Crooke's radiometer at different pressures. I removed a radiometer from its evacuated bulb and placed it in a vacuum chamber. I directed an intense incandescent light source onto the vanes of the radiometer. The chamber was evacuated to various pressures and the performance of the radiometer observed. The radiometer did not spin at pressures above a few torr. Neither did it work in vacuum. It worked best near 60 millitorr.

The correct explanation to the radiometer is due to the mean free path of gas molecules [11]. Even though molecules rebound from the hotter side of the vane with more velocity, they collide with cooler incoming molecules at a rate that causes the pressure on the hotter side to be the same as on the cooler side. However, molecules can "sneek" in near the edge of the vane on the hotter surface and recoil with excess velocity. These interactions take place within a distance on the scale of the mean free path from the edge of the vane and create the additional pressure responsible for the radiometer movement.

1.7 Experiments at BYU

In October 2001, Cody Bliss and Ben Belleville, BYU undergraduates, discovered three-dimensional single beam levitation and trapping of opaque particles [12] (unaware of previous work in this field). Soon thereafter I began to assist them in their work. The trapping is not wavelength specific as we learned by trapping with laser wavelengths of 457nm and 532nm. I assisted in trapping a variety of particles as can be seen in Table 1. We are not limited to highly or weakly absorbing particles.

Particle	Size	Trapped	Unable to Trap
Silver	1.3 - 2.3 μm	X	
Tungsten	1 - 5 μm	X	
Tungsten	4 - 6 μm	X	
Tungsten	12 μm		X
Aluminum	10 - 14 μm	X	
Aluminum	17 - 30 μm		X
Nickel	7 - 9 μm	X	
Iron	162 mesh	X	
Magnesium Oxide	100 mesh	X	
Charcoal	unknown	X	
Graphite	325 mesh	X	
Black Liquor	unknown	X	
Polystyrene spheres	3 μm	X	

Table 1. Trap performance of particle samples. [12]

In Cody's thesis, he speculated, similar to Pluchino, that optical trapping is due to dark pockets in the beam resulting from Fresnel diffraction from the hard aperture of the laser cavity. The dark regions are presumably imaged to locations near the focus by the focusing lens. It was speculated that particles become trapped in these dark pockets.

I have extensively checked the laser beams used in trapping for evidence of diffraction or intensity pockets. No pockets were seen in our beam. The results are shown in Chapter 2. Cody's and Pluchino's hypotheses were false; a new hypothesis is needed.

Chapter 2 also presents images of the microscopic particles sprinkled into the focus for capture and levitation. Using an Electron Scanning Microscope (ESM), we saw that the particles were a variety of shapes and sizes.

1.8 Convection Currents

This past year, Dr. Larry Baxter, a professor of chemical engineering at BYU, suggested that the trapping mechanism is due to buoyancy from convection currents [13]. In order for the convection currents to exist, gravity must exist so that "hot air will rise." In the convection picture, the temperature of the particle could be fairly uniform (as opposed to hotter on one side), as one might expect if the trapped particle were to spin in place. If convection is the primary trapping mechanism, then one might expect that in zero-gravity, this phenomenon might not work. To test this, we set up an experiment where a chamber containing a trapped particle can be dropped for ~ 2 meters while maintaining optical alignment with the levitating laser beam. The experiment is described in chapter 3. Evidence is presented that suggests that the particle remains trapped in the zero-gravity environment, which is the primary result of this thesis.

CHAPTER 2. ANALYSIS OF BEAM AND PARTICLE STRUCTURE

2.1 Laser Intensity Profile

Pursuant to the hypothesis that structure in the laser beam intensity profile might explain trapping, both laser beams that we have used in trapping were imaged onto a CCD camera. Specifically, I looked for evidence of structure in the beam near the focus. Both lasers had a reasonably smooth Gaussian intensity profile. Fig. 2.1 displays a series of beam images beginning a short distance before the focus and incrementally stepped to a position behind the focus of our 457 nm Argon-ion laser. Just beyond the focus, there is a lower intensity pocket in the laser profile. It was hypothesized that these low intensity pockets are where the particles become trapped. However, it is doubtful that trapping occurs only in these pockets, being as there is only one pocket and multiple particles have been trapped simultaneously, both before and after the focus.

