5 December 1980, Volume 210, Number 4474 SCIENCE

Applications of Laser Radiation Pressure

A. Ashkin

Historically, the idea that light carries momentum and therefore can exert forces on electrically neutral objects goes back to Kepler and Newton. It was confirmed by Maxwell. However, Maxwell found the momentum to be small, implying small forces when light from conventional sources is absorbed or reflected by macroscopic objects. Indeed, it was only after the turn of the century, when the high-vacuum pump was invented and experiments were performed with mirrors suspended on fine torsion fibers, that researchers were able to eliminate disturbing thermal or radiometric forces and detect minute forces from the reflection of light, in agreement with Maxwell's theory (1).

Summary. Use of lasers has revolutionized the study and applications of radiation pressure. Light forces have been achieved which strongly affect the dynamics of individual small particles. It is now possible to optically accelerate, slow, stably trap, and manipulate micrometer-sized dielectric particles and atoms. This leads to a diversity of new scientific and practical applications in fields where small particles play a role, such as light scattering, cloud physics, aerosol science, atomic physics, quantum optics, and high-resolution spectroscopy.

Nothing in this early history suggested that there would be practical applications for these light forces. Only in astronomy, where light intensities and distances were huge, did radiation pressure play a significant role in moving matter. It took another invention, that of the laser, to radically alter this situation and make radiation pressure a useful laboratory tool. The optical forces arising from the momentum of laser light are capable of strongly affecting the dynamics of small neutral particles ranging from micrometer-sized macroscopic particles down to molecules and atoms. This new capability permits one to stably trap small particles, levitate them against gravity, manipulate them singly, combine them in pairs, channel them selectively along laser beams, and use them as sensitive probes for measuring optical, electric, magnetic, radiometric, viscous drag, and gravity forces. These techniques based on light pressure have present and potential applications in a wide variety of subjects such as light scattering, cloud physics, aerosol science, planetary physics, laser fusion, atomic and molecular physics, quantum optics, isotope separation, and high-resolution spectroscopy.

Qualitatively, one can see how the properties of laser light, namely its high degree of spatial coherence and spectral purity, have resulted in large light forces. For example, by focusing a laser beam of modest power, about 1 watt, to a spot size of about a wavelength, λ, one can subject a dielectric sphere 1 micrometer in diameter to the very high light intensity of about 10^8 watts per square centimeter. Assuming the light is reflected from the sphere with an average reflectivity of 10 percent one achieves an acceleration of approximately 10^6g, where g is the acceleration due to gravity (2). This is huge by any previous terrestrial standard. Transparent dielectric particles are considered in this example in order to avoid thermal problems such as melting and radiometric forces.

For large forces to be exerted on atoms (2) it is necessary to use light of high spectral purity, which will interact strongly with narrow atomic resonance lines. Under strong excitation (or saturated conditions), an atom with a typical spontaneous emission lifetime of $\sim 10^{-8}$ second can absorb and spontaneously emit a maximum of about 10^8 photons per second. Since the velocity of atoms is changed by a few centimeters per second per photon absorbed or emitted, this gives forces that can significantly affect atoms moving with velocities typical of thermal atomic beams. To achieve saturation requires an intensity of only about 10^{-2} W/cm^2 because the absorption cross section of atoms for resonant light is very large, $\sim \lambda^2$. This intensity can be exceeded by factors of around 10^8 with dye lasers, which has important consequences for achieving large forces on atoms. Another feature of focused laser light not shared by any other light source is the existence of high-intensity gradients. This leads to large gradient forces (2-4) with the properties that make possible stable optical trapping and manipulation of particles on the scale of the optical wavelength.

In this article the discussion of radiation pressure will be restricted, as is traditional, to neutral particles, since it is here that one can best describe the forces as arising from absorption and scattering of light momentum. Forces on charged particles such as electrons can, of course, be similarly described. However, forces on electrons are most conveniently considered in terms of conventional electric and magnetic fields.

The author is head of the Physical Optics and Electronics Research Department at Bell Laboratories, Holmdel, New Jersey 07733.

0036-8075/80/1205-1081$01.75/0

Forces on Macroscopic Particles

Consider first the force of laser light on transparent uniform dielectric spheres (*2, 5–7*) in the size range 1 to 100 μm, for example. Let a sphere with an index of refraction higher than that of the surrounding medium be placed off-axis at position Q in the field of a nearly parallel TEM_{00}-mode Gaussian beam, as shown in Fig. 1. In a simple ray optics picture, the principal contribution to the force comes from rays such as a and b, which are predominantly refracted through the sphere, giving rise to forces F_a and F_b in the direction of the momentum change. Surface reflections are negligible. Since there is more light at a than at b, $F_a > F_b$, and one sees that there are two components to the net force: one in the axial direction of the light, denoted by F_{ax}, that would exist even for a plane wave, and the other a transverse gradient force, F_{tr}, pulling the sphere into the high-intensity region of the light. The gradient force can be comparable with the axial force for typical beam diameters, and at achievable light intensities both can be made as much as thousands of times the particle weight mg, where m is the particle mass.

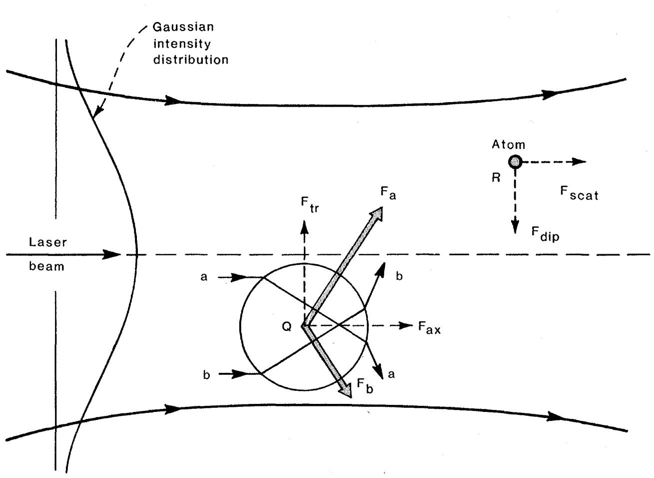
The existence of these light forces was first demonstrated in experiments with transparent micrometer-sized spheres in liquids, where viscosity is high and gravity plays a minor role. Spheres were guided along laser beams and driven by the light with velocities proportional to their radii. Stable optical trapping of individual particles was first observed with spheres in liquids in a trap geometry consisting of a pair of opposing focused beams (*2*). Optical trapping is also possible in less dense media, such as air, where one can stably trap or levitate particles against the force of gravity with a single, vertically directed laser beam (*5*).

