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Invited Paper

# Volumetric Display by Movement of Particles Trapped in a Laser via Photophoresis

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## ABSTRACT

Photophoresis can stably hold opaque microscopic particles in a laser focus surrounded by room air with strength sufficient to enable centimeter-scale patterns to be drawn by sweeping the laser beam. The resulting images rely on visual persistence as laser light scatters from the particle, which is rapidly swept through the 3-D pattern. Control can be maintained while moving the particle with air speeds up to 2 m/s. A desire to greatly increase the sweep speed motivates a re-examination of the fundamentals of photophoresis-based laser-particle traps. Most explanations offered are qualitative, with differing opinions as to whether, for example, asymmetric heating or asymmetric thermal accommodation is primarily at work. Which particles become trapped in the beam is typically based on self-selection, as a variety of particles with possible differing shapes and sizes are offered to the laser focus for capture. Characteristics that make some particles preferred over others are especially relevant. There is broad consensus that structure in the laser focus greatly aids in stable photophoretic trapping. An interesting question is how smooth can a beam be and still capture and hold particles. Even in a structured focus (i.e. with aberrations and local intensity minima and maxima), questions remain as to exactly how a particle becomes stably trapped in certain beam locations. A zoomed-in look at trapped particles reveals oscillations or orbits with excursions over tens of microns and accelerations up to 10 gs. We trapped particles in zero-gravity as well as 2-g environments with no noticeable difference in stability.

**Keywords:** photophoresis, optical trapping, volumetric display

## 1. INTRODUCTION

A half century ago, Eric G. Rawson and A. D. May observed dust particles executing motions in a laser-beam cavity.[1] They hypothesized that photophoresis was responsible for the behavior of the particles. In their words, "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." Arthur Ashkin attended a conference in which Rawson and May described their observations. In an interview decades later,[2] Ashkin 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." Ashkin went on to develop laser trapping for transparent particles, based on exchange of momentum with laser photons.[3] A transparent particle can be pulled into a tight laser focus, which has become well understood and has been exploited for a myriad of applications.

Somewhat later, it was discovered that the photophoresis effect noticed by Rawson and May can also lead to stable trapping of small opaque particles in a laser beam. In 1981, Lewittes et al. observed stable trapping of opaque particles near a laser focus.[4] Apparently unaware of the earlier observations by Rawson and May, they too concluded that radiometric recoil of gas molecules from the hotter side of the particle as the mechanism responsible for the levitation of particles in the laser focus. They argued that particles sought out intensity minima, and they employed a specifically non-Gaussian beam featuring structure with intensity minima. In 1983, Antonio Pluchino reported trapping of multiple microscopic carbon particles in a laser operating in the TEM00

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mode,[5] both before and after the focal plane. Pluchino was able to trap particles with the beam orientated in any direction. Pluchino believed that "due to the particle being surrounded by regions of higher energy density and swirling energy flow" they could become trapped in the laser beam. His explanation described a diffraction effect on tiny particles that caused greater light energy to be absorbed on the 'shady' side of the particle. In 2002, Huisken and Stelzer, levitated metal particles surrounded by air with an upward directed laser beam.[6] They suggested that the phenomenon is governed by thermal creep, a form of photophoresis involving diffusion of hot and cold molecules near the edges of a Crooke's radiometer. Around the same time, other researchers pursued two-dimensional trapping of opaque particles using a laser impinging on a transparent substrate.[7,8]

The trapping of opaque particles in three dimensions using a single laser beam was also noticed by the group of J. Peatross at Brigham Young University.[9] A series of student theses that investigated this phenomenon were produced between 2002 and 2010.[10–17] These studies examined the effects of material, particle size, beam power, ambient pressure, gravity, and beam structure, which are highlighted below. Starting in 2009, a group affiliated with the Australian National University reported on a remarkable series of experiments where aerosol particles in air were trapped and movements controlled over large distances in counter-propagating beams and single beams with exotic "vortex" and "bottle" beam profiles.[18–24] Other researchers[25–28] have also demonstrated trapping of small absorptive particles surrounded by air near the focus of individual laser beams, typically with beam structure intentionally introduced.