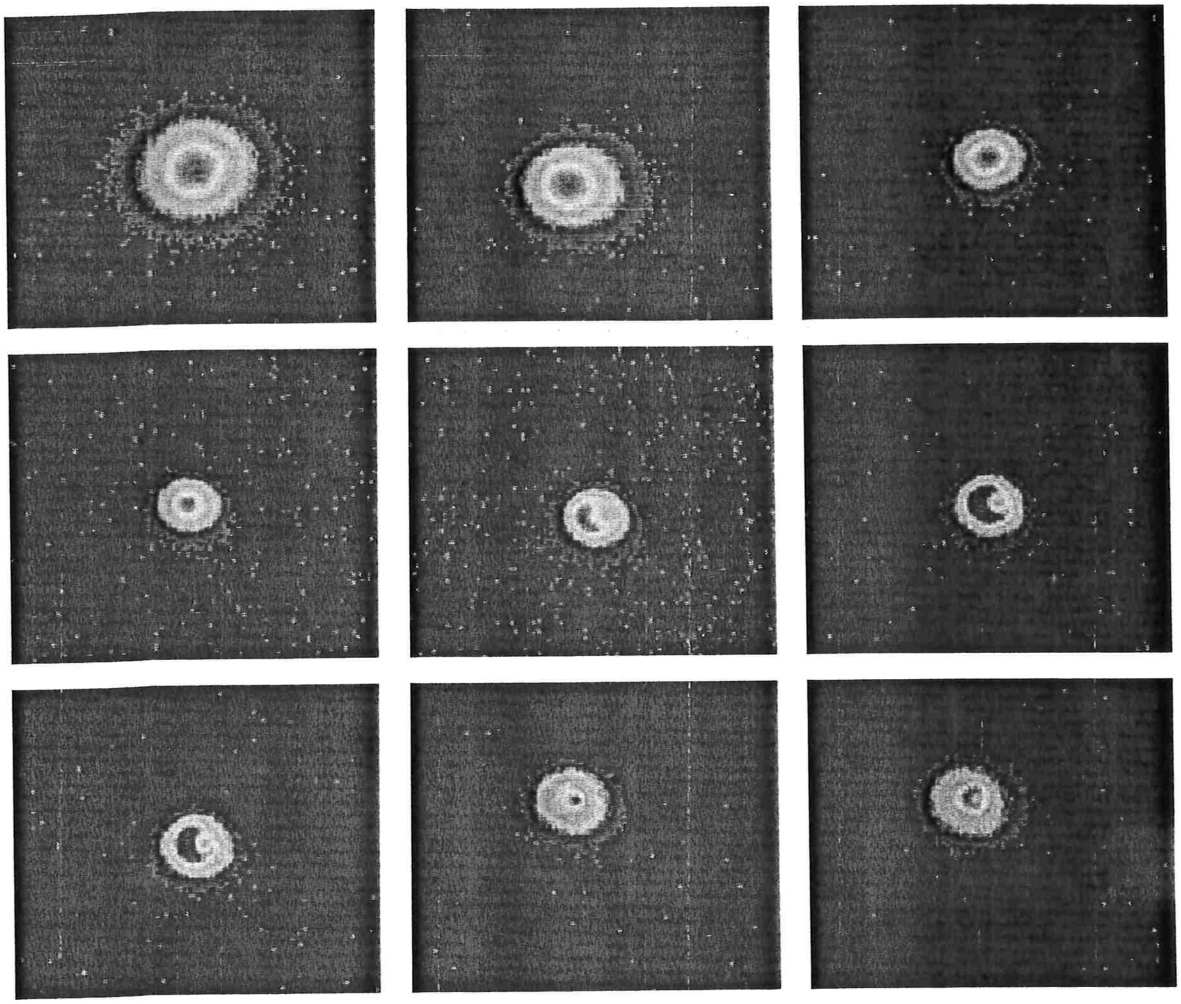

Fig 2.1 Focal region intensity profile of our Ar+ laser beam

2.2 Electron Scanning Microscope

We examined under an electron microscope samples of microscopic particles that were used for trapping. We hoped that there were certain shapes and sizes that would give clues into the trapping phenomenon. The pictures from the ESM revealed that each particle sample contained a variety of shapes and sizes (see Figs. 2.2-2.10). Some particles exhibit more consistency in their general shapes (Figs. 2.4 & 2.5), while others appear completely random (Figs. 2.9 & 2.10). Contained on each picture is a scale useful for determining the particle sizes. When the needle that has been dipped in the sample powder is shaken above the focus, many particles have an opportunity to be trapped, but only a few self-selected particles become trapped. We were unable to tell which particles from a sample become trapped.