Figure 2 shows the basic optical levitation apparatus. A uniform dielectric sphere is located at equilibrium point E above the focus of a TEM_{00}-mode Gaussian beam, where gravity and the axial light force in the upward direction balance. The equilibrium is stable since any vertical displacement from E results in a restoring force due to the change in light intensity caused by the beam divergence, and any transverse displacement results in a restoring force due to the transverse gradient force. Levitation is done in a glass cell to avoid disturbing air currents. Solid particles are introduced into the beam by lifting them off the transparent base plate. This requires an impulse from a piezoelectric ceramic shaker to break the van der Waals bond with the plate. Liquid drops can be captured by allowing drops produced by an atomizer to fall through a small hole in the roof of the cell and enter the light beam. If they are in the proper size range, they are captured. Inherent in the process of capturing a particle and bringing it to rest in a stable trap is the need for damping. In air, the viscosity of the gas prevents the escape of particles that enter the essentially conservative optical potential well from the outside. Once captured, a particle can be moved anywhere in the cell by simply moving the beam; the particle is constrained to follow. The power required to levitate uniform solid or liquid dielectric spheres in the size range 1/2 to 100 μm varies from microwatts to several watts cw (continuous wave).

For Gaussian beams with focal spots smaller than the particle diameter, there is another stable region of levitation below the focus of the beam (*6*). With a pair of opposing horizontal beams with focal spots less than the particle diameter there are several stable regions of levitation (*8*). One can also capture and hold assemblages of more than a dozen spheres in a single beam, locked in stable rigid arrays (*9*). Each sphere becomes trapped at a local intensity maximum in the optical diffraction pattern of all particles located below it. Drastic rearrangements occur only when one of the lower particles is displaced from its local trap. Nonspherical particles such as spheroids, teardrops, and spherical doublets, triplets, and quadruplets have also been levitated. Such particles were assembled in the air by an extension of the levitation technique, using two beams to make various solid and liquid spheres collide and combine (*10*). Such nonspherical particles orient themselves stably at fixed angles with respect to the levitating beam.

There is another class of particles for which the transverse gradient force is reversed and the particles are pushed out of the high-intensity region of a beam. Included in this class are transparent hollow dielectric spheres (*6*) and highly reflecting metals (*11*), where the transverse force is dominated by reflected rays, and low-index particles in a high-index medium, where refraction through the particles reverses (*2*). Such particles can be levitated or trapped by using the TEM_{01}* laser beam mode, which has an intensity minimum on the beam axis.

An important aspect of levitation is the remarkable visibility it affords. Particles



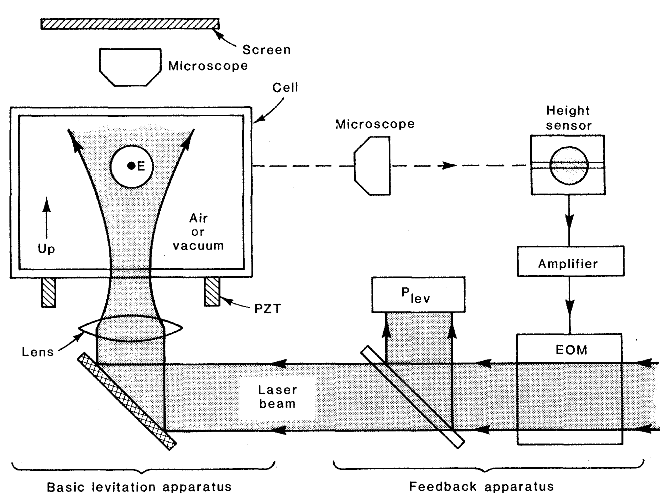


Fig. 1 (left). Optical forces on a dielectric sphere and an atom in a TEM_{00} mode Gaussian laser beam. Fig. 2 (right). Basic apparatus for optically levitating dielectric spheres and feedback stabilization apparatus for levitating in vacuum and measuring forces. Abbreviations: *PZT*, piezoelectric ceramic shaker; *EOM*, electrooptic modulator.

sit at rest in high-intensity light beams, free of other scattering sources. One can thus focus microscopes on the particles, as shown in Fig. 2, and project enlarged images on screens for convenient visual observation, measurement, or photography.

Levitation is also possible in high vacuum (*12*). This was done by capturing a particle in air, where the viscosity is high, and then slowly pumping out the air. If the particle's optical absorption is low enough, there are no serious disturbances from residual thermal or radiometric forces, which reach a maximum during the evacuation process. In high vacuum, viscous damping and radiation damping are weak and only radiation pressure forces are operative. One complication that then arises is the spontaneous buildup of random oscillations due to fluctuations in the levitating beam itself. This can be regarded as a form of kinetic heating, and it can result in escape of the particle.

The problem of kinetic heating was overcome by introducing feedback optical damping (*12*). A feedback system, as sketched in Fig. 2, senses the height and vertical velocity of the particle and electronically feeds back to an electrooptic modulator which controls the levitating light power. The system can "lock" the average position of the particle to a fixed height and change the optical power in proportion to the velocity to give strong optical damping. It can, in fact, damp both vertical and horizontal oscillations due to a coupling of these two motions. In practice, it holds particles motionless in high vacuum. Feedback control of levitated particles provides another important capability, namely automatic force measurement. By monitoring the laser power needed to levitate a particle at a fixed height, P_{lev}, in the presence of an external force, one automatically obtains a direct measure of the magnitude of the applied force relative to the particle's weight. This technique is useful in many applications of levitation in air as well as in vacuum.

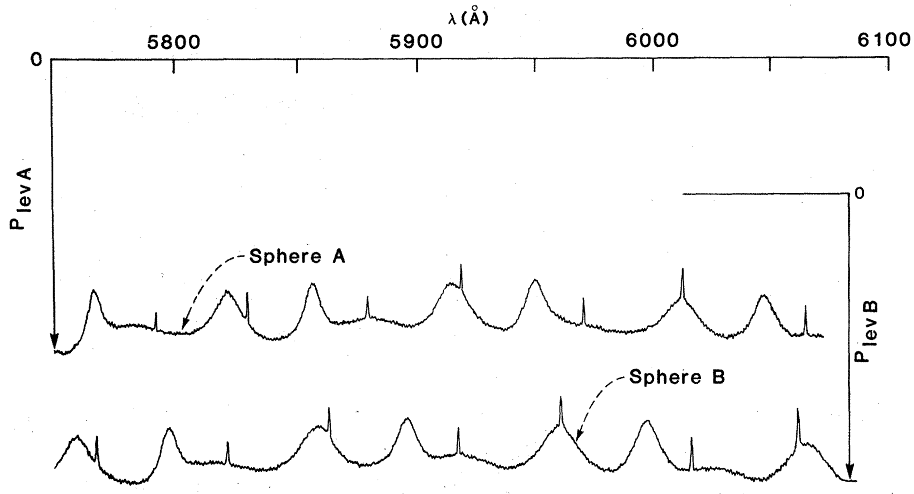


Fig. 3. Resonant behavior of light forces on dielectric spheres. The spectra show the variation with wavelength of P_{levA} and P_{levB}, the power needed to levitate oil drops A and B, which have index of refraction $n = 1.47$ and slightly different diameters (~ 10 μm). The resonances of sphere A are shifted ~ 50 Å higher in wavelength than the corresponding ones in sphere B.

