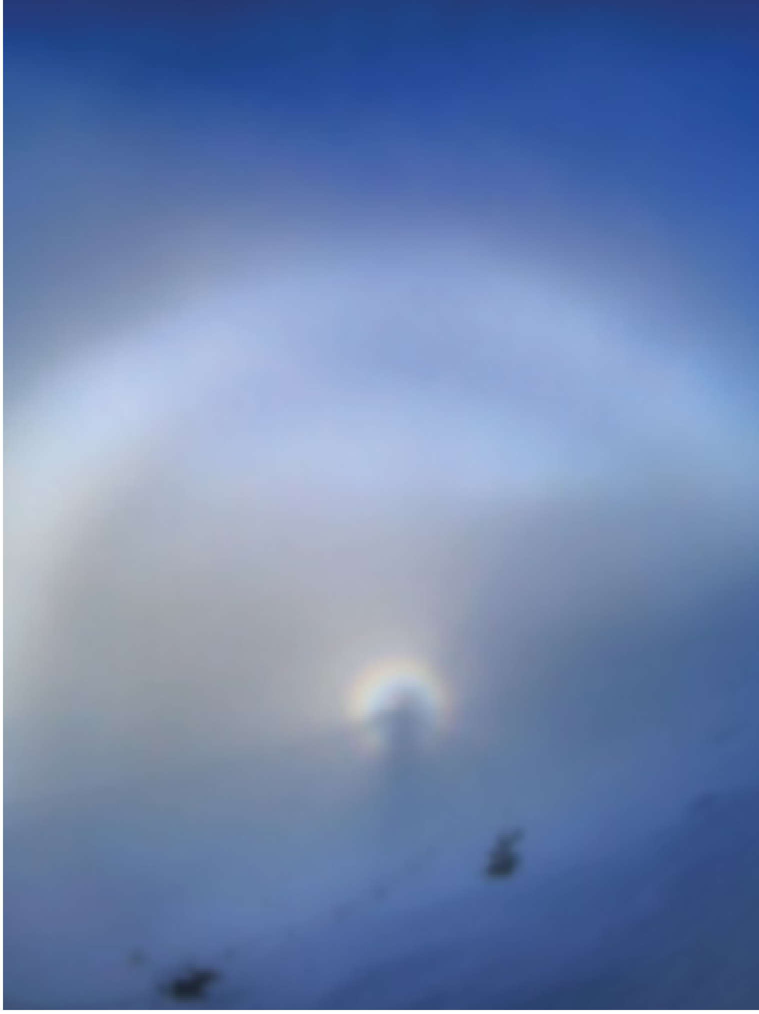
PHYSICS

THE SCIENCE OF THE GLORY

One of the most beautiful phenomena in meteorology has a surprisingly subtle explanation. Its study also helps to predict the role that clouds will play in climate change

By H. Moysés Nussenzveig

CLOCKWISE FROM TOP LEFT: STEVE JURVETSON; CLAUDIA HINZ; BARBARA LAUGHON; CLAUDIA HINZ



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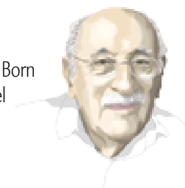


ON A DAYTIME FLIGHT PICK A WINDOW SEAT THAT WILL allow you to locate the shadow of the airplane on the clouds; this requires figuring out the direction of travel relative to the position of the sun. If you are lucky, you may be rewarded with one of the most beautiful of all meteorological sights: a multicolored-light halo surrounding the shadow. Its iridescent rings are not those of a rainbow but of a different and more subtle effect called a glory. It is most striking when the clouds are closest because then it dominates the whole horizon.

If you are a mountain climber, you may also see a glory soon after sunrise, around the shadow your own head casts on nearby clouds. Here is how it was described in the first reported observation, published in 1748 and made a decade earlier by members of a French scientific expedition to the top of Pambamarca in what is now Ecuador: "A cloud that covered us dissolved itself and let through the rays of the rising sun.… Then each of us saw his shadow projected upon the cloud.… What seemed most remarkable to us was the appearance of a halo or glory around the head, consisting of three or four small concentric circles, very brightly colored.… The most surprising thing was that, of the six or seven people who were present, each of them saw the phenomenon only around the shadow of his own head, and saw nothing around other people's heads."

Scholars have often suggested that the halo around the heads of deities and emperors in eastern and western iconography may have been a representation of a glory. Samuel Taylor Coleridge's celebrated poem "Constancy to an Ideal Object" is an allegorical tribute to it. In the late 19th century Scottish physicist C.T.R. Wilson invented the cloud chamber in an attempt to reproduce the phenomenon in the laboratory. (Wilson failed, but he quickly realized that he could use his cloud chamber to detect radiation and ultimately received a Nobel Prize for its invention.)