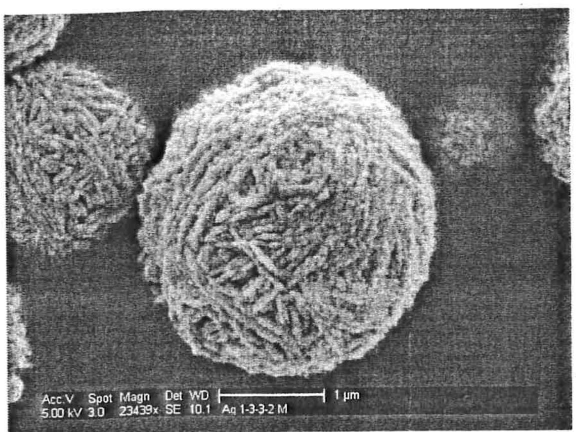

Fig. 2.2 Silver, 1.3-2.3μm

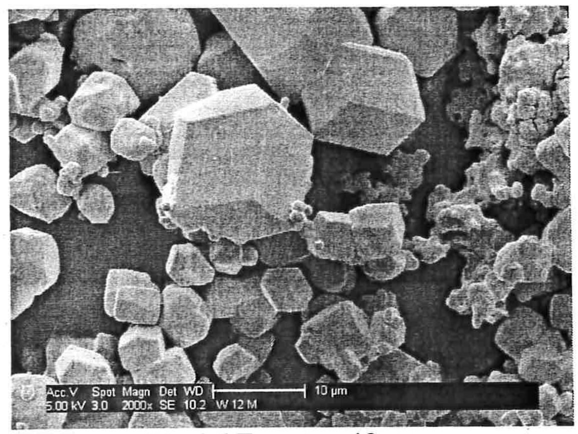

Fig. 2.4 Tungsten, 12μm

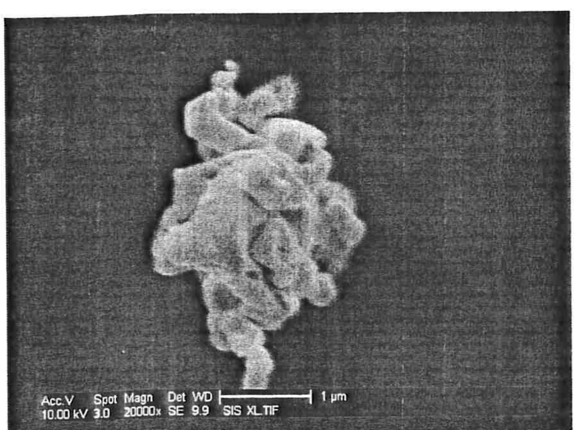

Fig. 2.3 Tungsten, 1-5μm

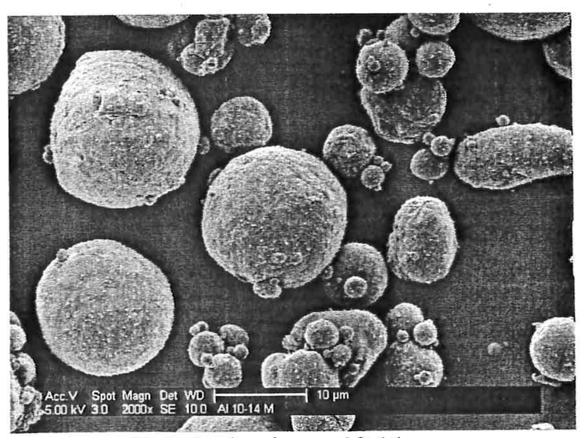

Fig 2.5 Aluminum, 10-14μm

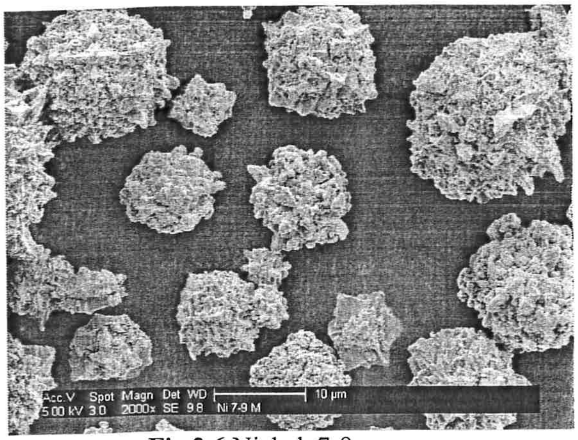

Fig 2.6 Nickel, 7-9μm

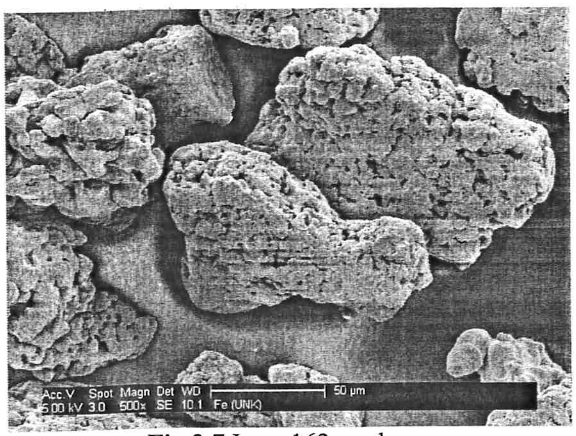

Fig 2.7 Iron, 162 mesh

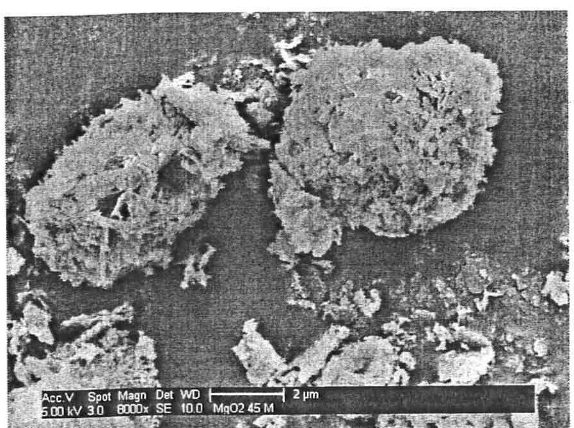

Fig 2.8 Magnesium Oxide, 100 mesh

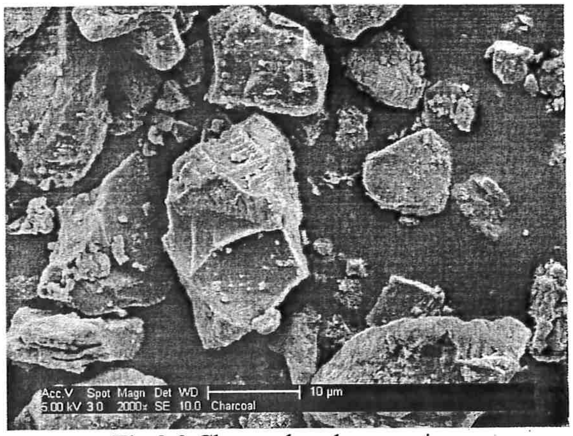

Fig 2.9 Charcoal, unknown size

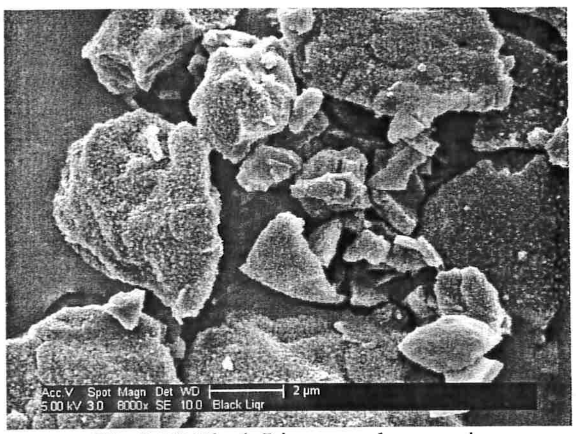

Fig 2.10 Black Liquor, unknown size

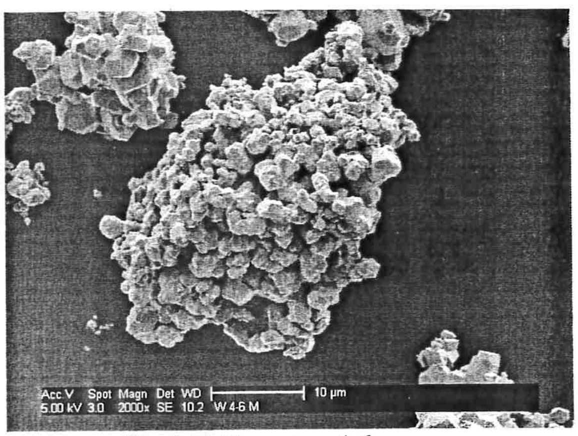

Fig 2.11 Tungsten, 4-6μm