Applications with Macroscopic Particles

One of the major applications of radiation pressure is to the study of light scattering. This is natural since the basic light pressure forces themselves arise from light scattering. Indeed, measurement of the wavelength dependence of radiation pressure forces on dielectric spheres by levitation techniques (*13*) revealed for the first time the existence of a complex spectroscopy of very sharp resonances. This is illustrated in Fig. 3, which shows the variation of P_{lev} for two spherical oil drops with slightly different diameters as the wavelength of a levitating dye laser is varied. The underlying spectroscopy of the sphere is shown by the fact that the sequences of force resonances for sphere A are identical with those for sphere B, only shifted in wavelength. The resonances were attributed (*13*) to the so-called van de Hulst dielectric surface waves (*14*), which couple into and out of spheres at the edges and can run around spheres and resonantly close on themselves. At resonance, the force increases and P_{lev} drops. This process involves diffraction and cannot be understood by simple ray optics.

Use of these surface wave resonances provides a new method of relative and absolute size measurement that is two to three orders of magnitude more accurate than previous methods based on Mie-Debye scattering theory (*14*) for spheres. Relative measurement of size is based on a comparison of the wavelength of a particular resonance for different spheres and can have an accuracy of about 1 part in 10^5, determined by the width of the sharp resonances. Absolute measurement of size and also index of refraction requires a comparison of experiment with theory. Recent high-resolution computer calculations of the force spectrum (*15*) from Mie-Debye theory gave impressive agreement with experiment but also predicted sharper resonances, which were unresolved experimentally. This implies that even more precise measurements may be possible.

Another sensitive way to detect surface wave resonances is by direct observation of near- and far-field light scattering from levitated spheres (*13, 16, 17*). Near-field observations, in addition, give information on the internal light fields and the origins of surface wave resonances. For example, in the photograph shown in Fig. 4 of the near-field backscatter from a levitated oil drop, one sees that surface wave emission from the edges of the sphere dominates the backscatter. The existence of sharp surface wave resonances can also affect the wavelength dependence of inelastic light scattering from small particles. Such particle resonance effects were recently observed in the fluorescence from dye-impregnated spheres (*17, 18*). Minute distortions of liquid drops—as small as 1 part in 10^5—caused by electric fields have been observed by shifts of surface wave resonances (*17*). Such distortions give a new way of measuring the surface tension of liquids. In retrospect, it is remarkable that it has taken so long to recognize the usefulness of the basic spectroscopy of the fundamental spherical scattering particle.

Extension of the levitation technique to nonspherical particles (*10*) should make possible equally detailed scattering and force measurements on these particles. For example, one can hope to measure surface wave resonances of spheroids. In levitation experiments with oriented particles of more complex shape and internal structure, the ability to directly observe near-field transmission patterns and correlate them with the full far-field scattering patterns provides a new way to understand complex scattering without need for difficult mathematics (*10*).

Application of radiation pressure to

cloud physics and aerosols is based on the ability to manipulate and sensitively observe individual cloud-size liquid drops (9). One can study such fundamental processes as drop evaporation or condensation, drop-drop collision, interaction of charged drops, supersaturation of drops, and their crystallization. Evaporation or condensation can be observed directly with microscopes or, more sensitively, by measuring size changes with surface wave resonances (13). For example, by observing the scattering from a drop with a fixed-wavelength laser as the drop diameter varies continuously with time, one obtains the full surface wave spectrum of the sphere. By tuning a laser to the steep wings of a narrow resonance, one can observe changes in the average diameter of a drop of 1 part in 10^6 or about 0.1 angstrom for a 10-μm drop—a sensitivity of a fraction of a monolayer. Collisions between two drops of known size and charge can be seen by using the two-beam levitation technique (10). Fusion of drops of opposite electric charge can be induced by an externally applied electric field (9). Supersaturation and crystallization were observed in levitation experiments with drops of various salt solutions in environments of varying humidity (17). Use of radiation pressure has also been proposed for manipulation of water droplets in the near-zero-gravity environment of the Atmospheric Cloud Physics Lab payload being designed for the Shuttle Spacelab (19).

Use of optically levitated particles for the measurement of applied forces relies on direct observation of the displacement of particles from equilibrium or on detection of changes in the stabilized levitating power in the feedback force measuring technique. Measurement of optical forces was discussed above.

Measurement of the electric force on charged levitated particles gives a sensitive determination of electric charge. Indeed, this led to the discovery of photoemission rates as low as a few electrons per minute from optically levitated fused silica spheres due to a new type of three-photon nonlinear photoelectric effect in dielectrics (20). Using the optical levitation feedback technique to measure electric force, one can detect changes of the electric charge of single-electron units (21). Figure 5 illustrates the steplike decreases in optical levitating power caused by feedback in response to increased electric force as the charge on a sphere changes by units, from −1 electron up to 10 electrons, due to charging by ultraviolet light. Transition to full electric field or Millikan-type support can be made with increased charge. Combining Millikan support of an oil drop with optical measurement of size, and therefore mass, makes possible an absolute measurement of the charge of the electron accurate to about 1 part in 10^4 to 10^5. It is also seen in Fig. 5 that one has a sensitivity of measurement of a fraction of an electronic charge with oil drops in this general size range, which makes a search for quarks possible. Static electric charges deposited on surfaces can be measured with a sensitivity corresponding to a few electrons and a spatial resolution of micrometers by scanning a charged levitated particle over the surface and detecting the electrostatic force. It is hard to conceive of measuring surface charge with comparable sensitivity by other methods.

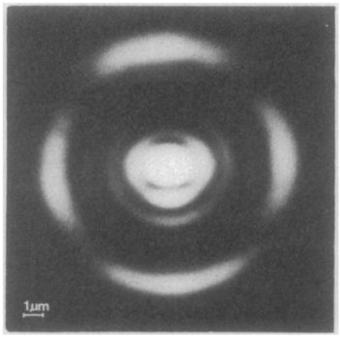


Fig. 4. Near-field photograph of ~ 12-μm dielectric sphere as seen in backscatter, showing the predominance of dielectric surface wave scatter from the sphere edges.