A fairly broad consensus has emerged among researchers that the trapping phenomenon is governed primarily by a photophoresis force. Photophoresis has been studied for over a century,[29–35] albeit not necessarily in the context of particles stably trapped in a single laser beam. Photophoresis arises from the heating of a particle by light absorption, which causes ambient gas molecules to recoil with extra momentum. A net force can occur when one side of the particle is hotter than the other, or when asymmetries in the particle shape or surface quality cause an otherwise uniformly heated particle to accommodate interactions with gas molecules differently on different sides.




Figure 1. Centimeter-scale images produced by rastering a cellulose particle trapped in a laser focus through free space in room air. Left frame: A vector image. Right frame: A registered image.

## 2. VOLUMETRIC DISPLAY

We recently demonstrated the ability to draw centimeter-scale patterns by sweeping a particle trapped in a laser focus through a volume of space.[36] Cellulose particles can become caught in a laser beam with sufficient stability to withstand mild breezes in the open air and to track with the beam at speeds up to 2 m/s. The generated images rely on visual persistence as laser light scatters from the particle while it is swept through the 3-D pattern. Figure 1 shows images produced by controlling a particle with a 405 nm laser, while in turn illuminating the particle with 635nm, 532nm, and 435nm co-propagating laser light to produce a full-color high-resolution image.



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The optical trap display is not clipped at a display aperture as is the case for holograms. Parallax can be seen from all angles, and images can also be created that wrap around physical objects.

The potential interest in three-dimensional displays based on this scheme provides strong motivation to try to greatly increase the sweep speed for particles that remain stably trapped in the laser beam. This no doubt necessitates improved understanding of the trapping phenomenon, how particle size, shape, and material qualities, as well as beam characteristics influence trapping and its ability to withstand wind. While it is readily seen how photophoresis can explain a force on a particle, it is less obvious how it leads to a stable trapping at locations in a unidirectional beam, even if there are local intensity minima or maxima present. This conceptual difficulty is probably why many have employed trapping schemes that use counter-propagating beams, a substrate to trap against, or rely on the force of gravity for balance against an otherwise unstable photophorific force.[6–8, 10, 19–22, 25–28] As was mentioned in the above discussion, a variety of explanations have been offered for the trapping phenomenon.

## 3. OBSERVATIONS

In the previous decade, students at Brigham Young University (BYU) performed a series of experiments, investigating how particles become trapped in a continuous laser beam while strongly scattering light. They used wavelengths 456 nm and 532 nm and powers up to a few watts. These studies developed expertise, which was helpful in creating the volumetric display described above. The BYU studies have much in common with the later work of Zhang et al.,[25] which was done independently, since the BYU work was documented mainly in a student thesis archive. The beams used in the BYU studies were focused using spherical optics, which likely introduced an uncharacterized amount of spherical aberration.[23]

In the BYU studies, a variety of particles were readily caught and held indefinitely in a Gaussian laser beam with f/10 or shorter focusing. In contrast with some recent experiments,[28] particles could be held in a laser beam that was open to the room, provided that air currents were minimal. We were able to trap small particles of tungsten, silver, aluminum, nickel, iron, magnesium oxide, charcoal, graphite, and cellulose (ranging in size from a few microns to ten or twenty microns).[11] The latter material, which was the easiest to trap, was in the form of "black liquor," a byproduct of the paper manufacturing industry.[37] When trapping, the different powders were sprinkled into the laser beam. Thus, large numbers of particles were presented to the various locations near the beam focus, where self selected particles would become trapped, presumably based on size, shape, and local beam characteristics. Once trapped, particles remained in a given beam location, even as the beam was moved by steering a mirror near the focusing lens.