The shadow of the observer or the airplane plays no role in creating a glory. The only reason for their association is that shadows mark the direction exactly opposite to the sun in the sky, signifying that the glory is a backscattering effect, in which sunlight gets deviated by nearly 180 degrees.

You would think that such a well-known effect, involving optics, a venerable branch of physics, would surely have been explained long ago. Yet for scientists this "phenomenon which must be as old as the world," in the words of the 1748 report, remained a challenge for centuries. Rainbows are themselves far more complex than introductory physics textbooks would lead one to believe. Still, rainbows are considerably simpler than glories.

In principle, both glories and rainbows are explained using a standard optics theory that was already available early in the 20th century, when German physicist Gustav Mie wrote down an exact mathematical solution of how water droplets scatter light. The devil, however, is in the details. Mie's method involves the summation of terms called partial waves. The summation includes infinitely many such terms, and even though only a finite number matter in practice, Mie's method still requires evaluating hundreds to thousands of mathematical expressions, each of which is rather complicated. Put the formulas into a computer simulation, and they will give the correct result but will provide no insight into the physical effects that are responsible for the phenomenon: the Mie solution is just a mathematical "black box" that, given certain inputs, generates an output. A remark attributed to phys-

IN BRIEF

Looking down on a cloud from a mountain or an airplane, sometimes you can spot a glory: rings of colored light around your shadow or the plane's.

As in a rainbow, the colors are produced by the microscopic water droplets that compose clouds, but in the case of glories the physics is more subtle.

The light energy beamed back by a glory originates mostly from wave tunneling, which is when light rays that missed a droplet can still transfer energy into it.

The understanding gained from glories is helping climatologists to improve models of how cloud cover may contribute to or alleviate climate change.

ics Nobel laureate Eugene Wigner is apt: "It is very nice that the computer understands the problem. But I would like to understand it, too." Blind faith in brute-force number crunching can also lead to incorrect conclusions, as will be shown.

In 1965 I began to develop a research program to provide, among other things, a full physical explanation of the glory—a goal that, with the help of several collaborators along the way, was finally completed in 2003. The answer involves wave tunneling, one of the most mystifying effects in physics, which Isaac Newton first observed in 1675. Wave tunneling is the basis of one type of modern touch screen, employed in computers and cell phones. It is also important in the notoriously complicated—and still incompletely solved—problem of determining how atmospheric aerosols, which include clouds but also dust and soot, contribute to climate change.

WAVES AND PARTICLES

OVER THE CENTURIES physicists have offered several explanations for glories that proved to be incorrect. At the beginning of the 19th century German physicist Joseph von Fraunhofer proposed that sunlight that is scattered—that is, reflected back—from droplets deep within a cloud would become diffracted by droplets at the outer layers. Diffraction is one of the wavelike features of light, enabling it to "go around corners," just as sea waves can negotiate an obstacle such as a vertical beam and proceed as if the obstacle had not been there at all.

Fraunhofer's idea was that such double scattering would produce colored diffraction rings like those of the corona seen on clouds surrounding the moon in the sky. In 1923, however, Indian physicist B. B. Ray refuted Fraunhofer's proposal. After experimenting with artificial clouds, Ray noted that glory rings have a distribution of brightness and colors very different from those in coronas and that they arise directly from the outer layers of a cloud, from single backscattering by individual water droplets.

Ray tried to account for that backscattering with the help of geometric optics, historically associated with the corpuscular theory of light, which models its propagation by means of rectilinear rays rather than waves. When light meets an interface between two different media, such as water and air, part of it is reflected and part of it is transmitted, or refracted (refraction is what makes a pencil half-dipped in water look like it is broken). Light entering a water droplet gets reflected one or more times at opposite droplet sides before exiting. Ray considered light that travels along the droplet axis and is reflected back as it enters and at the opposite side. Even considering multiple back-and-forth axial bounces, though, his result was far too weak to account for glories.

Thus, the theory of glories had to go beyond geometric optics and account for the wave nature of light as well—and in particular for wave effects such as diffraction. In contrast with refraction, diffraction gets stronger as the wavelength increases. That the glory is a diffraction effect can be seen from the fact that its inner rims are blue, whereas the outer rims are red, corresponding to shorter and longer wavelengths, respectively.