Diamagnetic forces on optically levitated particles have also been observed by manipulating the particles into regions with static magnetic field gradients (17). In this way one can sensitively measure relative diamagnetic susceptibilities. It is well known that stable diamagnetic levitation is possible at a magnetic field minimum (22). Surprisingly, one can apply sufficiently strong magnetic gradients to such weakly diamagnetic particles as fused silica spheres and glycerol drops to achieve stable diamagnetic levitation. These particles were transferred from optical levitation traps into small magnetic traps.

Another basic force on small particles that can be measured by levitation with the feedback force measuring technique is the radiometric force. This is caused by thermal gradients and is called photophoresis when the origin of the heat is optical absorption in the particle. The variation of the radiometric force with pressure can be observed (12) from its value at atmospheric pressure through its maximum and down to negligible values in high vacuum. The radiometric force is a sensitive measure of optical absorption in particles. Levitation under high vacuum, where radiometric forces are less than 10^{-7} of the radiation pressure forces, proves unequivocally that particles can be trapped solely by the forces of radiation pressure.

Whenever gas surrounding a fixed levitated particle flows, it subjects the particle to viscous drag forces by Stokes' law. Measurement of the viscous forces as a function of position with a maneuverable levitated particle gives a means of mapping gas flow patterns in chambers of varying shape. Flows as low as micrometers per second are readily detectable, for example, when vacuum chambers are slowly evacuated (12).

An important potential application of radiation pressure is to high-speed mechanical rotation of micrometer-sized particles in vacuum (12). This is possible with the feedback stabilization technique, which damps all linear motion while leaving rotational motion undamped. If one calculates, for example, the highest rotational frequency and centrifugal acceleration possible with a 4-μm-diameter silica sphere, at the point of rupture, one obtains ~ 1500 megahertz with an acceleration of ~ $10^{12}g$. This exceeds by a factor of about 10^3 the record values achieved by Beams (23) in his classic ultracentrifuge experiment on 0.4-millimeter-diameter magnetically levitated steel spheres. Angular acceleration can be achieved with torques based on the angular momentum of light. Measurable torques in reasonable agreement with the angular momentum of circularly polarized light have been observed on optically levitated particles at atmospheric pressure (17). In planetary science the lifetime of moderate-sized interplanetary dust grains is thought to be governed by just such a rotational bursting process driven by solar radiation pressure (24). The optical torques, however, are due to a windmill-type effect caused by asymmetries in particle shape. Attempts to study such torques are being made with lasers and levitation techniques (25).

It has been suggested that optical levitation could be useful for the support of targets in laser fusion experiments (6, 26). This is based on actual levitation of hollow quartz Microballoons that are typical of fusion targets and on the ability to stabilize the position of particles in high vacuum by optical feedback. Levitation may also be useful for manipulation and fabrication of more complex fusion target structures (10).

Another potential application of radiation pressure is to the separation and manipulation of biological particles such as cells and viruses in liquids (2). Lasers can do this with transparent dielectric spheres in liquids, where the spheres range in size from about 0.1 to 50 μm. With real biological particles care must be taken to avoid thermal absorption in the particles and the liquid. In order to understand optical forces on particles smaller than the wavelength of light (~ 0.5 μm), one has to abandon simple ray optical pictures (*2*) and invoke Rayleigh scattering (*14*). Indeed, the trapping of particles in the 0.1-μm region is more akin to the trapping of atoms in the off-resonance regime.

Radiation pressure from lasers has been used to help resolve some fundamental questions about the momentum of light in dielectric media. In a well-known gedankenexperiment, the sign of the light force on a free liquid surface is used to distinguish between the proposals of Minkowski and Abraham for the momentum in dielectrics (*27*). A pulsed laser experiment of this sort was performed on a water surface and sufficient force was achieved to overcome surface tension and generate a readily observable surface distortion (*28*). The result favored the Minkowski momentum. Analysis of this and other force measurements in liquids with conventional light sources has given a better picture of momentum in dielectrics (*29, 30*).

Radiation Pressure on Atoms

The basic forces and applications of radiation pressure on atoms are conceptually similar to those already discussed for macroscopic particles. For example, there is a scattering force that drives atoms in the direction of the light and a gradient force that pulls atoms into or out of regions of high light intensity. Use of these forces leads to transverse confinement of atomic beams within an optical beam and to the possibility of stable trapping of individual atoms in single Guassian beams, in analogy to levitation. The concept of heating of trapped macroscopic particles due to laser beam fluctuations and the idea of optical damping have their direct counterparts in atomic behavior. Applications to isotope separation are analogous to macroscopic particle sorting. There is a similar capability for particle manipulation on the scale of the light wavelength. Potential applications to high-resolution atomic spectroscopy are reminiscent of the demonstrated spectroscopic applications to macroscopic dielectric spheres. The details of radiation pressure on atoms must, however, be different because of the considerable difference in particle

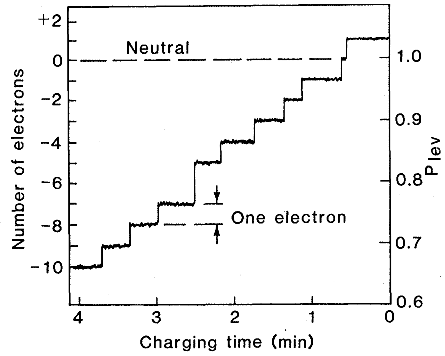


Fig. 5. Changes in the optical levitating power caused by the automatic feedback system as the charge on a sphere in an electric field increases by single-electron amounts.

size and the quantum nature of the interaction. Indeed, light forces on atoms are large only in the vicinity of a resonance transition. Their effects have therefore been termed resonance radiation pressure.

Figure 1 shows the resolution of the average forces on an atom into axial and transverse gradient components when the atom is off-axis at position R in an essentially parallel, nearly resonant Gaussian beam. The axial force is called the spontaneous scattering force and is denoted by F_{scat}. It is the average driving force in the direction of the incident light arising from the scattering process involving absorption of photons and their subsequent, on the average symmetric, spontaneous emission. This scattering force exists even for incident plane wave light. The idea of atomic recoil, which is the basis of this force, goes back to Einstein. Recoil of an atom due to absorption and emission of a single photon (the Einstein Rückstoss) was observed (*31*) with resonance lamps in prelaser times. At laser intensities the scattering force (*32*) increases to a maximum value set by saturation of the atomic transition. The force is a maximum at exact resonance. Its saturated magnitude is sufficient to stop a sodium atom moving at thermal velocities of $\sim 5 \times 10^4$ cm/sec in about 10 cm if continuously applied.

