THE GLORY

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THE GLORY

This halo of prismatic colors is most often seen around the shadow of an airplane on a cloud. Its cause is not the same as that of the common rainbow, and involves phenomena at the frontier of physics

by Howard C. Bryant and Nelson Jarmie

"If it be shortly after sunup of a morning when the fog has obliterated the highway below, I am then rewarded with a spectacle rare to witness. Looking up the coast toward Nepenthe... the sun rising behind me throws an enlarged shadow of me into the iridescent fog below. I lift my arms as in prayer, achieving a wingspan no god ever possessed, and there in the drifting fog a nimbus floats about my head, a radiant nimbus such as the Buddha himself might proudly wear. In the Himalayas, where the same phenomenon occurs, it is said that a devout follower of the Buddha will throw himself from a peak—'into the arms of Buddha.'"

So does Henry Miller, in *Big Sur and the Oranges of Hieronymus Bosch,* describe his observation of the meteorological phenomenon known as the glory. He conveys his feeling of apotheosis on viewing his shadow on a fog bank, "glorified" with colored rings similar to those of the rainbow. The spectacle is indeed a rare one for ground-based observers such as the solitary hiker in Miller's narrative, because it requires an unusual configuration of the sun, the observer and a cloud composed of droplets of uniform size. It is seen regularly, however, by air travelers, particularly those who know where to look. In fact, it is sometimes called the pilot's bow. Other names for the glory are the anticorona and the brocken bow.

Like the common rainbow, the glory is caused by the scattering of sunlight by droplets of water. Like the primary rainbow, the brightest in a series of rainbows, it consists of concentric rings of color, with red the outermost and violet the innermost, encircling a bright central region in the direction opposite to that of the sun. Unlike the primary rainbow, whose red ring is invariably at an angle of 42 degrees from the direction of the shadow cast by the observer, the glory has rings whose angular diameter varies inversely with the diameter of the droplets that give rise to them. The primary rings are often accompanied by as many as four similar sets of rings of larger angular diameter. Typically the innermost red ring has a diameter of two or three degrees.

To see a glory close up you must view the cloud of uniform water droplets in such a way that your shadow is projected on the cloud. You will be rewarded by a vision of the shadow of your head surrounded by a series of colored haloes. Moreover, a feeling of uniqueness may be oddly enhanced: if someone else is with you, his shadow will not appear to be so endowed. One may even speculate that the artistic practice of rendering the heads of holy or powerful personages with luminous and sometimes colored haloes or nimbuses could have arisen from the observation of such haloes on fog banks by solitary mystics on well-illuminated heights. The use of the halo is not restricted to Christian iconography: glorylike structures can be seen surrounding the heads of Roman emperors and Greek gods, and of icons from China, Burma and India, suggesting that such representations may have a universal natural origin.

The first scientific record of the glory was a drawing made by Antonio de Ulloa during a French expedition to Peru in 1735. Both he and Pierre Bouguer also wrote descriptions, translations of which can be found in R. A. R. Tricker's *Introduction to Meteorological Optics.* Balloonists in the 19th century were able to see the glory encircling the shadow of the basket of the balloon, as Gaston Tissandier relates in his *Observations météorologiques en ballon.* These sightings and others are described in detail in the classic work *Meteorologische Optik,* by Josef M. Pernter and Felix M. Exner, published in Vienna in 1910.

C. T. R. Wilson built the first cloud chamber in 1895 for the purpose of recreating the glory in the laboratory. He put aside his original objective when he found that energetic charged particles leave visible tracks of water droplets in the moist air. In his Nobel prize lecture of 1927 he reported: "In September, 1894, I spent a few weeks in the observatory which then existed on the summit of Ben Nevis, the highest of the Scottish hills. The wonderful optical phenomena shown when the sun shone on the clouds surrounding the hilltop, and particularly the colored rings surrounding the sun (coronas) or surrounding the shadow cast by the hilltop or observer on mist or cloud (glories), greatly excited my interest and made me wish to imitate them in the laboratory."

What is the explanation of this lovely apparition? We have indicated that the glory is caused by the scattering of light from water droplets back toward the source of the light. In the process the scattered light is enhanced. To be sure, light is enhanced when it is scattered backward from many things other than fog or clouds, including plowed fields, foliage, the eyes of many animals and dewy grass. Let us first discuss some of these nonglory effects to illustrate the variety of the mechanisms at work.

The "cornfield effect," or backscattering from a plowed field or foliage, can actually be observed on any rough surface that casts small shadows. When we look at the surface from the direction of the illumination, we do not see the shadows and the surface looks unusually bright. The reason is that the brightness is contrary to our expectation: from other directions parts of the surface are darkened by the shadows, and the eye

GLORY FROM THE AIR surrounding the shadow of an airplane projected on a cloud below is seen in this photograph made by Fritz Goro. Since the glory is often visible under these circumstances, it is sometimes called the pilot's bow. Around the shadow there is a glow covering a circular area half-obscured by the shadow. Surrounding the central area are two sets of concentric colored rings with blue on the inside and red on the outside. To unaided eye the colors are sometimes much brighter than they appear here.

GLORY FROM THE GROUND was photographed by John C. Brandt of the National Aeronautics and Space Administration at the Zodiacal Light Observatory on Haleakala Crater on the Hawaiian island of Maui. The picture was taken before sunset as the crater was filled with cloud or fog. Five glory rings are visible; their angular radii, measured from the red rings, are 1.2 degrees, 3.0 degrees, 4.9 degrees, 6.7 degrees and 8.3 degrees. Normally the shadow of the person viewing the glory is visible, but here it is not.

integrates the image so that the surface appears uniformly darker.

Backscattering from animal eyes arises from the fact that the illuminating light ray is reversed with high precision. Light entering the animal's eye from the direction of the observer is brought to a focus on the animal's retina; then some portion of it is scattered back toward the lens of the animal's eye and refracted back in the direction from which it came. The result is that the animal's eye appears to be illuminated from within.

The effect is enhanced in cats, dogs, rabbits and other animals because they have a reflecting layer behind the retina. Man lacks this layer, but on occasion his eyes backscatter very well. David L. MacAdam, editor of *The Journal of the Optical Society of America,* comments: "Any photographer who has taken many close-up color pictures with a flash lamp built into his camera, close to the lens, will recall his dismay when some of his pictures were ruined by brilliant red spots coincident with the pupils of the eyes of some of his subjects. A considerable portion of fair-haired, light-eyed persons have such strong reflection from the fundus of the eye as to produce this Heiligenschein [the German for halo]. It can also be seen clearly by another person over whose shoulder a bare incandescent tungsten bulb is shining directly into the eyes of the subject, in an otherwise poorly lighted room."

It is effects of the Heiligenschein type that are seen against a background of dewy grass. When one looks at the grass from the direction of illumination, the shadow of one's head appears to be surrounded by a bright area. As with animal eyes, the water droplets, which are more or less spherical, serve as miniature converging lenses that collect the light and focus it on the blades of grass on which they rest. Much of the focused light is scattered in all directions by the leaf, but some of it reenters the droplet and is refracted backward in the direction from which it came.