The mathematical theory of diffraction by a sphere such as a water droplet, known as Mie scattering, calculates the solution as an infinite sum of terms called partial waves. Each partial wave term is a complicated function of the droplet's size, of the refractive index—a measure of how strongly water bends light rays compared with other media—and of the distance of a light ray from the droplet's center, called the ray's impact parameter. The calculations involved in Mie scattering from droplets of a sufficiently broad range of sizes are forbiddingly complex without a high-speed computer, and it was not until the 1990s that supercomputers began to be fast enough to give realistic results over the broad range of droplet sizes found in clouds. Researchers needed better ways to grasp what was going on.

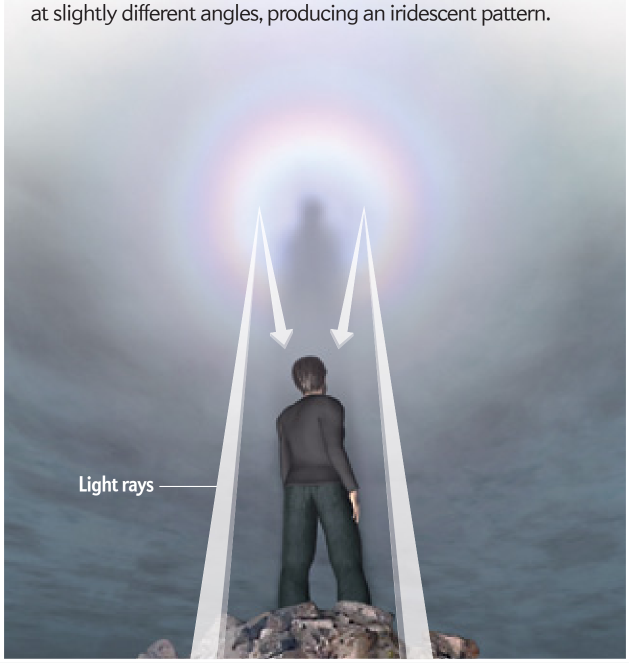
Hendrik C. van de Hulst, a pioneer of modern radio astronomy, provided the first significant insight into the physical explanation of glories in the middle of the 20th century. He pointed out that a light ray that entered a droplet very close to the droplet's edge might follow a V-shaped trajectory inside the droplet, bouncing off at the back, and return almost exactly in the same direction that it came from. Because droplets are symmetric, among the bundle of parallel rays coming from the sun the favorable impact parameter would occur not just for one ray but for a whole circle's worth of rays all at the same distance from the droplet's center—a focusing effect that would dramatically enhance the backscattering.

The explanation sounds clear-cut, but unfortunately it had a serious snag. As a ray entered and exited the droplet, it would bend via refraction. But the refractive index of water is not large enough to scatter a ray back in the same direction after just one internal reflection. The best that water can do is send

THE CONDITIONS FOR A GLORY

Why Does It Always Surround Your Shadow?

Because a glory is made of light that bounced back nearly in the same direction that it came from, it requires a particular and serendipitous alignment of sun, observer and cloud. Consequently, it is always seen as a halo surrounding the observer's shadow on the cloud. Different colors of the spectrum come off at slightly different angles, producing an iridescent pattern.



Illustrations by Alfred T. Kamajian

HOW NATURE MAKES A GLORY

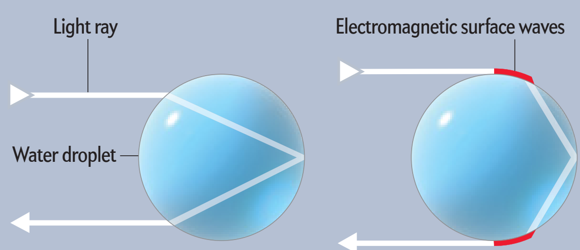
Light at the End of a Tunnel

Glories have been known for centuries, but only in recent years (and after some false starts) have researchers gained real physics insight into them, based on a phenomenon called tunneling.

A "Wrong" Attempt and a Better One

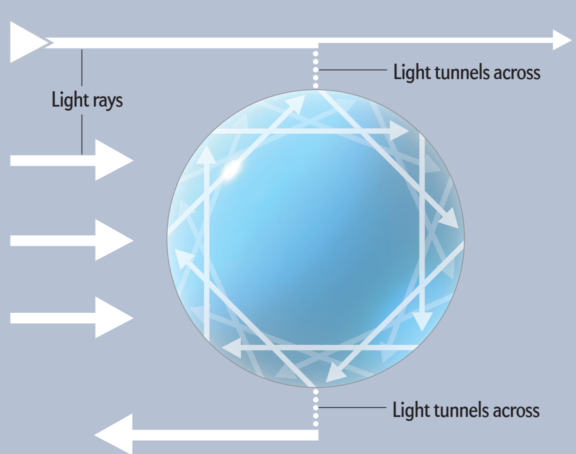
Researchers first tried to attribute the phenomenon simply to light bouncing back inside the microscopic water droplets that compose clouds. Light rays would bend (refract) as they entered a droplet and would get reflected inside. Then they would bend again as they exited, going back in the direction they came from (*below left*). But water does not bend light rays enough for rays to go back in the exact same direction.