The scattering force has been directly observed in atomic beam deflection experiments with lasers (*33-35*). In these experiments resonant light striking a collimated atomic beam at right angles to its direction of motion causes sizable transverse deflections. The frequency sensitivity of this process has been used in high-resolution atomic beam deflection spectroscopy (*35*). Such deflections have also been used as a method of isotope separation (*34*) based on the finite isotope shift of resonance frequencies. A scheme for a continuously operating atomic beam velocity selector has been proposed (*32*) that uses the scattering force. The scattering force has also been observed to exert a significant pressure on a resonant atomic vapor; light-induced pressure increases of about 50 percent were seen (*36*). The strong velocity dependence of the scattering force due to the Doppler shift led to the important concept of optical cooling or damping of atomic motions (*37*). A pair of oppositely directed plane wave beams of equal intensity, tuned to a frequency below an atomic resonance, should damp any atomic motion along the direction of the beam pair since the Doppler shift always increases the scattering force of the opposing beam. Cooling of all components of atomic motion in an atomic vapor and transverse cooling of an atomic beam were proposed as uses for this technique. More will be said about this in connection with atom traps.

The transverse component of the average force on an atom in the Gaussian beam of Fig. 1 is due to the so-called dipole force (*3, 4, 38, 39*) and is designated by F_{dip}. This force arises in general from a gradient of the light intensity. The dipole force can be considered as the force on an optically induced atomic dipole in the gradient of the optical electric field. It is directed along the intensity gradient and is dispersive in nature because of its dependence on the atomic polarizability. Atoms are pulled either into or out of the region of high light intensity, depending on whether the light frequency is tuned below or above resonance. The dipole force is zero, on the average, right at resonance. It is the near-resonance form of electrostriction in gases. The dipole force arises from stimulated emission processes and can be equivalently understood in terms of the net light scattering coming from the interference of dipole radiation from the atom and the stimulating incident beam (*40*). To obtain large dipole forces one has to balance the effect of detuning from exact resonance and the amount of saturation for a given amount of available power (*3*). It was shown that the dipole force can be represented as the negative gradient of a potential which, for ~ 1 W of power and sodium atoms, for example, can be as deep as $\sim 10^4\ h\gamma_N \cong 10^{-4}$ electron volt, where h is Planck's constant and γ_N is the natural width of the resonance line. A potential of this depth is capable of confining atoms moving with a velocity of $\sim 2 \times 10^3$ cm/sec.

Observations of this dipole force of resonance radiation pressure at optical frequencies were first made in a Gaussian laser beam where the transverse component of the dipole force was used to transversely confine and focus a copropagating neutral sodium atomic beam to a small spot size (*41*, *42*). Figure 6 shows the experimental setup used to inject the atomic beam into the core of a tunable Gaussian dye laser beam. Figure 7A shows the shape of the atomic beam at the focal plane of the optical beam in the presence of light. When light tuned below resonance is turned on, atoms are transversely trapped within the light beam and focused or concentrated to an intense spot as shown. For light tuned above resonance (Fig. 7B), atoms are ejected or defocused from the beam, as expected from the dispervise character of the dipole force. One can in principle also trap atomic beams within light beams with light tuned above resonance by confining them on the axis of the TEM_{01}* mode of the laser beam, where the light intensity is a minimum. This is analogous to levitation of hollow dielectric spheres in air or of bubbles in liquids with the TEM_{01}* laser mode.

The fundamental experiment described above not only shows the essential properties of the dipole force but suggests several applications. For example, one should be able to perform isotope separation with an atomic beam containing two isotopes and a laser beam tuned between their resonance frequencies. The light beam should confine one isotope and eject the other, thereby achieving single-step separation ratios that can approach 10^3 (*41*). Optical steering of atomic beams was experimentally demonstrated by moving the guiding light beam (*41*). Other possibilities are the cleaning up of "dirty" atomic beams by confining only a desired species of atom. The ability to increase atomic beam intensities in small focal spots or in a long apparatus by the focusing and confining action of the dipole force is also useful.

Other proposals for use of the dipole force involve the transient behavior of the force when the interaction of the atoms with the light is short compared to a natural lifetime (*43*, *44*). Transient acceleration of atoms to high velocity in a rapidly moving standing wave field has been analyzed theoretically (*38*). Use of the transient dipole force to deflect atoms passing transversely through a standing wave field has been considered for isotope separation (*43*, *45*). Atomic beam deflection has been observed experimentally under these circumstances (*46*).

We now turn to the important topic of the fluctuations of the light forces acting on atoms due basically to the quantum nature of the interaction. Indeed, the forces described above, for cases where the atom interacts with the field for times long compared to a natural lifetime, were only the average forces that the light exerts on atoms. Fluctuations in spontaneous scattering are intuitively understood as arising from the temporal and spatial randomness of the absorption and spontaneous emission processes (*39*, *47*–*49*). Less obvious is the origin of fluctuations in the dipole force (*48*–*51*). Force fluctuations add randomness to the prediction of the dynamics of motion of atoms based on the average force and can be considered as a constant source of heat, which is added to the initially cold orbits predicted by the average force. The limiting effects of the fluctuations of the scattering force were observed directly, for the first time, in the atomic beam focusing experiment, where the size of the atomic focal spot as calculated for a transversely cold beam was found to increase monotonically with the amount of fluctuation heating of the transverse motion of the atoms (*52*). This fluctuation heating, in the absence of any additional cooling mechanism, must eventually lead to escape of all the initially cold atoms from the light beam.

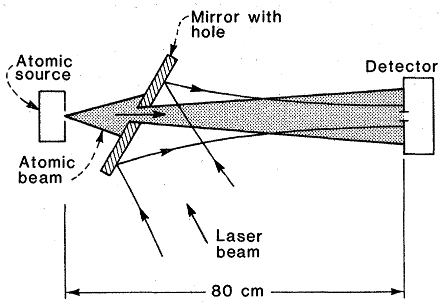


Fig. 6. Apparatus for observing focusing and defocusing of an atomic beam by the dipole force of a nearly resonant laser beam.