I attempted to capture individual particles from the trap to be viewed by the ESM, but was unable to do so. The particles were often knocked out of the trap by the air currents created when trying to capture them. The ESM revealed many different particles on slides that were supposed to have only one particle captured. Therefore it was impossible to make any conclusions about the shapes and sizes of trapped particles (other than that our samples have large variety).

CHAPTER 3. ZERO-GRAVITY EXPERIMENT

3.1 Laser

For our trapping experiments, we used a 5-watt laser with wavelength of 532 nm (Coherent Verdi). We typtically set the laser power at ~3.5 watt. The initial beam diameter is ~ 3mm. Experience has shown that a low f-number focus makes it easier to trap particles. To accomplish this, we expanded the beam in a Galilean telescope (magnification 5) to get a collimated beam with diameter ~17 mm, almost the entire diameter of the 20 mm focusing lens.

We directed the collimated beam up to the ceiling and reflected it across the room to where the experiment takes place (a distance of ~10m). Once at the wall where the apparatus is mounted, the laser beam was sent downward and parallel to a rail system.

3.2 Rail and Carriages

As shown in Fig. 3.1, we attached a 3-meter aluminum rail vertically to a solid cement wall in our lab. Two metal plates, one near each end of the rail, were used as spacers from the wall to ensure that the rail was straight (as opposed to following curves in the wall). This minimizes friction and ensures alignment during freefall. To improve smoothness of gliding during drops, the chamber was attached to the rail using two ball-bearing carriages.