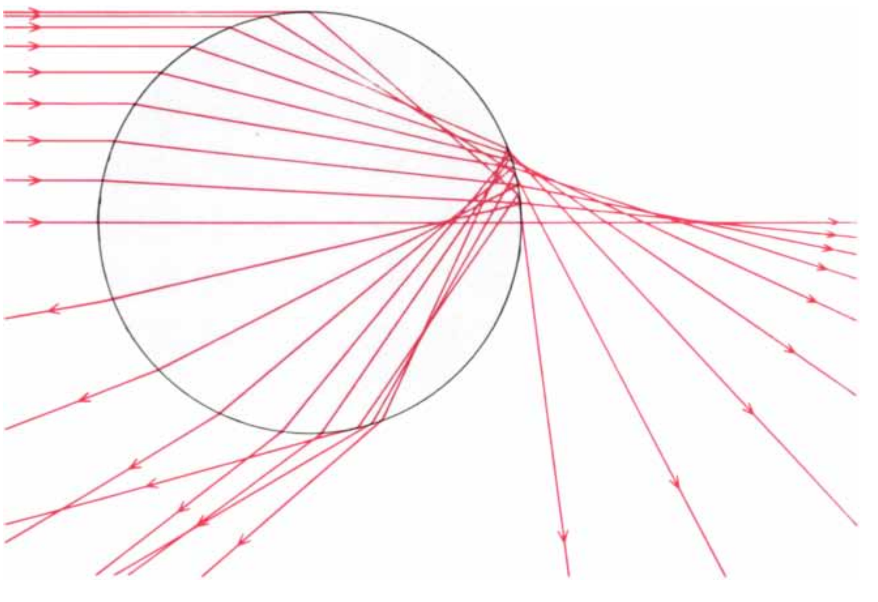
A completely different mechanism is needed to account for the glory. In 1947 the Dutch astronomer H. C. van de Hulst put forward the explanation that the light of the glory is sent back from the edges of the spherical water droplets in the cloud. For the moment let us set aside the question of how the light is returned from the droplet's edge and concentrate on understanding how the glory would be produced in that way by a random distribution of uniform droplets.

Since each droplet is returning the light from its edge, each is effectively a ring-shaped light source sending light back toward the sun. One way to simulate examining the optics of a field of backward-scattering water droplets is to replace the droplets with an opaque screen that has ring-shaped apertures in it and illuminate the screen from behind with a beam whose rays are parallel [*see bottom illustration on page 64*]. When the screen is viewed from a distance, the resulting diffraction pattern, or distribution of the intensity of the scattered light, will be very much like the diffraction pattern of the glory.

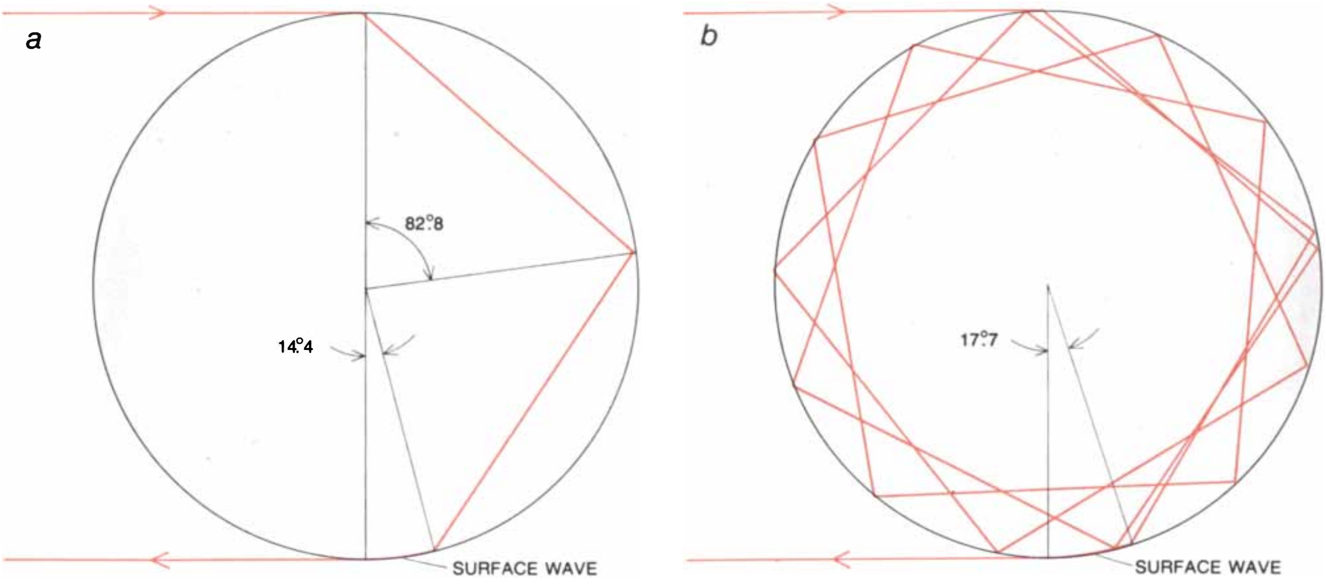
Why should this be so? The diffraction pattern from a single ring can be understood by regarding each point on the ring as a separate source of coherent light waves. This means that all the wavelets coming from each point on the ring will be in phase with one another. The light arriving at any particular point on another screen at some distance from the aperture will consist of contributions from all the points around the ring. Only on the part of the screen that is directly in front of the ring will the wavelets be exactly in phase, since it is only there that the distance each wavelet has traveled from the ring's edge is the same as the distance every other wavelet has traveled. At that point on the screen there will be a circular spot of maximum brightness.

In a region at a small angle away from the spot of maximum brightness the path each wavelet takes is either longer or shorter than the path of its neighbor, and the wavelets begin to interfere destructively with one another. The intensity of the light falls to a minimum, and there is a ring of minimum brightness around the central bright spot. At a greater angle away from the bright spot the light intensity begins to increase again to a second-order maximum: wavelets from opposite sides of the ring have a difference of one wavelength in the distance they travel to the screen and are back in phase again. This second-order maximum (and successive maximums at even greater angles, for which the differences in path length differ by two, three, four or any other whole number of wavelengths) is not as intense as the principal maximum in the center because it is only at that one central spot that all the wavelets are in phase.

So far we have described what happens with only one ring. To illustrate what happens in a glory we prepared a random array of many ring sources. First we drew 241 circles two millimeters in diameter with black ink on a piece of white paper about 12 centimeters on a side. Then we photographed the piece of paper to get a 35-millimeter negative; the negative showed transparent rings on a black background reduced in size by a factor of 16. We set up a parallel-ray source of coherent light by passing the red beam of a helium-neon laser through a shutter into a microscope lens with a pinhole at its focal point. The beam was then directed through a converging lens whose focal point was also at the pin-



LIGHT THAT ACCOUNTS FOR THE COMMON RAINBOW is not sent straight back toward the observer. The primary rainbow is caused by parallel light rays that are incident from the left being refracted off to lower left by a spherical water droplet. The rays to the right of the droplet are those that go straight through without contributing to the rainbow.