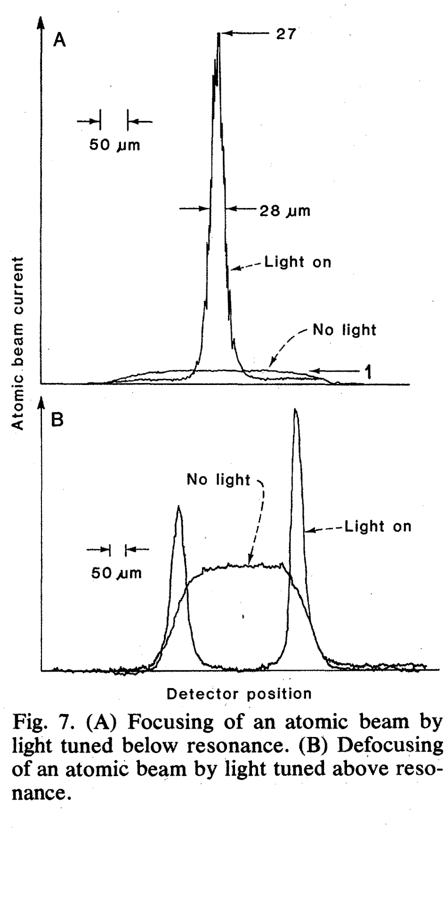


Fig. 7. (A) Focusing of an atomic beam by light tuned below resonance. (B) Defocusing of an atomic beam by light tuned above resonance.

Consider now ideas of how to make optical traps, using the above information on light forces. The observed confinement of atomic beams within the core of light beams (*41*, *42*, *52*) is a form of atom trapping, but only in two dimensions. Trapping of atoms in stable circular orbits was also considered in early proposals for use of the saturated scattering force (*32*). More recent concepts consider localized traps (*3*, *39*, *48*, *49*), with the atoms held as nearly at rest as possible. Thus the basic optical trap consists of an optical field configuration with a point of stable equilibrium such that any displacement of an atom from this point results in an average restoring force. The maximum kinetic energy of an atom that can be confined in a trap is defined as the well depth. If one places an atom with zero velocity at the equilibrium point of a trap, one expects that the average energy of the atom will increase at a steady rate due to heating from the quantum fluctuations until the atom eventually escapes from the trap in a time called the retention time. If the fluctuation heating of atoms can be counteracted by a sufficiently strong damping or cooling mechanism, such as optical cooling (*37*), then presumably atoms can be retained indefinitely. Indeed, the equilibrium kinetic energy of an atom in a trap results from a balance of the heating and cooling rates (*39*, *48*, *49*). The effectiveness of a trap in containing an atom is determined by the Boltzmann factor, given by the ratio of the well depth to the equilibrium kinetic energy. A large Boltzmann factor implies a low probability of thermal excitation over the top of the trap barrier and a very low probability of quantum mechanical tunneling through the barrier for typical trap dimensions. In practice, therefore, we seek both a low average kinetic energy and a large Boltzmann factor.

It has been proposed (*39*) that atoms of an atomic vapor can be trapped in relatively large volumes on the many local intensity maxima of three orthogonal pairs of standing wave beams tuned $\sim \gamma_N/2$ below the atomic resonance. This tuning was chosen to provide trapping and optimal damping. The resulting well depth of the trap is $\sim h\gamma_N$. Unfortunately, it was recently shown (*48*, *49*) that damping for a standing wave field varies as a function of position, at low atomic velocities, and is actually zero at the maximum of the standing wave, where atoms are expected to collect. A further problem with traps tuned for maximum damping is that one obtains an equilibrium kinetic energy of $\sim h\gamma_N$, giving a Boltzmann factor of about unity. Such traps are therefore very leaky.

Traps proposed more recently have wells that are two to three orders of magnitude deeper (*3*) than the standing wave traps considered above. These traps are based on strongly focused Gaussian beams tuned to produce essentially maximum depth for a given laser power. In geometry, they resemble the macroscopic particle traps described above. Perhaps the simplest such atom trap is a single strongly focused Gaussian beam. In this trap stability is achieved by making the axial gradient strong enough that the backward dipole force on an atom exceeds the scattering force tending to drive it away from the focus. For a tuning of $\sim 10^2$ to 10^3 γ_N below resonance, trap depths of $\sim 10^2$ to 10^3 $h\gamma_N$ are possible, but with much reduced damping. In fact, the Boltzmann factor is again ~ 1. However, use of an additional optimally tuned plane wave damping beam has been considered as a means of cooling atoms in such a trap to a minimum kinetic energy of $\sim h\gamma_N$. This corresponds to a large Boltzmann factor and a minimum temperature of $\sim 10^{-3}$ to 10^{-4} K. A possible problem with this damping scheme is related to the optical Stark shift of the atomic resonance of atoms moving in the trapping beam. Solutions to this problem have been proposed (*45*). It has been shown, however, that single-beam traps with no additional damping beams can be designed with sufficiently low dipole and scattering force heating that the retention time of initially cold atoms can be many seconds (*49*). This implies that an experimental demonstration of localized atom trapping is not contingent on damping. The effects of adding cooling beams can then be studied subsequently. Other versions of cooled traps based on a pair of opposing focused Gaussian beams having deep transverse and deep standing wave potentials are possible (*3*, *48*).

Injection of slow or cool atoms into traps will probably involve radiation pressure slowing of atomic beams with the scattering force (*3*, *53*). This is necessary because of the well-known absence of slow atoms in the low-energy tail of the Maxwellian distribution of atomic beams. Slow atoms are generally useful for other devices such as atomic clocks. Atoms caught in optical traps should be directly observable by their scattered fluorescence. Indeed, it should be possible to see even single atoms in this fashion, since scattering rates of about 10^6 to 10^8 photons per second are expected. Single atoms have been experimentally detected by their resonance fluorescence in other contexts (*54*, *55*). The ability to observe the fluorescence of a single atom also leads to the interesting possibility of sensing the position and velocity of an atom in a trap and then using electronic feedback on the trapping laser power to damp out fluctuations, just as was done for dielectric spheres in vacuum (*12*).

In the well-developed field of ion trapping there have recently been some highly relevant experiments on the optical cooling of ions (*56*, *57*). The concepts of optical cooling of ions held in electromagnetic traps were developed independently of those for radiation pressure cooling of neutral atoms, although in essence they are equivalent (*58*). The experiments have demonstrated significant optical cooling of ions by laser light. This success with ion traps bolsters hopes for optical cooling of neutral atoms in the more complex environment of an optical trap.

One immediate application of optical atom traps is to the study of basic atomic behavior under high optical excitation: the radiation forces, their fluctuations, the optical Stark shifts and other nonlinearities, and optical cooling mechanisms. High-resolution spectroscopy is an application common to optical neutral atom traps and ion traps. With very slow confined atoms one can make observations for long periods of time under conditions where first- and second-order Doppler effects are small. For many spectroscopic studies with optical traps the presence of the high-intensity light with its optical Stark shift would be undesirable. This problem could be overcome by turning the trapping beam off periodically for times long enough to study the high-resolution spectroscopy of the cold unexcited atoms but short enough to prevent escape of the slow atoms.