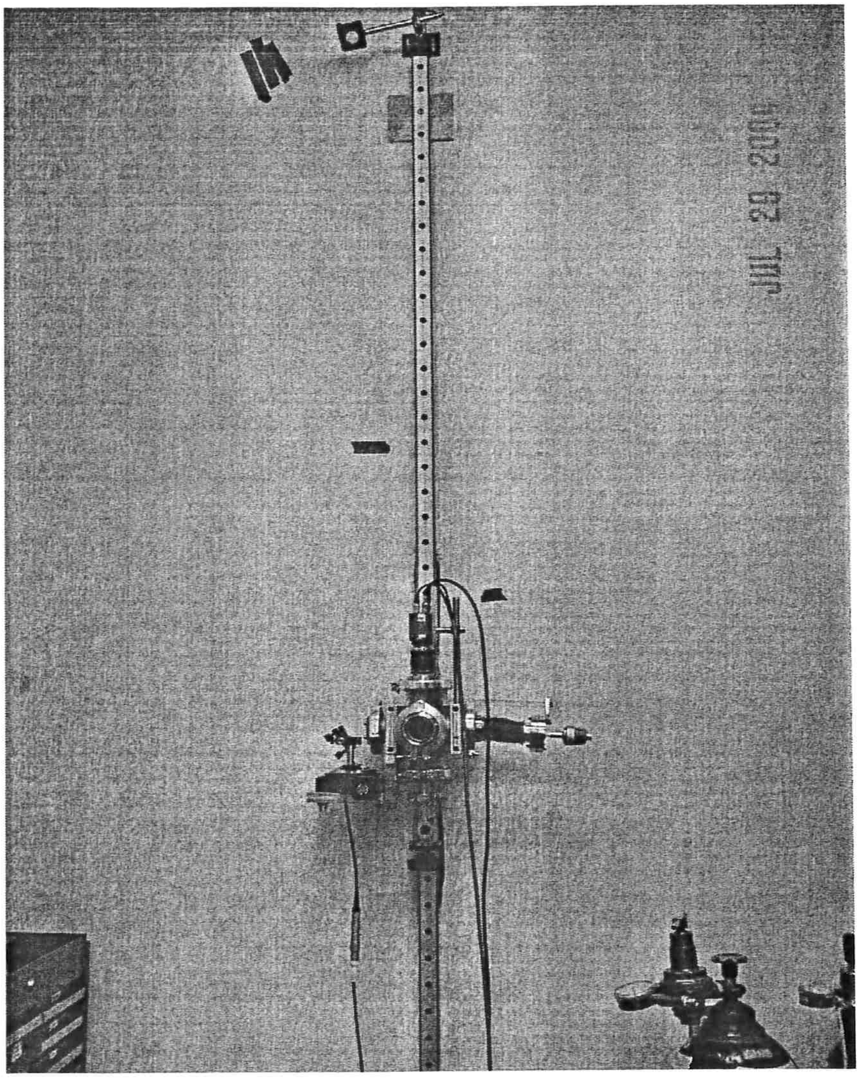

Fig. 3.1 Rail with chamber used in drops.

3.3 Chamber

The chamber that we constructed for the drop experiments has five ports (NW 50). Each port has diameter of 5 cm. The overall width of the chamber (vertical or horizontal) is 16 cm. The weight of the chamber with all attached components was approximately 15 lbs. A schematic of the chamber is shown in Fig. 3.2.

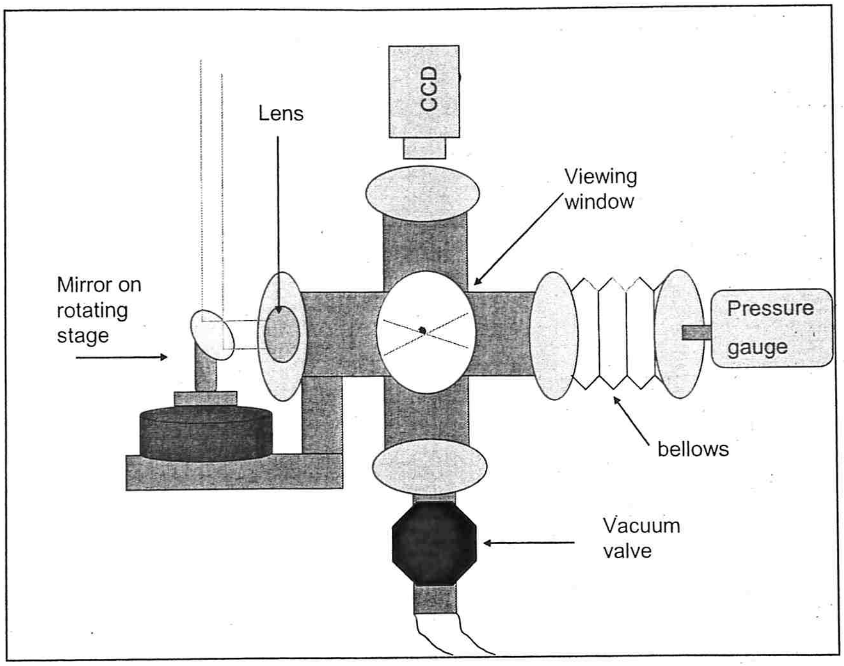

Fig. 3.2. Schematic of the chamber used for the drop

On the left-side port, we attached an 8-cm focal-length lens, which places the focus in the center of the chamber. A mirror diverts the beam, which is parallel to the rail, horizontally through a lens which serves as a window on the left port. The experimenter can observe the focus through a viewing window on the front port of the chamber. The beam is aligned such that the location of the focus in the chamber is identical whether the chamber is at the top of the rail or near the bottom.