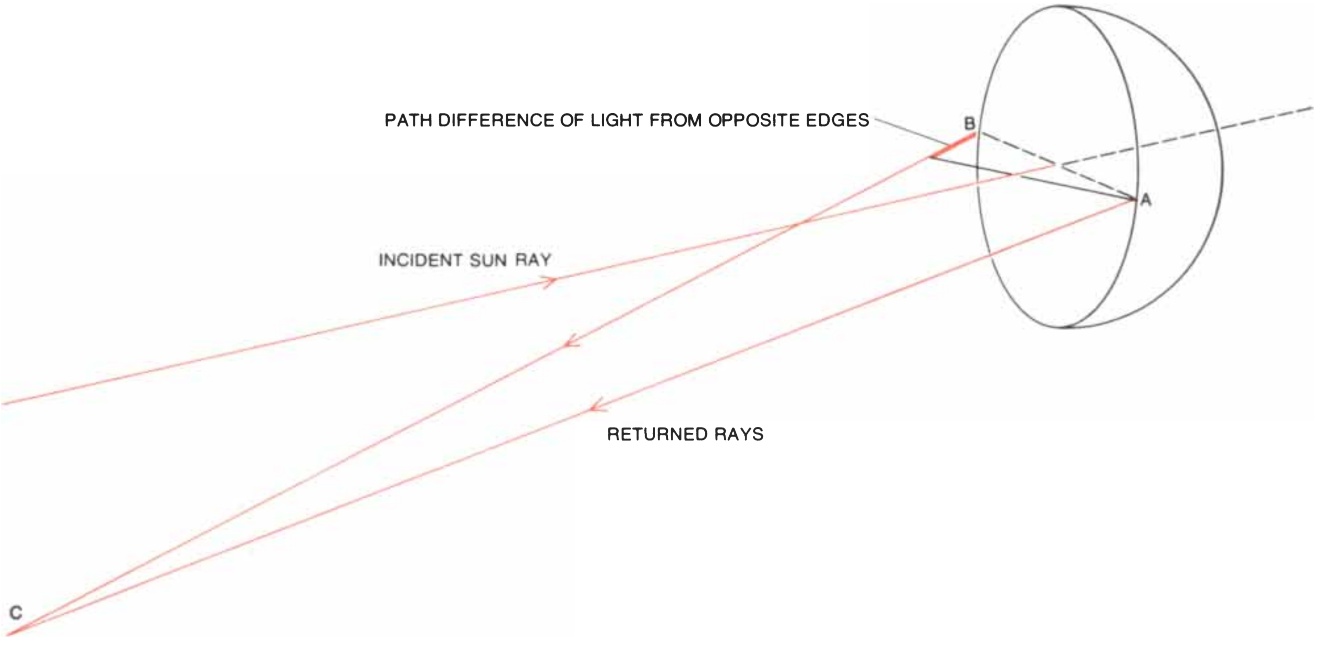


LIGHT THAT ACCOUNTS FOR THE GLORY follows paths that are different from those that are responsible for the common rainbow. The paths consist of light that is reflected repeatedly at an angle of 82.8 degrees within the droplet, together with small segments of surface waves in which the light clings to the surface of the droplet and is conveyed the rest of the way around the droplet to the backward direction. When a number of different paths give rise to light waves that are in phase, there is a resonance, or enhancement, in the backscattered light. The glory is believed to be due principally to the paths in which the light travels halfway around the droplet (*a*) and those in which it travels three and a half times around the droplet (*b*) before being sent straight back.

hole. This train of optical devices gave us a parallel-ray beam of coherent light two centimeters in diameter, into which we inserted the photographic negative of the array of rings.

We now had a field of coherent ring sources, each about 125 micrometers across, which together simulated the effect of a uniform field of spherical droplets that are backscattering light. In order to record the diffraction pattern as it would appear at a distance from the array we put a lens with a focal length of one meter in front of the array and placed a sheet of photographic film in its focal plane. The resulting photograph of concentric bright and dark rings approximately represents the appearance of a glory seen through a red filter [*see illustration on page 65*].

We can now explain the presence of

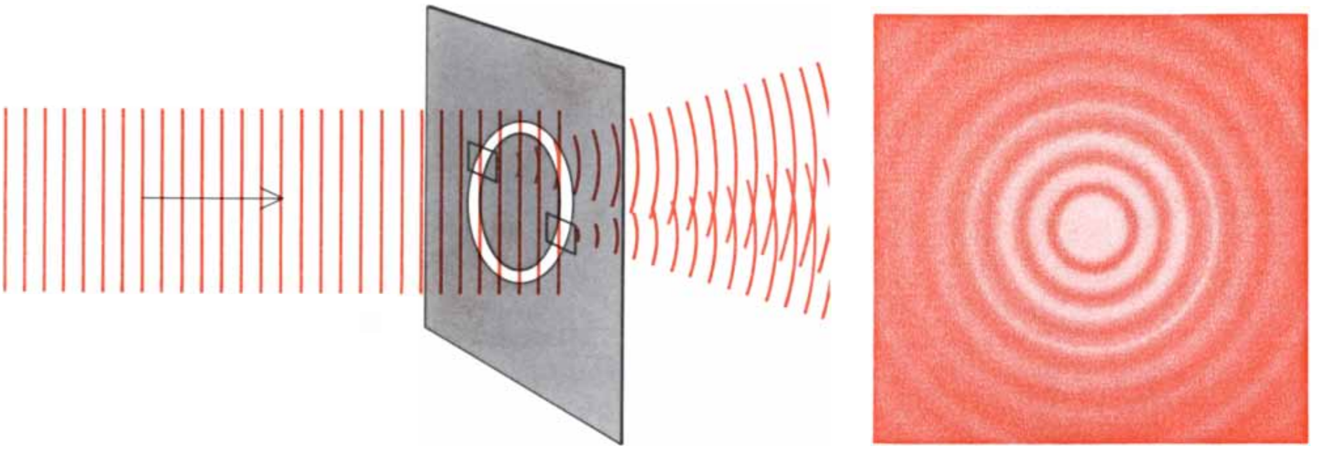


EDGES OF WATER DROPLETS of uniform size scatter sunlight back toward the observer in the formation of a glory. Here the path of rays returning from a single droplet is traced; the droplet is cut in half to show the geometry of the rays. If the observer is straight back from the droplet, the waves on every ray from the edge of the droplet will be in phase and will reinforce one another. As the angle of the observer to the path of the light falling on a droplet increases, the waves from opposite edges begin to go out of phase and interfere. As the angle increases further, they come back into phase and reinforce again. A secondary maximum in brightness is reached near the point where the difference between paths *AC* and *BC* is one wavelength. The rings of the glory are colored because the many different wavelengths in sunlight go through their cycles of maximum and minimum brightness at different angles.