In our studies, we found that trapped particles could be held with as little as ten milliwatts of laser power, although power on the scale of a watt or more makes the initial trapping of a particle much easier.[11] We also controlled ambient gas pressure and found that the trapping phenomenon can be sustained at pressures as low as a few torr and at pressures as high as ten atmospheres.[14, 16] Particles 'fall out' of the trap at the pressure extremes. The most stable trapping pressure for our conditions occurred around 200 torr. The trapping phenomenon behaved similarly when helium or argon was substituted for air.

To investigate the role of gravity,[12] in 2006 BYU students performed laser trapping experiments onboard a NASA jet that simulated a zero-gravity environment. Routine trapping and holding of graphite particles in a laser beam were carried out during 30-second intervals of zero gravity interspersed by similar intervals of roughly 2 gs. The trapping behavior showed no apparent sensitivity to gravity; the trapping worked the same whether done at zero, one or two gs. This result rules out convection,[38] at least if oriented by gravity, i.e., 'hot air rising', as the primary mechanism for the trapping phenomenon.

The relative unimportance of gravity to the trapping phenomenon is consistent with zoomed-in pictures of trapped particles viewed from the side of the trapping laser beam. A microscope objective was used to record close-up movies of trapped particles.[13] It was found that particles typically execute rapid oscillations along the direction of laser propagation. The excursions range from a few microns to many tens of microns within a trapping region. Recorded movies have revealed particle accelerations in excess of 10 gs. Clearly the forces involved in the trapping phenomenon dwarf the influence of gravity.



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Given that a particle, when it becomes trapped in the beam, is tethered to a particular location, it is plausible that a local intensity minimum or maximum, or perhaps an intensity gradient, plays a role in the trapping. In this context, it is surprising that Pluchino,[5] our group,[15] and Zhang[25] came to the conclusion that a relatively smooth beam can trap particles, a claim we plan to reinvestigate. In any case, it is likely instructive to explore the extent to which structure in a laser beam is required to capture particles.

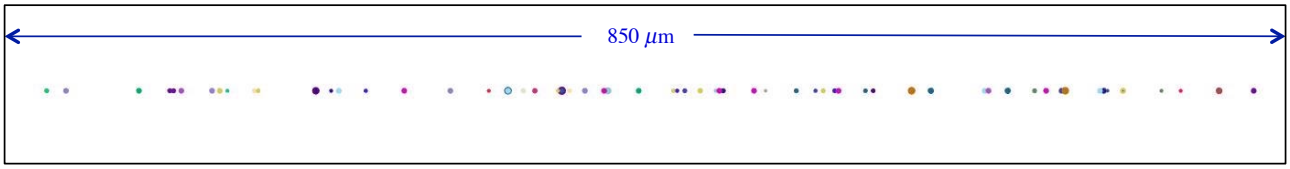



Figure 2. Distribution of particle locations from 25 different trapping trials. One to six particles become trapped in a given trial with three being the average number of particles. The laser propagation direction is from left to right.

In a recent experiment, we recorded the positions of particles trapped in a 1-watt 532nm laser beam focused with f/10 optics (using a plano-convex lens positioned 10 cm from the focus). Particles were imaged via scattered laser light using a 20× microscope objective positioned out the side of the laser beam. Fig. 2 shows the distribution of trapping locations in the beam for 25 trials where cellulose particles were sprinkled into the laser focus. Several particles typically became trapped on a given trial. All particles from a given trial were plotted using the same marker color. The circular markers that describe particle locations were drawn with sizes proportional to observed particle size. It is striking that, at least along the dimension of laser propagation, there does not appear to be preferred trapping locations or preferred spacings between trapping locations, over the 1-mm range where particles readily became caught. We did not determined whether the trapping region was situated before, after, or centered on the laser laser beam waist. While presumably beam structure plays a role, it seems as though the size and/or shape of the particles also play an important role in determining where along the beam they become trapped, if they are capable of becoming trapped.

