

An optical tractor beam sorts microscopic particles

A change in the polarization of a light field can sufficiently change the scattering forces experienced by spherical particles to reverse their direction of motion.

Light typically pushes particles forward thanks to radiation pressure. But it can also pull them backward. A gradient in laser intensity, for instance, can produce optical forces large enough to move the particles—either upstream or down—toward a beam's focus, where they remain trapped, a phenomenon known as optical tweezing (see *PHYSICS TODAY*, December 1997, page 17). In 2006 Philip Marston of Washington State University realized that even a nonspreading beam could pull particles backward and do so over a far broader range than is possible with optical tweezers. As if caught in a tractor beam à la *Star Trek*, the particles may be reeled all the way back to the source of the beam, at least in principle.

Marston presented his theory in the context of acoustic waves,¹ but it applies equally to photons.^{2,3} His trick was to use a Bessel beam, which has the unusual property of not dispersing as it

propagates. It's essentially the superposition of plane waves whose wavevectors are canted at an angle with respect to the propagation axis and form a cone along it. If that angle is steep enough, once such a beam encounters an object, more of the photons can be scattered forward than backward. By conservation of momentum, the object has no choice but to recoil backward.

But even slight changes in the object's size, shape, surface roughness, or refractive index can alter the photon scattering direction. Exploiting that sensitivity, Pavel Zemánek from the Institute of Scientific Instruments of the Academy of Sciences of the Czech Republic, Tomáš Čižmár of the University of Saint Andrews in the UK, and their colleagues have now designed an elegant scheme that uses a tractor beam to separate different types of particles in a mixture.⁴

Key to the achievement was their realizing that two plane waves, steeply

angled toward each other and symmetric along the propagation axis, mimic a Bessel beam well enough to be used in the way Marston envisioned, at least over the range where the beams overlap. Illustrated in the figure, the team's experimental geometry could hardly be simpler. A single, relatively wide Gaussian laser beam is reflected from the mirrored bottom of an aqueous cell containing two sizes of polymer spheres. Interference of the incident and reflected waves forms fringes that determine the spheres' net deflection—either to the right or left.

From their calculations, the researchers also realized that changing the beam polarization—with the electric field pointed either parallel or perpendicular to the plane of incidence—changes the scattering pattern enough that it can be used as a knob to reverse, on demand, the sign of the recoil force on certain sized spheres and thus their motion. Indeed, although the difference in optical force is slight, on the scale of piconewtons, only a perpendicularly polarized beam produced a pulling effect in the group's liquid-cell experiments. In one example, tens of

physics update

These items, with supplementary material, first appeared at <http://www.physicstoday.org>.

Light-field camera snaps dusty plasma. Dusty plasmas consist of charged microparticles embedded in a lightly ionized gas (see *PHYSICS TODAY*, July 2004, page 32). In space, such plasmas pervade planetary rings. In the lab, where higher microparticle densities can be achieved, the plasmas form crystals, melt, carry waves, and exhibit other collective behavior. Observing the microparticles, which dominate the

dynamics, is tricky. Although individual particles are large enough to resolve using optical techniques, monitoring all of them requires a combination of magnification and

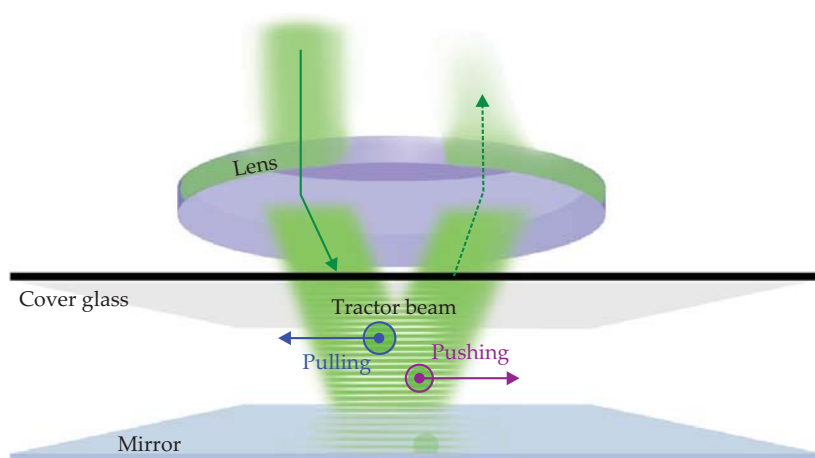
depth of field that standard cameras lack. Péter Hartmann of the Institute for Solid-State Physics and Optics in Budapest, Hungary, and his colleagues are tackling the problem by using a nonstandard camera, the Lytro. Thanks to an array of microlenses that sits between the camera's main lens and detector, the Lytro and its built-in software can determine not only the direction of incoming light (corresponding to the

x and y of a two-dimensional image), but also where in the scene it originated (x , y , and z ; the light field). Processing the three-dimensional data yields a set of sharp images for all values of z . Despite the novel optics, a typical plasma cloud, which measures a few tens of millimeters in diameter, still exceeds the camera's depth of field. Nevertheless, peripheral particles are resolved well enough for an algorithm that Hartmann devised to crunch through the images and reconstruct the 3D particle distribution. The accompanying figure shows one such reconstruction: of a flat, circular cloud about 14 mm across and containing 60 particles. (P. Hartmann, I. Donkó, Z. Donkó, *Rev. Sci. Instrum.* **84**, 023501, 2013.) —CD

A sharpened meteor-impact dinosaur-wipeout connection.