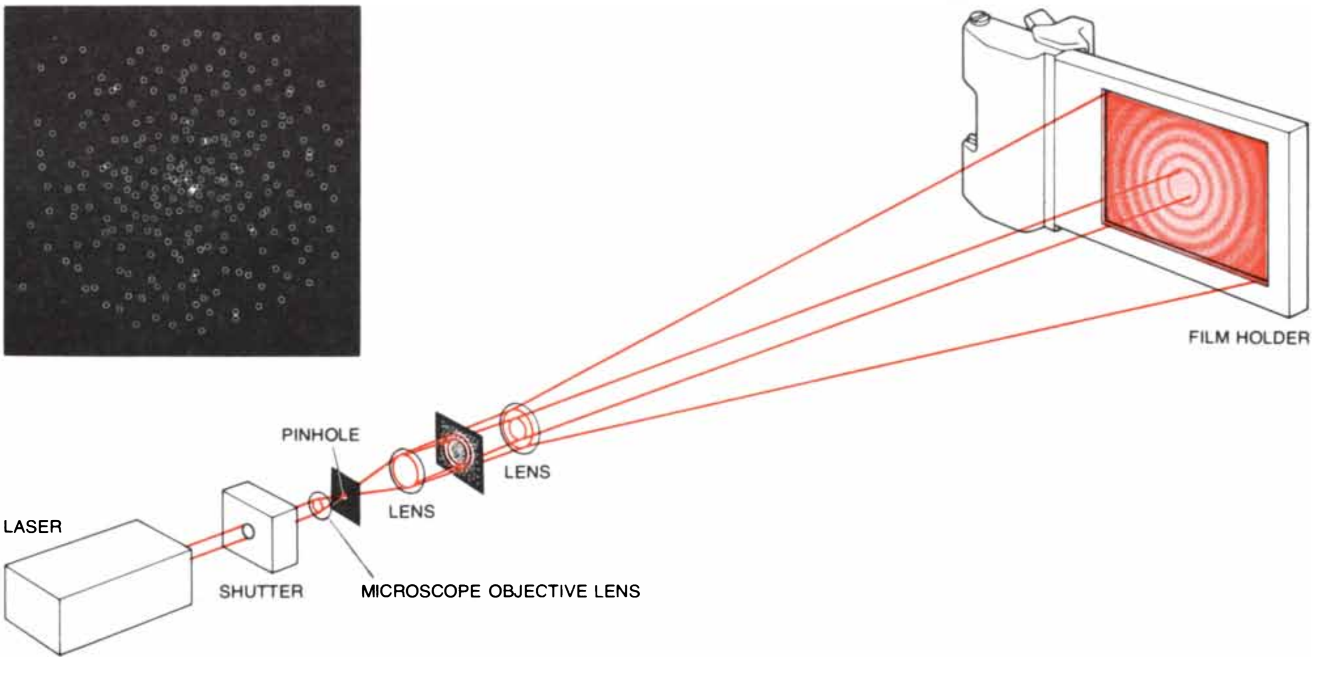
colored rings in the glory. When each wavelength in the solar spectrum is backscattered from an array of droplets of uniform diameter, it will give rise to a pattern similar to the pattern of concentric rings in the photograph. The longer the wavelength, the larger the diameter of the diffraction rings. Although all wavelengths will contribute to the bright central maximum, at other angles only light of certain wavelengths will be at a maximum. Therefore the light in the glory away from the central maximum will be colored. In every sequence of spectral colors red will be at the largest angle from the center, since it has the longest wavelength. Thus the outermost ring of the glory is always red.

Of course, our artificial ring sources are only an approximation of the optical properties of an array of backscattering water droplets. One difference is that the laser light giving rise to the diffraction pattern in the artificial array is not backscattered. We have left out the effects of the polarization of the light; we have also neglected the beam directly reflected from the center of the droplet. The correct treatment of polarization alters the distribution of the light's intensity somewhat, and the inclusion of the central point source produces an enhancement or diminution of every other ring, depending on its phase.

We now return to the question of how droplets scatter light backward from their edges. The fact that they do so can be demonstrated by constructing a large transparent sphere and directing sunlight at it. Permanently mounted in a lecture hall at the University of New Mexico is a heliostat, an optical mechanism made up of a series of mirrors that tracks the sun across the sky during the course of a day and sends a sunbeam 35



SINGLE RING APERTURE (*left*) **illuminated by plane-parallel light** (*color*) **gives rise to a diffraction pattern that is a series of concentric circles. The ring aperture can be regarded as one droplet in the cloud that causes the glory. Each point on the ring** (*indicated by the two rectangles*) **acts as a separate source of wavelets of coherent light. Wavelets interfere either constructively or destructively at different angles away from direction of light coming straight back. This interference produces the light and dark rings** (*right*).



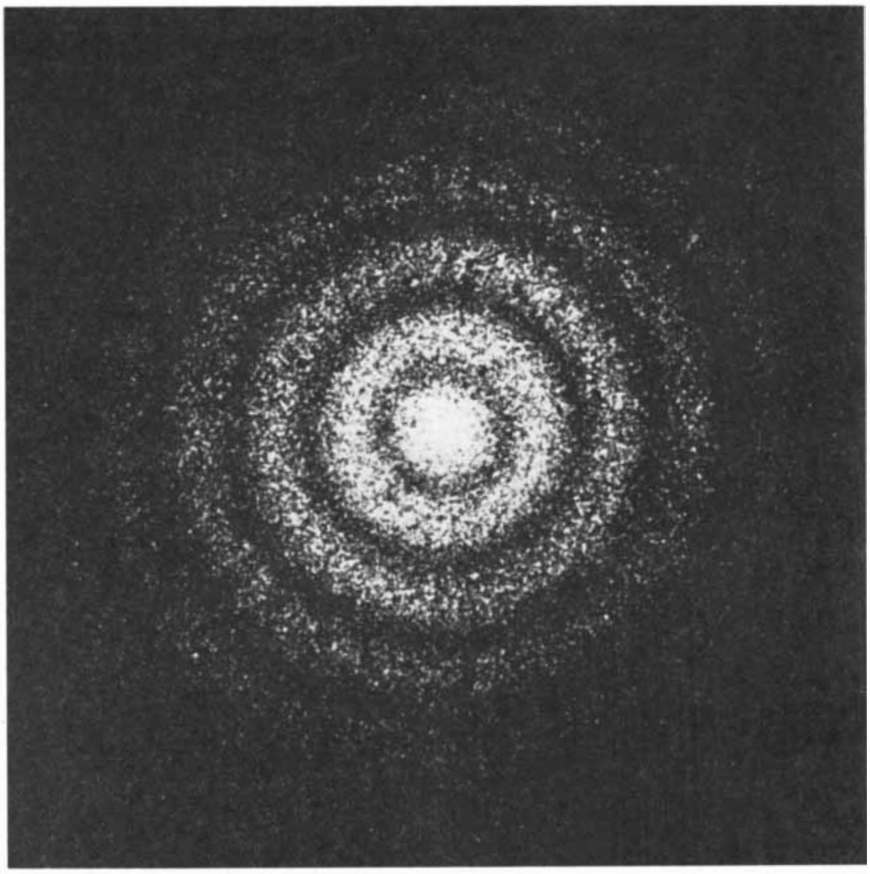
MANY RING APERTURES together (*insert at top left*) **act as a cloud of uniform water droplets and generate a diffraction pattern that resembles the glory. First a series of 241 randomly placed circles were drawn on white paper. Then a much reduced photographic negative was made from the drawing. A parallel-ray beam of red light from a helium-neon laser was directed through the array of rings; a lens formed an image of the diffraction pattern that was recorded on Polaroid film** (*see illustration on opposite page*).

centimeters in diameter across the front of the hall. Into this beam we can insert a Lucite sphere with a diameter of 30.48 centimeters (12 inches).