The mirror that directs the beam into the focusing lens is mounted on a nanorotator (Melles Griot, 17AMR101). The nanorotator confirms that the particles are indeed trapped in the beam during free fall (i.e. not just accidentally staying in the focus). The nanorotator is connected to a stepper motor controller (Melles Griot, 17BSC002), which can be programmed to rotate the mirror with different velocities and accelerations. For our experiment we used the following values as we swept the direction of the focused beam through an angle of 6 degrees; vel. = .32 mm/sec and accel. = .05 mm/sec^2. This results in the laser focus sweeping side-to-side (in an oscillating fashion), with a period of 2 seconds. The total range of motion in this time is ~7.5mm each way.

On the right-side port, a particle loading tool is attached, which has a vacuum bellows and a rod with a sewing needle attached to the end. We placed a particle sample holder inside the chamber, which had a swinging cover to contain the particles during drops. To load particles into the trap, one dips the needle into the particle sample and then shakes it above the focus until a particle falls into the beam and becomes trapped. A pressure gauge was attached to the loading tool to measure the pressure inside (and also to act as a handle when loading particles).

A CCD camera attached to the top port takes images of the trapped particles at a rate of 15 per second. A valve and a removable roughing line is attached to the bottom port to acquire the desired pressures for trapping. For tungsten, a good pressure is near 220 torr.

3.4 The Drop

More than one person was needed to perform the drop experiment. My lab partner, Adam Hendrickson, was responsible for running the software for controlling the nanorotator and image acquisition, while I dropped the chamber and made sure that it landed on a large block of foam placed at the bottom of the rail.

From Newtonian mechanics we calculated time interval of freefall. Starting from rest at height h=1.6m, the freefall time is found to be

$$t = \sqrt{\frac{2h}{g}} = 0.57\,\text{sec}. \qquad (3.1)$$

The number of frames acquired during freefall is therefore

$$15\frac{\text{frames}}{\text{sec}}\times 0.57\,\text{sec} = 8.6\,\text{frames}. \qquad (3.2)$$

3.5 Results

Fig. 3.3 shows images of two trapped tungsten particles (4-6μm) during the free fall. The laser beam (not visible) runs top-to-bottom in the images (corresponding to left-to-right in the chamber). The particles are visible due to scattering of the light. A 2mm-spacing grid is overlaid on the images as a reference. As can be seen in the frames, the particles stay in the beam throughout freefall (or they would not scatter light). As a result of scanning the mirror with the nanorotator, the laser focus (and the trapped particles) moves side-to-side about 2mm during freefall. We checked that this amount is expected by comparing with images taken when the chamber is at rest.

Given air friction for a moving particle, it seems unlikely that the particles accidentally followed the beam laterally for 2 mm during freefall if they were not trapped. In fact since there are two particles, both moving in the direction of the sweeping beam, it suggests that they are trapped. Some movement along the axis of the laser can be seen by the particles, more for the larger particle downstream. It is not unusual for a trapped particle to jitter several millimeters along the beam, even when the chamber is at rest. Sometimes the jitter is decreased with an increase in laser power. However, the additional scatter in the chamber saturates the CCD camera, which makes the images difficult to interpret. The ninth frame (not shown) is the frame of impact, which shows the particles are gone from the beam. Particles are knocked out of their trapping locations when the chamber strikes the foam block.