About 65 million years ago, dinosaurs and other species died out in a geological eye blink. Many scientists attribute the disappearance to environmental changes precipitated by a meteor slamming into the Yucatán Peninsula of Mexico. But other factors—volcanic eruptions, for example—may have played an important role. Unraveling the principal cause of the extinction has remained problematic in part because the best that geochronological evidence could do was to place the meteor impact and mass extinction within a few hundred thousand years of each other. Indeed, some data indicate that the impact postdated the extinction. Now a multinational research group led by Paul Renne of the Berkeley Geochronology Center and the University of Cali-





A laser beam (green) reflected from the mirrored bottom of an aqueous cell interferes with itself and forms interference fringes (white). If the angle between incident and reflected beams is sufficiently wide, nearly antiparallel, those fringes can produce enough forward scattering (to the right) that microscopic particles start to recoil to the left, against the momentum direction of the light field. Because the scattering is sensitive to particle size and beam polarization, it's possible to create conditions whereby differently sized particles move in opposite directions. (Adapted from ref. 4.)

spheres of 800-nm and 1000-nm diameters were sorted in a light beam within two seconds of the researchers' switching the beam's polarization to the perpendicular orientation—one size pulled and the other pushed along the fringes.

Optical sorting isn't the only possible

result. Light scattering can also mediate particle interactions. The light scattered by one particle interferes with the light scattered by another and prompts either repulsion or attraction between them. An assembly of like particles may thus migrate to antinodes in the interference pattern and, although relatively

far apart, become self-organized, or optically bound to each other in the light field.

Although the new scheme exerts tractor-beam-like forces, don't expect it to reel in moon dust, let alone spacecraft. Indeed, mesoscopic particles can only be pulled over a distance—to date, about $30\text{ }\mu\text{m}$ —equal to the width of the enveloping beam. That width, however, is limited only by the available laser power.

Zemánek imagines that the group's method will prove useful in compact lab-on-a-chip settings. New York University's David Grier speculates that the range of applications may turn out to be wide. "Tractor beams, optical sorting, and optical binding are now all their own distinct subfields. The new scheme unites them in a single experiment—it's a potpourri of classical optical manipulation techniques."

Mark Wilson

References

1. P. L. Marston, *J. Acoust. Soc. Am.* **120**, 3518 (2006).
2. J. Chen et al., *Nat. Photonics* **5**, 531 (2011); L. Zhang, P. L. Marston, *Phys. Rev. E* **84**, 035601 (2011).
3. For a review of optically induced pulling forces, see A. Dogariu, S. Sukhov, J. Sáenz, *Nat. Photonics* **7**, 24 (2013).
4. O. Brzobohatý et al., *Nat. Photonics* **7**, 123 (2013).

KLAUDIA KUIPER



pany analyzed numerous tektites, glassy droplets created by the meteor's energetic impact. To determine the time of the extinction, the group studied clays obtained from coal-bed strata such as the ones in Montana shown in the figure; the strata were at or near the level where clues such as pollen changes indicate a shift from the dinosaurs' Cretaceous period to the following Paleogene period. The million years before the mass extinction saw numerous episodes of significant global cooling. The associated stress, suggest the researchers, may have made Earth's ecosystem particularly susceptible to the environmental havoc wrought by the meteor's devastating strike. (P. Renne et al., *Science* **339**, 684, 2013.)

—SKB

Cellular rain gauges. Knowing where and how hard rain is falling is important not only for deciding whether to take an umbrella, but also for managing water resources, improving precipitation models, anticipating floods, and assessing climate. Yet many parts of the globe lack good data, whether from weather radar or from rain gauges. (Gauge prevalence is less than half what it was a decade or two ago.) Meanwhile, the world is being increasingly covered by cellular communications networks, and radio signals broadcast between cell towers have been proposed as a new means of monitoring rainfall: At common communications frequencies (roughly 7–40 GHz), the attenuation of signals transmitted from one cell tower to another is mainly due to absorption and scattering by raindrops along the path. Such attenuation data are typically gathered by cellular companies every 15 minutes or so to monitor the stability of their networks. Armed with attenuation data from a Dutch telecom for 2400 network links, Aart Overeem, Hidde Leijnse, and Remko Uijlenhoet at Wageningen University and the Royal Netherlands Meteorological Institute have now dynamically mapped rainfall over all the Netherlands. For each link, the researchers extracted the spatially averaged rainfall intensity during each 15-minute interval, compensating in real time for such systematic issues as water films on the cell-tower antennas. The intensities correlate well with radar imaging and can identify and track individual storms. (A. Overeem, H. Leijnse, R. Uijlenhoet, *Proc. Natl. Acad. Sci. USA* **110**, 2741, 2013.)

—RJF