In addition to producing a marvelous rainbow that covers one of the white walls of the lecture hall, the system demonstrates the "backward" optics of transparent spheres. We can view the sphere from the direction of the sunbeam by inserting a small mirror into the beam. It can be seen that the backward-directed light indeed comes principally from the edge of the sphere, with a small additional contribution from specular reflection at the center of the sphere's face.

When the sphere is viewed from a point that is even at a slight angle to directly backward, its appearance changes considerably. Its edge is still well illuminated, and the equatorial region of the edge is particularly bright. The specular reflection from the face is off center.

If a plant leaf or a piece of paper is placed five centimeters behind the sphere, one can see the Heiligenschein. The sphere becomes very bright. The presence of the leaf greatly enhances the amount of light sent backward in the direction from which it came, to the extent that the glow reflected back to the mirror of the heliostat can be seen throughout the lecture hall.



DIFFRACTION PATTERN that approximately represents the appearance of a glory seen through a red filter was photographed with the apparatus that is shown in the illustration at the bottom of the opposite page. Graininess in the picture is caused by interference among individual apertures; if the number of apertures were increased, graininess would decrease.

This procedure with sunlight and the Lucite sphere is instructive, but more relevant studies have been made in the laboratory with laser light and real droplets of water suspended in midair. Theodore S. Fahlen, who was then working at the university, found that droplets could be suspended in two different ways. In the first method a resonator made from a cylindrical piezoelectric crystal and a circular watch glass produced an acoustical standing wave. Droplets as large as a millimeter in diameter could be suspended in midair at the region of maximum acoustical pressure for up to several minutes without appreciable vibration.

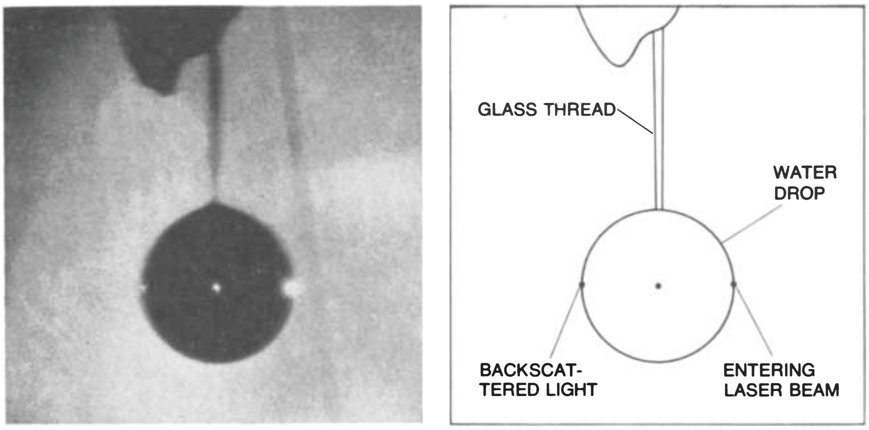
The second method simply entailed suspending the droplet by its own surface tension from a glass fiber whose end had been enlarged to form a tiny bead; the fiber could hold droplets two or three millimeters in diameter. This method proved to be more useful than the other one. If the optical effects are to be observed, the surface of the droplet must be exceedingly quiet and smooth, much quieter and smoother than the droplets that were levitated in the acoustical resonator. M. J. Saunders of Bell Laboratories has used the fiber method to make and study water droplets as small as nine microns in diameter. (His fibers were bits of spider web.) Saunders has verified that even with such small droplets the backscattered light comes from the edge of the sphere.

Why should the light be scattered mostly from the edge? In trying to answer that question we approach some current frontiers of optics and particle physics, even though the precise solution of how an electromagnetic wave (in this case light) is scattered from a transparent sphere has been known since the beginning of the century.

In 1908 the German physicist Gustav Mie showed that the intensity of an electromagnetic wave scattered from a sphere can be calculated as precisely as one wants for any angle, including angles in the backward direction. He showed that the intensity of the light scattered at any angle can be represented as a sum of a series of algebraic terms, each composed of involved mathematical expressions. These terms are not of the type that can be easily computed on the back of an envelope. In addition the number of terms that must be evaluated in order to arrive at the intensity at a given angle for a specific wavelength is somewhat larger than the circumference of the sphere in nanometers divided by the wavelength in nanometers. For a droplet one millimeter in diameter, for example, and green light of a wavelength of 500 nanometers, some 6,300 terms have to be evaluated and added together. And to get the entire intensity pattern for just one wavelength of light requires repeating the process for a number of angles.

Thus in addition to a desire to learn the details of Mie's predictions for a given case one must have access to the services of a high-speed computer. It is only within the past decade that Mie calculations for large spheres have been conducted to any extent. To make matters worse, the intensity of the backscattered light is extremely variable. As A. J. Cox has demonstrated at the University of New Mexico, a very small change in the wavelength of the light can result in a change of intensity as large as a factor of 100.

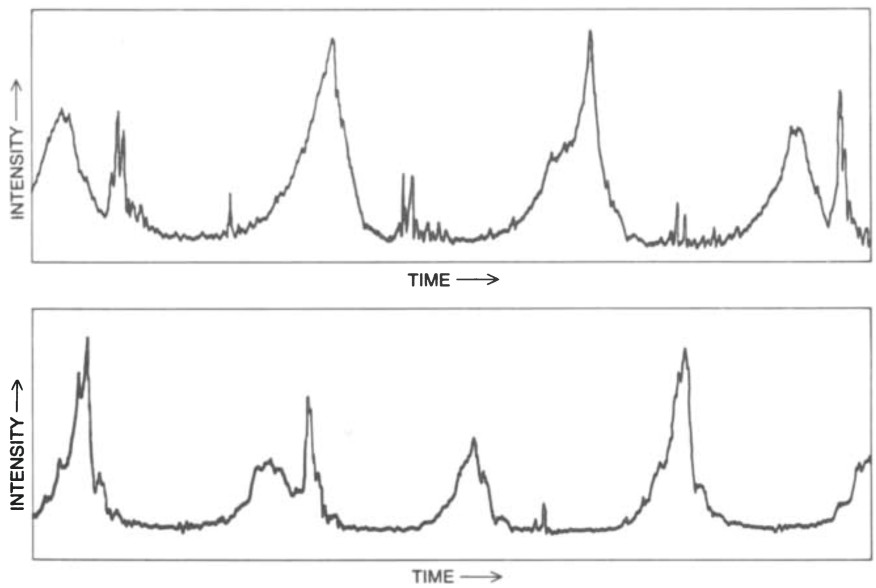
There are less exact but perhaps more instructive ways to treat the scattering



WATER DROPLET SUSPENDED from a glass thread returns a beam of laser light straight back toward the observer. The beam entered at the right edge of the droplet and was sent back at the left edge. Experiment demonstrates that in giving rise to the glory, light waves must be conveyed around the surface of the droplets. Droplet is two millimeters in diameter; thread is 40 micrometers thick. Central bright spot on droplet is due to backlighting.

of light. For instance, primary and secondary rainbows can be explained in terms of geometrical optics: the primary bow is produced by light that is reflected once inside a droplet of water and the secondary bow is produced by light that is reflected twice. The glory cannot be explained on this basis, because in an ordinary rainbow the rays striking the edge of the droplet do not come straight back. It is nonetheless possible to understand in terms of ray optics the small contribution made to the glory along the axis of the incident light beam.