A second theory posited that light rays grazing a droplet could temporarily turn into electromagnetic surface waves. By following the curved surface for small distances (*seen exaggerated, below right*) before entering and exiting from the droplet, the light could turn by just the angle needed to return in the same direction. This effect can take place, but it gives a relatively minor contribution to the overall energy seen in a glory.



A Fuller Understanding

A mathematical theory of light scattering later explained glories through lengthy calculations but did not provide insight into the underlying physics. Instead the author demonstrated that most of the light seen in a glory is the result of energy "tunneling" into water droplets from light rays that would otherwise seem to miss the droplets altogether. Tunneling is a common feature of waves of all kinds, in both quantum and classical physics.



light backward in a direction within 14 degrees of the original ray.

Van de Hulst suggested in 1957 that this 14-degree gap could be bridged by extra paths in which the light travels as a surface wave along the droplet surface. Surface waves attached to an interface between two different media arise in a variety of situations. The idea was that a tangentially incident ray would graze the droplet, travel along its surface a short distance, then propagate through the droplet to its rear. There it would again travel along the surface and reflect back through the droplet. A final passage along the surface would send it on its way. The overall effect would be to scatter the ray back in the same direction that it came from.

One potential difficulty is that surface waves lose energy by shedding radiation tangentially, but van de Hulst conjectured that this damping would be more than compensated for by the axial-focusing enhancement. At the time when he proposed his conjecture, no quantitative procedure to evaluate the surface-wave contributions was available. Still, all the information about the physical origin of glories, including the role of surface waves, had to be implicitly contained within the Mie partial-wave series: the challenge was how to extract it.

MIND BEATS COMPUTER

SURFACE WAVES are not the only potential solution to the riddle of glories. In 1987 Warren Wiscombe of the NASA Goddard Space Flight Center in Greenbelt, Md., and I came up with a new insight into diffraction: that light rays passing outside the sphere could make a significant contribution. At first glance, this seems absurd. How can a ray be affected by a droplet if it does not even pass through it? Waves, however—and light waves in particular—have the uncanny ability of "tunneling," or jumping through a barrier. For instance, light's energy can leak out in circumstances where it would be expected to stay within a medium, as is seen in the following situation.

Typically light propagating in a medium such as glass or water will be totally reflected at the separation with another medium of lower index of refraction, such as air, if it hits the surface of separation at a shallow enough angle. Such total internal reflection is what keeps signals within optical fibers, for instance. Even if all the light bounces back, however, the electric and magnetic fields that make up the light waves do not drop completely to zero at the interface. Instead the fields still extend for a short range beyond the surface, forming evanescent waves that do not propagate away from the immediate vicinity of the interface and do not carry any energy through the boundary. Evanescent waves make the electromagnetic field near the surface vibrate in place, like the strings of a guitar.

What I just described is a situation in which no tunneling occurs. If, however, a third medium is placed within a short distance of the boundary so that it overlaps with the evanescent waves, the waves can resume their outward propagation in the third medium and thus siphon energy away. As a result, the internal reflection in the original medium will weaken. The intermediate medium, which before acted as a barrier, has now been tunneled through.

Appreciable tunneling can take place only if the gap is not much greater than one wavelength across—about half a micron or less in the case of visible light. Yet Newton himself already observed the phenomenon as far back as 1675. He was investigating patterns of interference now known as Newton's rings by laying a convex lens on a flat glass plate. The rings should appear only when light can directly propagate from the lens to the plate. What Newton found out was that even when an extremely narrow air gap separated the surface of the lens from the plate—so that the two surfaces were not quite in contact with each other—some light that should have undergone total internal reflection jumped across the gap instead.

Tunneling is highly counterintuitive. Russian-born physicist George Gamow was the first to employ it in quantum mechanics in 1928 to explain how certain radioactive isotopes can emit alpha particles. Gamow observed that alpha particles should not have enough energy to detach from a larger nucleus, just as a cannonball cannot reach escape velocity and leave the earth's gravitational field. He was able to demonstrate that because of their wavelike nature, alpha particles can still tunnel through this energy gap and escape.