Some of the fascination with optical atom traps comes from their manipulative possibilities. For example, one can conceive of doing chemistry with individual atoms by combining separately trapped neutral atoms to form molecules, in analogy with the experiments on combining levitated macroscopic particles (*10*). With trapped cold neutral atoms one could study forces between atoms such as the weak van der Waals forces. There is also the possibility of observing for the first time coupling forces that exist between pairs of atoms under strong optical excitation when they approach one another in the near field of their radiation patterns (*59*). Furthermore, with atoms closely coupled to one another in their near field, or similarly an atom coupled to itself through its image in closely spaced mirrors, one has the prospect of observing modifications of the natural lifetime and radiation patterns of free atoms (*60*). One can also imagine arrays of atoms. The closest possible distance of approach of individually localized optically trapped cold atoms is a quarter of the optical wavelength of the trapping beam. This is possible in standing wave traps based on a pair of focused Gaussian beams (*3*). Tunneling of atoms between the successive field maxima of a standing trap has been considered (*39*). Tunneling between shallow standing wave maxima can be conveniently studied in traps with strong overall confinement in regions of focused-beam standing wave traps (*48*). The periodic potential of an optical standing wave has been considered for use as a stop and passband filter for the transmission of atoms of different velocities (*39*).

Many of the applications of optical traps mentioned above should be realizable with single-beam traps, in which the retention time for cooled atoms can be seconds. Successful addition of optical cooling, giving minimum kinetic energies of 10^{-3} to 10^{-4} K and much longer retention times, would greatly increase the utility of the technique. Whether this additional cooling can be achieved is the biggest unresolved question in optical trapping of atoms.

Although little direct work has been done on resonance radiation pressure on molecules, the same basic principles should apply. The scattering forces in general will be weaker because of the longer lifetimes, but strong dipole forces and trapping should be possible near molecular resonances.

References and Notes

1. P. Lebedew, *Ann. Phys. (Leipzig)* **6**, 433 (1901); *Astrophys. J.* **31**, 385 (1910); E. F. Nichols and G. F. Hull, *Phys. Rev.* **13**, 307 (1901); *ibid.* **17**, 26 (1903).
2. A. Ashkin, *Phys. Rev. Let.* **24**, 156 (1970).
3. _____, *ibid.* **40**, 729 (1978).
4. G. A. Askar'yan, *Zh. Eksp. Teor. Fiz.* **42**, 1567 (1962) [*Sov. Phys. JETP* **15**, 1088 (1962)].
5. A. Ashkin and J. M. Dziedzic, *Appl. Phys. Lett.* **19**, 283 (1971); A. Ashkin, *Sci. Am.* **226**, 63 (February 1972).
6. A. Ashkin and J. M. Dziedzic, *Appl. Phys. Lett.* **24**, 586 (1974).
7. G. Roosen, *Can. J. Phys.* **57**, 1260 (1979).
8. _____, *Opt. Commun.* **21**, 189 (1977).
9. A. Ashkin and J. M. Dziedzic, *Science* **187**, 1073 (1975).
10. _____, *Appl. Opt.* **19**, 660 (1980).
11. G. Roosen and C. Imbert, *Opt. Commun.* **26**, 432 (1978).