Rays are reflected not only from the outer surface of the drop but also from the inner surface. Since only some 2 percent of the light falling perpendicularly on an interface between air and water is reflected, the amount of light traversing paths that involve more than one such reflection will be negligible compared with the two direct reflections. The relative phase of the two rays comprising the axial contribution varies with the diameter of the droplet. The two beams interfere with each other to give rise to an intensity that varies on a sine curve as the diameter of the droplet varies. This property has been used, in fact, to make precise determinations of the rate at which droplets of various sizes evaporate.



OSCILLOGRAPH TRACINGS of the intensity of a laser beam emerging from the margin of an evaporating droplet over a period of 20 minutes show a repetitive pattern of three humps on which are imposed spikes. The tracing at the top was made when the droplet had a diameter of 1,153 micrometers; the tracing at the bottom was made when it had shrunk to 741 micrometers. Humps are due principally to paths taken by light traveling halfway around droplet and 3½ times around it. Spikes are resonances from hundreds of paths.

The explanation of why the light is returned from the edge of the droplet is surprising even to many people familiar with physical optics. There must be a process that takes light impinging on one edge of the droplet and sends it back in the opposite direction from the opposite edge. The mechanism that produces the rainbow, in which rays are refracted into the sphere, are reflected internally once and are refracted back out again at a preferred angle of 42 degrees from the backward direction, at first appears to be inadequate to explain the glory. Van de Hulst proposed that an internally reflected ray is important but that it is combined with another mechanism we have not yet considered: the surface wave.

When a light beam strikes the air-water interface from the water side, there is a critical angle at which the beam refracted into the air is parallel to the interface. At that angle the beam has a long "tail" on the "downstream" side. This tail is the surface wave, or more properly the lateral wave, and it carries some of the light farther around the circumference of the droplet than one would expect from geometrical optics alone. Thus the surface wave provides the necessary ingredient that makes van de Hulst's hypothesis viable.

As the diameter of the droplets that give rise to the glory is increased, the intensity of the glory shows periodic resonances, or fluctuations. These resonances indicate that the effect must be due to two or more beams whose difference in phase depends on the size of the droplet. When the two or more beams interfere constructively, the intensity of the glory will be high; when the beams interfere destructively, the intensity will be low.

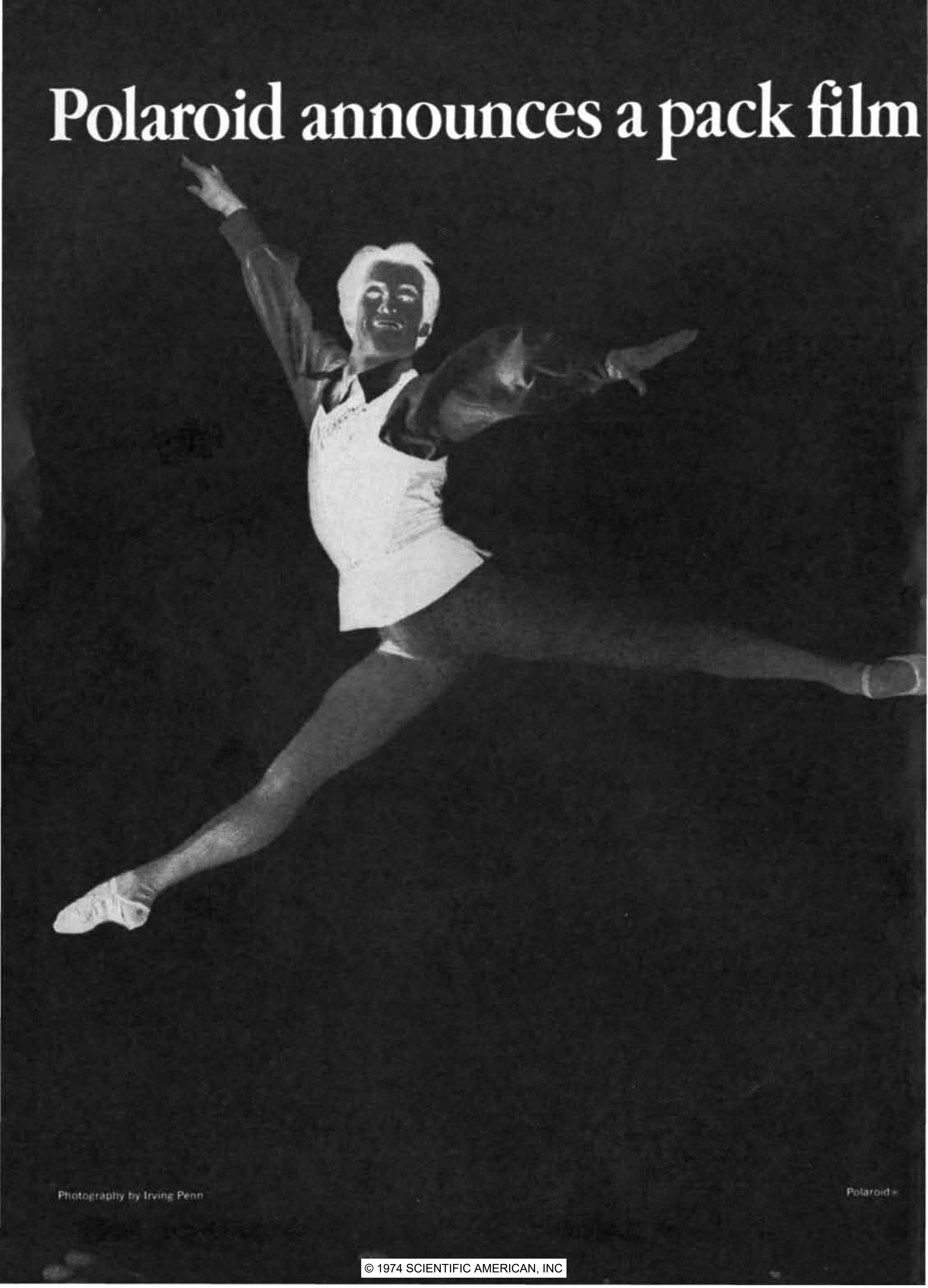
The existence of such multiple-beam resonances has been confirmed experimentally. Fahlen suspended a very quiet evaporating droplet and focused light from a helium-neon laser on it through a small hole in a mirror set at an angle of 45 degrees. The returning light was reflected by the same mirror through a system of variable-aperture lenses onto the photocathode of a photomultiplier, which converts the light into an electric current. When the laser beam was directed along a tangent to one side of the droplet, the returning beam was received coming back along a tangent to the opposite side of the droplet. The amplitude of the current produced by the photomultiplier was recorded with a light-beam oscillograph, an instrument that writes on a rapidly moving strip of photosensitive paper with a narrow ultraviolet beam. The deflection of the beam along the paper was made proportional to the amount of laser light received by the photomultiplier [*see bottom illustration on opposite page*].