Contrary to popular prejudice, however, tunneling is not an exclusively quantum effect: it also occurs with classical waves. Sunlight traveling well outside a water droplet in a cloud can, against intuitive expectations, penetrate within it by tunneling and, in this way, contribute to the production of a glory.

In our initial analysis in 1987 Wiscombe and I studied scattering by a totally reflecting sphere such as a silvered ball. We found that partial waves associated with above-edge rays can, if the rays pass close enough to the sphere, tunnel all the way to the surface and still give a sizable contribution to diffraction.

In the case of a transparent sphere such as a water droplet, after tunneling to the surface the wave can propagate inside. Once there the wave hits the internal surface at a shallow enough angle to be totally reflected, thus staying trapped inside. A similar situation occurs with sound waves: at the celebrated whispering gallery under the dome of St. Paul's Cathedral in London, a person who whispers facing the wall at one side can be heard far away at the other side because the sound undergoes multiple reflections, bouncing around the curved walls.

For light waves, however, light that has tunneled in can also tunnel back out. For certain wavelengths, after multiple internal reflections the wave reinforces itself by constructive interference and produces what is known as a Mie resonance. This effect may be compared with pushing a swing just in time with the rhythm of its natural pendulum oscillations, driving it higher and higher. Because of the acoustic analogy, these resonances are also known as whispering gallery modes. A tiny change in wavelength suffices to detune the resonance so that Mie resonances are extremely sharp and concentrated and yield large intensity enhancements.

To summarize, three potential effects contend for primary contributors to the glory phenomenon: rays that hit the sphere, including Ray's geometric-optic axial backscattering; edge rays, which involve the van de Hulst surface waves; and contributions from Mie resonances, arising from the tunneling of light. In 1977 Vijay Khare, then at the University of Rochester, and I evaluated the contribution from near-edge rays, including van de Hulst's term, and resonances were treated by Luiz Gallisa Guimarães of the Federal University of Rio de Janeiro and me in 1994. In 2002 I made a detailed analysis to determine which of these effects is the most important. As it turns out, axial backscattering is negligible; the main contributions arise from the above-edge tunneling resonances. The inescapable conclusion is that glories are a macroscopic light-tunneling effect.

GLORIES AND CLIMATE

BESIDES AFFORDING US the intellectual satisfaction of finally understanding the origin of glories, light-tunneling effects also have practical applications. Whispering gallery modes have been employed to build lasers, using water microdroplets and solid microspheres, as well as other geometries such as microscopic disks. A recent application of light tunneling is used in multitouch screens. The approach of a finger to the screen plays the role of Newton's convex lens, enabling light to tunnel through, get backscattered and provide a signal. Evanescent light waves produced by tunneling also have many important applications in a technology called near-field microscopy because they can resolve details smaller than the wavelength—beating the notorious diffraction limit below which ordinary microscopes give blurry images.

Perhaps most crucially, understanding droplet scattering is necessary for estimating the role that clouds will have in climate change. Water is highly transparent in the visible spectrum, but—like carbon dioxide and other greenhouse gases—it absorbs certain bands of the infrared. Because Mie resonances usually involve long paths with huge numbers of internal reflections, a small droplet may end up absorbing a significant amount of radiation, especially if the water contains contaminants. As the average cloud cover changes, will it help keep the planet cool by reflecting more sunlight back into space, or will it contribute to heating by acting as an additional blanket to trap infrared radiation?

Until a decade or so ago simulations of light scattering from clouds performed Mie computations for relatively few droplet diameters that were thought to be representative for typical clouds. This rule of thumb reduced the need for machine time on supercomputers—but with an unexpected snag. As I demonstrated in 2003 using the methods I had developed for the analysis of rainbows and glories, the standard simulation methods could produce errors of up to 30 percent over narrow bands of the spectrum. Those brute-force techniques could calculate the scattering from droplets by sampling selected sizes but miss important contributions from many narrow resonances that fall in between—for example, if they performed calculations for sizes of one micron, two microns, three microns, and so on, they could miss a very sharp resonance at 2.4 microns. My prediction was confirmed in 2006 by a study that took into account droplet-size distribution in the atmosphere; in recent years models have been updated to include droplet sizes with much finer increments.

As Wigner had warned, even results from state-of-the-art supercomputers, if employed without physical insight, can be untrustworthy. Something to ponder, perhaps, next time you have a window seat. SA

MORE TO EXPLORE

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