12. A. Ashkin and J. M. Dziedzic, *Appl. Phys. Lett.* **28**, 333 (1976); *ibid.* **30**, 202 (1977).
13. ______, *Phys. Rev. Lett.* **38**, 1351 (1977).
14. H. C. van de Hulst, *Light Scattering by Small Particles* (Wiley, New York, 1957); M. Kerker, *The Scattering of Light and Other Electromagnetic Radiation* (Academic Press, New York, 1969).
15. P. Chýlek, J. T. Kiehl, M. K. W. Ko, *Phys. Rev. A* **18**, 2229 (1978); *Appl. Opt.* **17**, 3019 (1978).
16. ______, A. Ashkin, in *Light Scattering by Irregularly Shaped Particles*, D. W. Scheuerman, Ed. (Plenum, New York, 1980), p. 153.
17. A. Ashkin and J. M. Dziedzic, unpublished results.
18. R. E. Benner, P. W. Barber, J. F. Owen, R. K. Chang, *Phys. Rev. Lett.* **44**, 475 (1980).
19. L. R. Eaton and S. L. Neste, *AIAA J.* **17**, 261 (1979).
20. A. Ashkin and J. M. Dziedzic, *Phys. Rev. Lett.* **36**, 267 (1976).
21. ______, unpublished results. Such a single electron sensitivity with a feedback scheme was recently demonstrated in an all-electrical modified Millikan support technique [S. Arnold, *J. Aerosol. Sci.* **10**, 49 (1979)].
22. G. Morpurgo, G. Gallinaro, G. Palmieri, *Nucl. Instrum. Methods* **79**, 95 (1970).
23. J. W. Beams, *Science* **120**, 619 (1954); *Rev. Sci. Instrum.* **21**, 182 (1950).
24. N. Y. Misconi, *Geophys. Res. Lett.* **3**, 585 (1976); S. J. Paddock and J. W. Rhee, *ibid.* **2**, 365 (1975).
25. N. Y. Misconi, S. J. Paddock, K. Ratcliff, private communication.
26. G. Roosen, B. G. de Saint Louvent, S. Slansky, *Opt. Commun.* **24**, 116 (1978).
27. M. G. Burt and R. Peirls, *Proc. R. Soc. London Ser A* **333**, 149 (1973).
28. A. Ashkin and J. M. Dziedzic, *Phys. Rev. Lett.* **30**, 139 (1973).
29. J. P. Gordon, *Phys. Rev. A* **8**, 14 (1973).
30. I. Brevik, *Phys. Rep.* **52**, 133 (1979).
31. O. R. Frisch, *Z. Phys.* **86**, 42 (1933).
32. A. Ashkin, *Phys. Rev. Lett.* **25**, 1321 (1970).
33. R. Schieder, H. Walther, L. Woste, *Opt. Commun.* **5**, 402 (1972).
34. A. F. Bernhardt, *Appl. Phys.* **9**, 19 (1976).
35. P. Jacquinot, S. Liberman, J. L. Pique, J. Pinard, *Opt. Commun.* **8**, 163 (1973); A. F. Bernhardt, D. E. Duerre, J. R. Simpson, L. L. Wood, *ibid.* **16**, 166 (1976).
36. J. E. Bjorkholm, A. Ashkin, D. B. Pearson, *Appl. Phys. Lett.* **27**, 534 (1975).
37. T. W. Hänsch and A. L. Schawlow, *Opt. Commun.* **13**, 68 (1975).
38. A. P. Kazantsev, *Zh. Eksp. Teor. Fiz.* **63**, 1628 (1972) [*Sov. Phys. JETP* **36**, 861 (1973)]; *Zh. Eksp. Teor. Fiz.* **66**, 1599 (1974) [*Sov. Phys. JETP* **39**, 783 (1974)].
39. V.S. Letokhov, V. G. Minogin, B. D. Pavlik, *Zh. Eksp. Teor. Fiz.* **72**, 1328 (1977) [*Sov. Phys. JETP* **45**, 698 (1977)]; V. S. Letokhov and V. G. Minogin, *Appl. Phys.* **17**, 99 (1978).
40. J. P. Gordon, private communication.
41. J. E. Bjorkholm, R. R. Freeman, A. Ashkin, D. B. Pearson, *Phys. Rev. Lett.* **41**, 1361 (1978).
42. D. B. Pearson, R. R. Freeman, J. E. Bjorkholm, A. Ashkin, *Appl. Phys. Lett.* **36**, 99 (1980).
43. A. P. Kazantsev, *Usp. Fiz. Nauk* **124**, 113 (1978) [*Sov. Phys. Usp.* **21** (No. 1), 56 (1978)].
44. R. J. Cook, *Phys. Rev. Lett.* **41**, 1788 (1978).
45. ______ and A. F. Bernhardt, *Phys. Rev. A* **18**, 2533 (1978).
46. E. Arimondo, H. Lew, T. Oka. *Phys. Rev. Lett.* **43**, 753 (1979).
47. A. Yu. Pusep, *Zh. Eksp. Teor. Fiz.* **70**, 851 (1976) [*Sov. Phys. JETP* **43**, 441 (1976)].
48. A. Ashkin and J. P. Gordon, *Opt. Lett.* **4**, 161 (1979).
49. J. P. Gordon and A. Ashkin, *Phys. Rev. A* **21**, 1606 (1980).
50. A. P. Botin and A. P. Kazantsev, *Zh. Eksp. Teor. Fiz.* **68**, 2075 (1975) [*Sov. Phys. JETP* **41**, 1038 (1975)].
51. R. J. Cook, *Phys. Rev. Lett.* **44**, 976 (1980).
52. J. E. Bjorkholm, R. R. Freeman, A. Ashkin, D. B. Pearson, *Opt. Lett.* **5**, 111 (1980).
53. V. I. Balikin, V. S. Letokhov, V. I. Mishin, *Pisma Zh. Eksp. Teor. Fiz.* **29**, 614 (1979) [*JETP Lett.* **29**, 560 (1979)].
54. W. Neuhauser, M. Hohenstatt, P. Toschek, H. Dehmelt, *Appl. Phys.* **17**, 123 (1978).
55. W. M. Fairbank, Jr., and C. Y. She, *Opt. News* **5** (No. 2), 4 (1979).
56. D. J. Wineland, R. E. Drullinger, F. L. Walls, *Phys. Rev. Lett.* **40**, 1639 (1978).
57. W. Neuhauser, M. Hohenstatt, P. Toschek, H. Dehmelt, *ibid.* **41**, 233 (1978).
58. D. J. Wineland and W. Itano, *Phys. Rev. A* **20**, 1521 (1979).
59. N. I. Zhokova, A. P. Kazantsev, E. F. Kazentsev, V. P. Sokolov, *Zh. Eksp. Teor. Fiz.* **76**, 896 (1979) [*Sov. Phys. JETP* **49**, 452 (1979)].
60. K. H. Drexhage, *Prog. Opt.* **12**, 165 (1974); W. Lukosz and R. E. Kunz, *J. Opt. Soc. Am.* **67**, 1607 (1977).

Seismic Models of the Root of the Sierra Nevada

L. C. Pakiser and James N. Brune

The deep crustal structure of the root of the Sierra Nevada in California has been studied periodically since 1936. At that time Lawson (*1*) used average crustal and upper-mantle densities and isostatic principles to estimate that the Sierran root extends downward into the mantle to reach a total crustal thickness of 68 kilometers in the vicinity of Mount Whitney. At Lawson's request, Byerly (*2*) in 1937 reviewed seismic evidence bearing on the Sierran root. Byerly demonstrated that seismic waves from earthquakes in northern and central California, as recorded at seismograph stations in Owens Valley, just east of the Sierra Nevada, arrived late when compared with seismic waves recorded at the same stations from earthquakes in Nevada and southern California. He concluded that these delays in travel times supported Lawson's findings.

Byerly assumed that the P_n seismic waves, which travel in the uppermost mantle and arrived at seismograph stations at Tinemaha and Haiwee from earthquakes to the west and northwest, emerged from a sharp western edge of the Sierran root. He further assumed that they were delayed by propagation through the low-density rocks of the Sierra Nevada batholith, in which seismic wave velocity is low. On the basis of these assumptions, the observed delays, and P-wave velocities through the crust and upper mantle of 5.6 and 8.0 kilometers per second, respectively, he calculated that the maximum width of the root is 70 km and that the minimum is 40 km. Byerly made no estimate of the depth of the Sierran root because, according to his assumptions, Owens Valley would lie in a "shadow" of the batholith in which waves emerging from the bottom of the root would not be observed as first arrivals.

In 1939, Byerly (*3*) elaborated on his earlier study and concluded that seismic waves arriving at Santa Barbara from an earthquake in Nevada could have been delayed as much as 1.2 seconds, owing to diffraction under the root. From this he calculated that the maximum crustal thickness beneath the Sierra Nevada could be as much as 71 km.

Recent Evidence Confirms, and Denies, the Existence of a Sierran Root

In the early 1960's, the U.S. Geological Survey conducted an extensive seismic-refraction study of crustal structure in the western United States (*4*). Eaton (*5*) interpreted a profile of that study recorded across the Sierra Nevada between explosion sites near San Francisco, and Fallon, Nevada. His analysis of travel times of waves generated by the explosions indicated that the Mohorovicic (Moho) discontinuity at the base of the crust descends to a depth of at least 40 km beneath the Sierra Nevada. Eaton later interpreted two seismic-refraction profiles based on explosions at Shasta Lake, Mono Lake, and China Lake, California, and concluded that the high southern part of the Sierra Nevada is underlain by a crust about 54 km thick. Oliver (*6*) demonstrated that gravity data in the Sierra Nevada are consistent with Eaton's crustal model. Prodehl (*7*) reinterpreted the profiles originally analyzed

L. C. Pakiser is a geophysicist with the U.S. Geological Survey, Denver, Colorado 80225. James N. Brune is professor of geophysics, Institute of Geophysics and Planetary Physics, University of California, San Diego, La Jolla 92093.