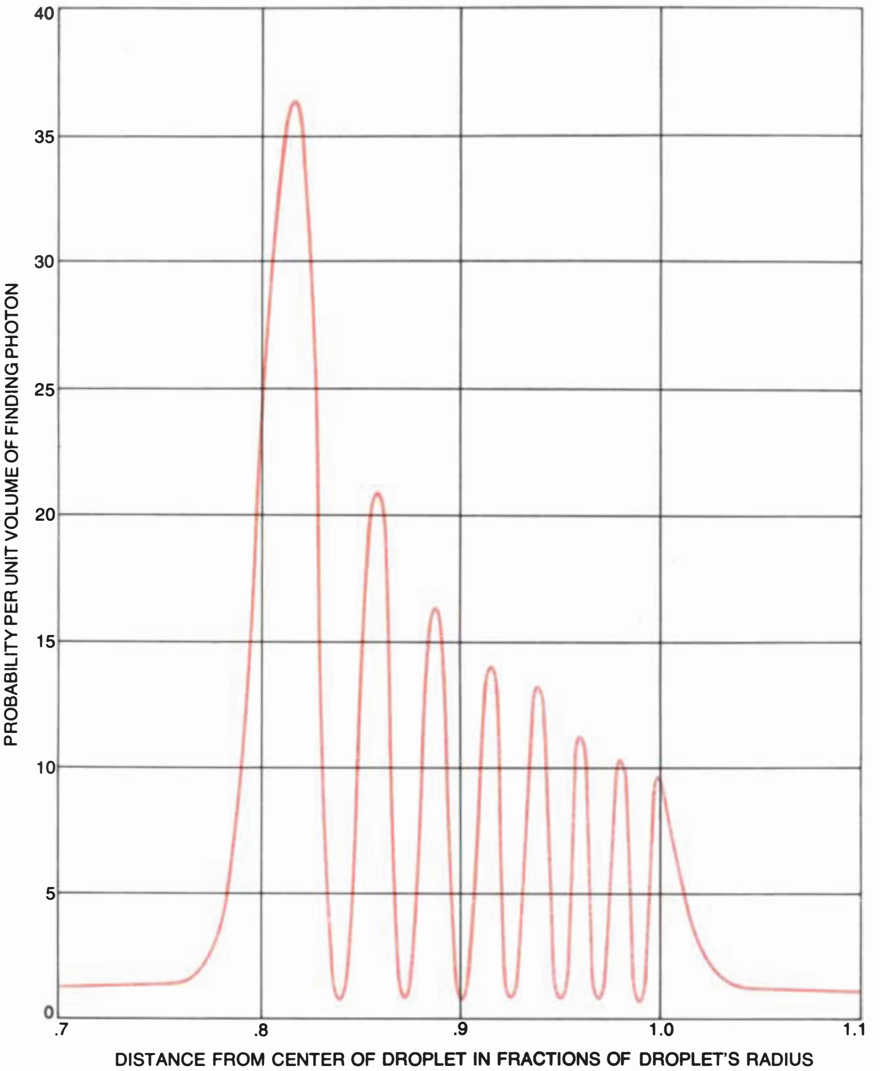
The oscillograph tracings clearly showed the highly structured periodic fluctuations in the intensity of the returning ray as the droplet evaporated. The signal was composed of a periodic set of humps with a series of sharp spikes on top of them; the time that elapses between repetitions of a certain spike structure is about three times longer than the time between adjacent humps.

Although it is not apparent from short sections of the traces, the oscillograph record covering the 20-minute lifetime of the droplet shows striking long-term changes in the basic three-hump structure. The spikes slowly change their magnitude and their position on the humps. A new spike rises to prominence at about every 72nd hump. If we number the humps in cycles of three, we find that the most prominent spike of all occurs on the same hump in the cycle every 73rd cycle. From this Fahlen and one of us (Bryant) concluded that the spike period is about 73/74 of the three-hump cycle.

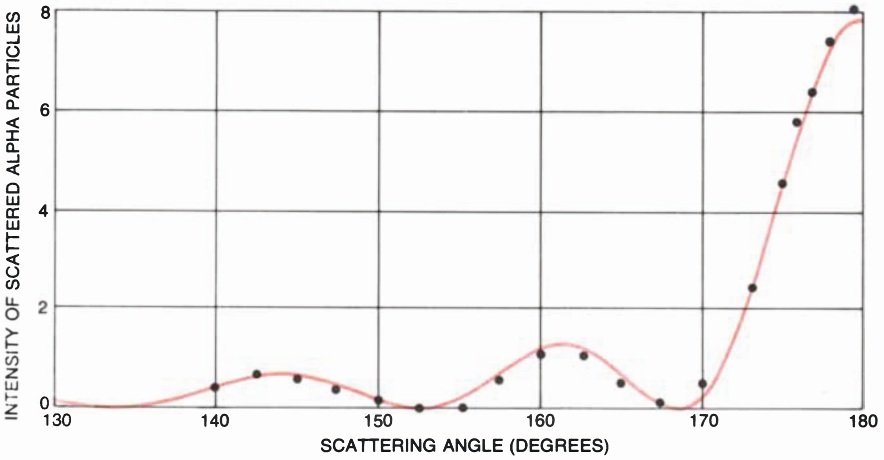
What is the significance of these humps and spikes? The elapsed time between humps can be directly related to the change in the diameter of the droplet by monitoring this intensity of the axial ray. When the intensity goes from a maximum to a minimum and back to a maximum again, wave optics tells us that the diameter of the water droplet has changed by about three-eighths of the wavelength of the light. This fact enables us to determine that the hump period and the spike period respectively correspond to changes in the droplet diameter of .09 and .26 wavelength. The fluctuations in intensity therefore reflect very small changes indeed. For example, for the red laser beam, which has a wavelength of 630 nanometers, the hump period corresponds to a change in the droplet diameter of only .056 micrometer. For a droplet one millimeter in diameter that is a change of only 56 parts per million.

Needless to say, great pains are required to obtain a droplet quiet enough to yield these results, which indicates how complicated a complete explanation of the glory must be. Although the droplets studied in the laboratory have diameters that are 50 times greater than those of the droplets in the clouds where the glory occurs in nature, Mie calculations undertaken by Cox and Fahlen show


Polaroid announces a pack film
Photography by Irving Penn
Polaroid®



PROBABILITY OF FINDING A PHOTON at a given distance from the center of a droplet shows a set of maximums and minimums that one would expect from rays traveling around the droplet at a resonance similar to that producing one of the narrower spikes seen in the oscillograph tracings in the bottom illustration on page 66. Example corresponds to a droplet with a diameter of 40.44 micrometers illuminated by light from a helium-neon laser.



SUBATOMIC PARTICLES PRODUCE A GLORY, as can be seen in this distribution of alpha particles (helium nuclei) at an energy of 29 million electron volts backscattered by nuclei of calcium 40. The solid line is the prediction based on a theory of the glory developed by the authors; the points are actual measurements made by A. Budzanowski and colleagues at the Institute of Nuclear Physics at Cracow in Poland. The maximums at the angles of 180 degrees, 162 degrees and 144 degrees are analogous respectively to the central bright region and the side rings of the optical glory. Intensity is given in arbitrary units.

that the behavior of light in the smaller droplets is much the same as it is in the larger ones.