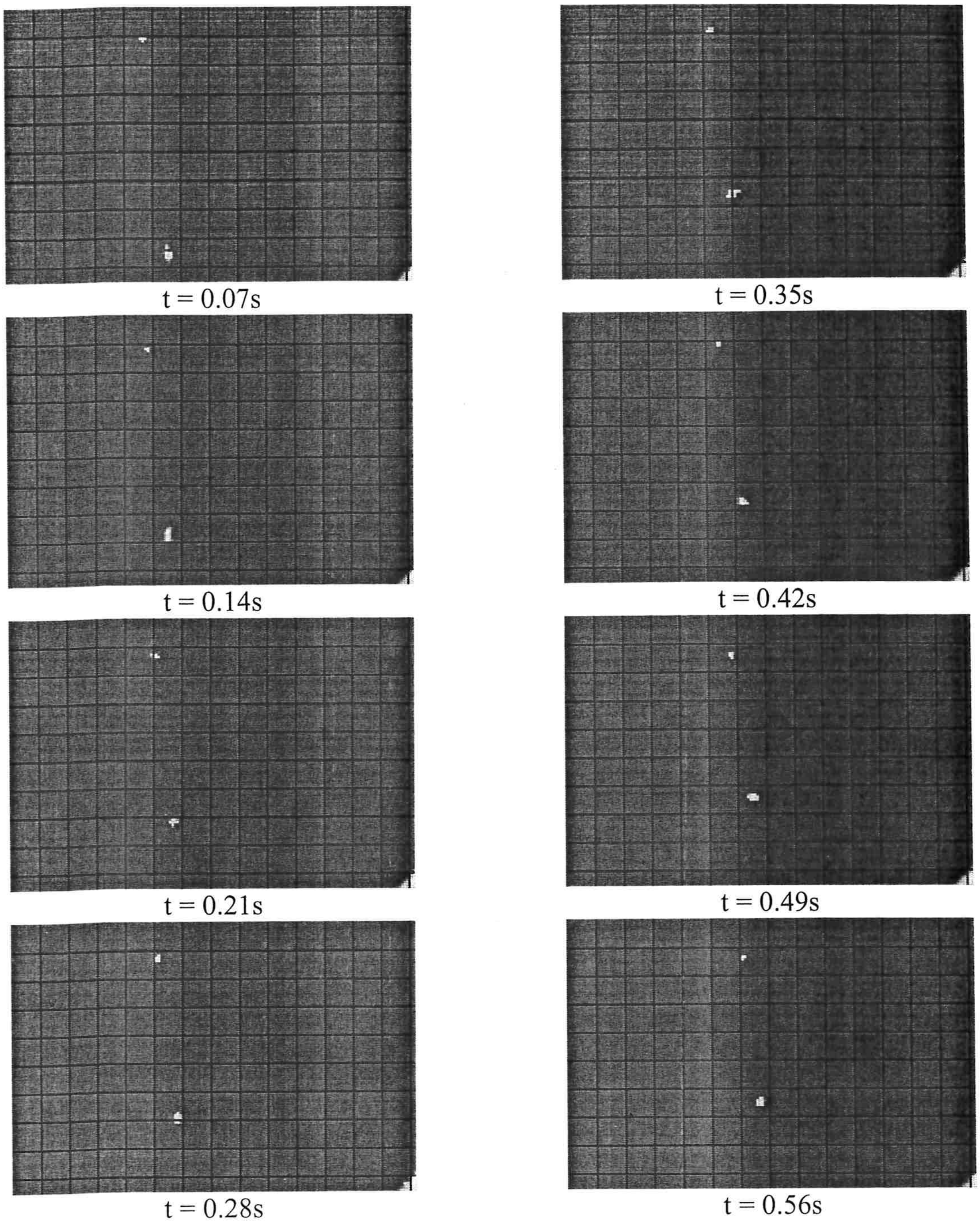

Fig. 3.3 Trapped tungsten particles.

Occasionally particles would fall out immediately at the beginning of freefall, but we found this was caused by a jolt when the chamber was released from rest at the beginning of the drop. Typically, if the particle remained trapped through the first two or three frames of freefall it stayed trapped the entire drop.

Compelling evidence has been presented that the trapping mechanism still works in the absence of gravity. This suggests that convection (hot air rises) is not the primary trapping mechanism; it should be possible to trap opaque particles in a laser on the Space Shuttle.

3.6 Future Work

In eliminating convection as the cause of particle trapping, we look again to thermal creep (the diffusion of gas molecules due to heating) as the answer. The radiometer only works in a range of pressures; both a lower limit and upper limit of pressure were found experimentally. We have found a lower limit for which trapping of particles in a laser no longer occurs, beneath a few torr. However, we have not tried to trap at pressures higher than one atmosphere. This could shed light on the whether or not the same theory for the radiometer is true for particle trapping.

We plan to do more dropping experiments to gather images of a trapped particle while it turns around at the end of the sweep. This will give more evidence to the particle being controlled by the trap and not kept moving horizontally by momentum.

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