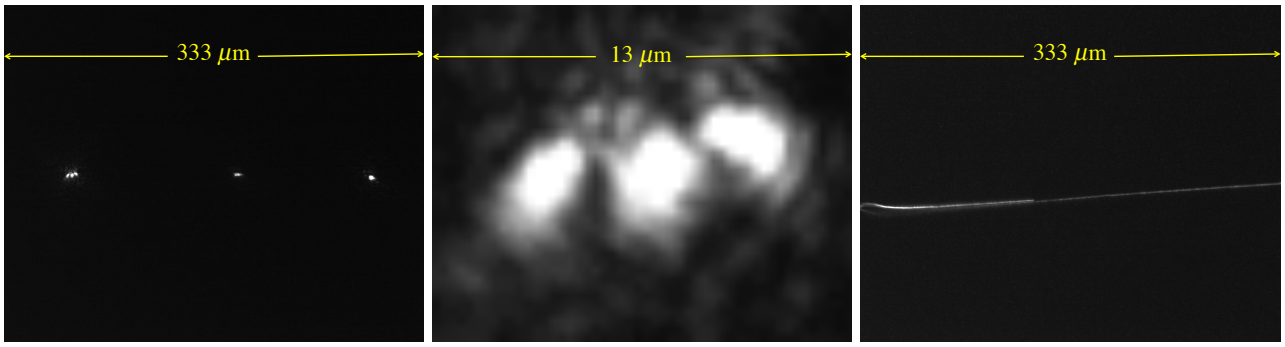



Figure 3. Side view of particles trapped near the focus of a laser beam that travels from left to right. Left frame: Three particles execute synchronous motion along laser-propagation direction with excursion distance approximately 10 $\mu$m. Middle frame: Closeup view of left particle of left frame. Right frame: A different particle seen executing large oscillations over hundreds of microns.

We captured high-resolution images of the particles making up the distribution in Fig. 2. The trapped particles we observed ranged in size from a few microns up to about 10 microns. All of the particles exhibited rapid oscillations along the dimension of the laser with excursion ranges well exceeding the sizes of the individual particles. The left frame of Fig. 3 shows three particles that were trapped together on a given trial. Even though the spacing between the particles is on the scale of a hundred microns, the three particles executed synchronous motion, i.e., in phase oscillations left to right. This synchronous behavior is typical of multiple trapped particles sharing a neighborhood. The middle frame of Fig. 3 shows a close-up view of the left particle in the group, which is the largest of the three, and which exhibits interesting structure. The particle held its orientation while



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executing the oscillations. In other trials, we have occasionally seen particles that appear to rotate or tumble as they execute oscillations.[13] Finally, the right frame of Fig. 3 shows a trapped particle from a separate trial executing comparatively enormous oscillations – on the scale of a half millimeter. During the frame exposure time, the particle is seen streaking quickly to the left (upstream in the laser), making an abrupt turn, and streaking part way back across the screen to the right. The particle executed these dramatic oscillations stably over thousands of orbits.

## 4. SUMMARY

We have demonstrated a volumetric display that utilizes individual microscopic particles trapped in a laser beam, which are swept through the air to create three-dimensional images. The strong amount of light typically scattered from the particle is useful for making a bright display. The particle can be illuminated with additional wavelengths of light to create color images. While it is plausible that photophoresis (i.e., particle heating through light absorption and subsequent momentum exchange with ambient gas molecules) is the primary force responsible for holding particles in place in the laser beam, the details of how a particle chooses a preferred location and how it becomes stably trapped is a difficult problem. The curious behaviors of trapped particles outlined above may provide further insights into the mechanisms for stable trapping. Improved understanding of the mechanisms may lead to dramatic increases in sweep speeds of arbitrary motion while maintaining control of the particle.

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