Fahlen and one of us (Bryant) have been able to devise a simple mathematical model that can predict intensity fluctuations that are in qualitative agreement with experiment and with the exact predictions from the Mie theory. In principle the model includes an infinite series of paths through and around the surface of the sphere. H. M. Nussenzveig of the University of Rochester has developed a rigorous treatment of the scattering of waves by a sphere. Like the Mie theory his analysis consists of an infinite series of terms, but unlike the Mie theory each term can be directly interpreted as representing a light ray being internally reflected one, two, three or more times as it passes around and through the droplet. The humps observed in the oscillograph traces are principally the result of interference between a strong rainbowlike ray (a ray that is internally reflected only once) and a ray that is internally reflected 14 times, traveling around the droplet three and a half times. The spikes, being very narrow, must be the result of constructive interference among a large number of rays of similar intensities.

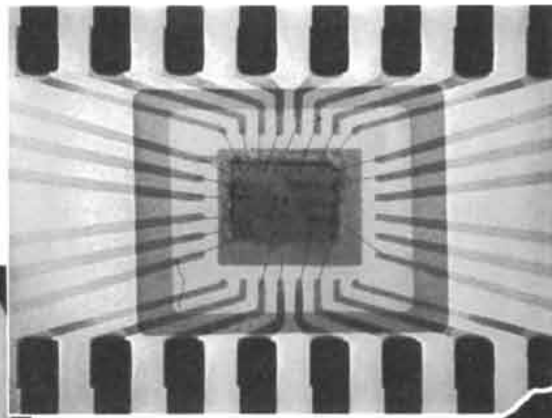
In master's theses at the University of New Mexico, Robert Thede and later Jaime Wong analyzed a certain class of spikes according to a description of light waves that neglects polarization effects. Their results can be interpreted to obtain the probability of finding a particle of light (a photon) at a given point in space. Thede and Wong found that there are several different types of spike that can be classified according to the probability of finding a photon at a given distance from the center of the water droplet. One such probability plot is shown in the top illustration at the left. We call it a Type 8 spike because it has eight maximums. Spikes of Type 6, Type 7 and Type 9 were found to be prominent for droplets with a diameter of 30 microns. The peaks and troughs in the probability curve can be interpreted in terms of waves reflecting around the inside of the droplet and interfering with one another constructively (the peaks) and destructively (the troughs). These waves correspond to light rays bouncing around inside the droplet at close to the critical angle.

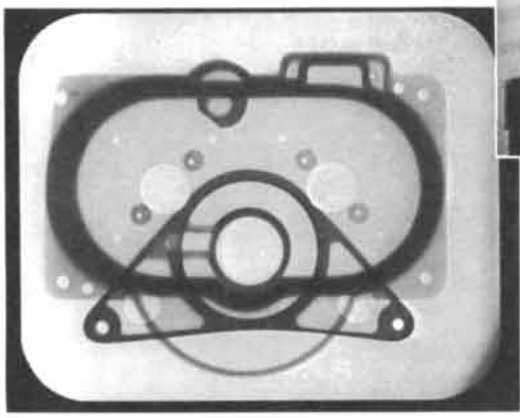
In 1971 Lawrence Sromovsky of the University of Wisconsin, following on the work of Nussenzveig, showed in detail that the spikes are efficiently described by a mathematical concept close to the hearts of some elementary-particle theorists. The concept is that of the Regge pole, introduced by the Italian physicist Tullio Regge. The Regge pole is an abstract mathematical way of representing an entire class of physical situations. For example, all our Type 8 spikes can be described as originating from one Regge pole, so that instead of needing an infinite number of mathematical terms to describe the behavior of Type 8 resonances, one can make do with the Regge pole alone. Thus we find that an important component of the explanation of the glory is quite similar to one concept in the theory of elementary particles.

Since the wave-particle duality exhibited by light is shared by all elementary particles, beams of particles scattered in accelerator experiments may also show optical effects such as the rainbow and the glory. In fact, the concept of a surface wave in a water droplet can be applied to the behavior of high-energy particles bombarding an atomic nucleus. There is no direct correspondence, however, between the scattering of light by a transparent sphere and the scattering of particles by a nucleus. In the nuclear optical model the nucleus is rather like a muddy droplet with a poorly defined surface, so that surface waves would be strongly absorbed and not as clearly defined as they are in a droplet of clear water. Nevertheless, a simple extension of the glory mechanism serves very well in describing certain instances of the backscattering of high-energy particles by nuclei.

Like elementary particles and nuclei, entire atoms and molecules exhibit wave behavior when they are accelerated and scattered. In such experiments nothing comparable to the backward-scattered glory is observed, but wave effects resembling the rainbow have been. Moreover, there is a distinct interference pattern in the forward direction; it is often called the forward glory. Changes in such patterns produced by molecular beams have been utilized by chemists to investigate the energetic threshold of chemical reactions.

We hope that, having read this article, the reader who has never seen a glory will now be on the lookout for one. The easiest way to see a glory in this age of air travel is to watch for the small shadow of one's airplane on a layer of cloud below. If the conditions are right, the shadow will be surrounded by the bull's-eye pattern of the glory—a striking demonstration of the wave nature of light and a colorful reminder of the underlying unity of the physical world.





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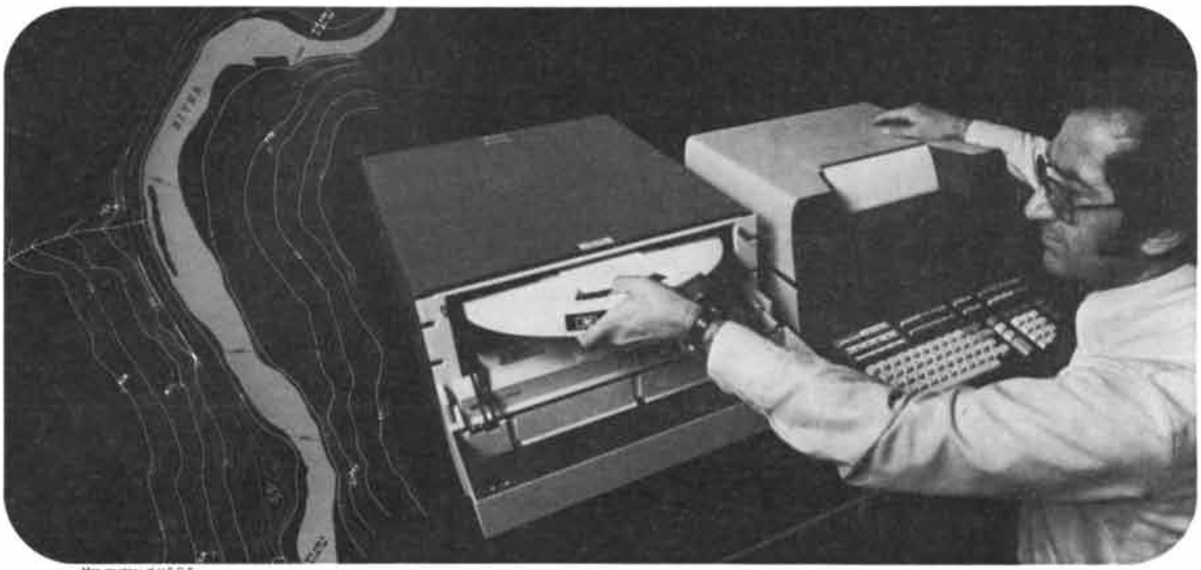

Map courtesy of U.S.G.S.

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