search & discovery

Mather and Smoot share Nobel physics prize for measuring the cosmic microwave background

In the early 1990s, NASA's *Cosmic Background Explorer* first revealed the microwave background's spectral perfection—and spatial imperfection—required by Big Bang cosmology.

The Royal Swedish Academy of Sciences has awarded the 2006 Nobel Prize in Physics to John Mather and George Smoot "for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation."[1,2] Mather and Smoot were leading members of a large team that designed, built, and operated NASA's *Cosmic Background Explorer*. *COBE* was launched into a 900-km-high polar Earth orbit in November 1989 and, over the next four years, observed the spectral and spatial properties of the cosmic microwave background (CMB) over the whole sky.

Mather, lead scientist of the *COBE* project, has been at NASA's Goddard Space Flight Center in Greenbelt, Maryland, since 1976, when the project began in earnest. Smoot, who had charge of *COBE*'s differential microwave radiometer (DMR), one of the satellite's three principal instruments, has been at Lawrence Berkeley National Laboratory since 1970. For the past 12 years, he has also been a professor of physics at the University of California, Berkeley.

Since its accidental discovery in 1964 by Arno Penzias and Robert Wilson, the CMB was widely presumed to be the relic radiation from the first moment of cosmic transparency, some 400 000 years after the Big Bang. That's when the cosmos had finally cooled enough (to about 3000 K) for neutral atomic hydrogen to be stable and photons to stream largely unhindered. It was, in effect, the transition that decoupled ordinary (baryonic) matter from the cosmic radiation field.

The universe—and with it the wavelengths of the liberated photons—having expanded a thousandfold in the succeeding 10^{10} years, the temperature of the CMB would now be about 3 K. And indeed, balloon and ground-based measurements at a few wavelengths in the years after the Penzias–Wilson discovery were roughly consistent with an isotropic CMB having a 3 K blackbody spectrum.

But by the early 1970s, Big Bang cosmology was making predictions that called for much better measurements: The CMB's blackbody spectrum had to be essentially perfect. Its thermal isotropy, on the other hand, had to be imperfect. The CMB, said the theorists, had to exhibit parts-per-ten-thousand fluctuations from point to point on the sky. Such small temperature fluctuations, it was argued, trace the required shallow mass-density fluctuations that would be slowly amplified by gravity into deep potential wells in which galaxy clusters would form. The details of the power spectrum of CMB temperature fluctuations promised to be a rich source of information about the earliest moments of cosmic expansion.

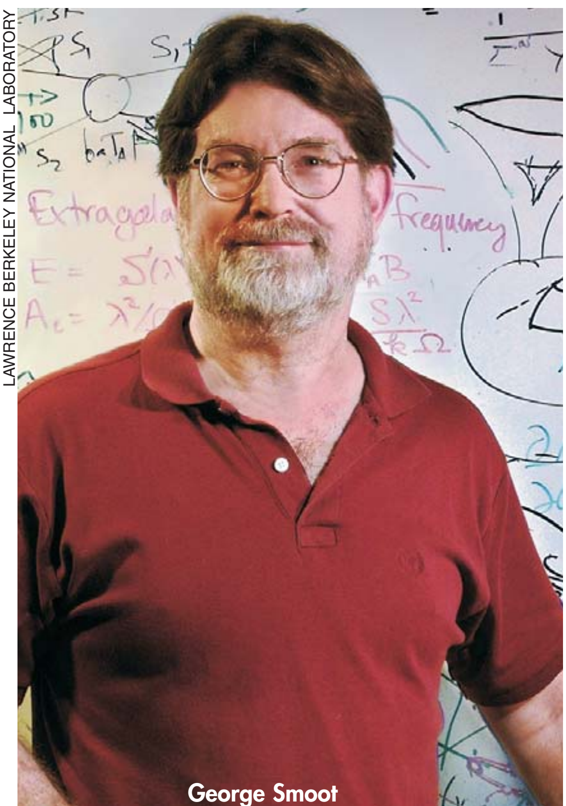
Opportunity knocks

The Big Bang was, in the early 1970s, still a somewhat embattled hypothesis in need of more evidence. But ground-based measurement of the CMB is severely limited by atmospheric absorption, and observing at high altitude with balloons, sounding rockets, or U2 airplanes posed other difficulties. In 1974, NASA promulgated an Announcement of Opportunity (AO) that invited observers to propose scientific instruments that could be flown aboard satellites. The call for experiments was quite general; NASA did not have the CMB particularly in mind. But Mather and Smoot, both then young postdocs on opposite coasts, responded independently to NASA's call with propos-

NASA

John Mather

LAWRENCE BERKELEY NATIONAL LABORATORY



George Smoot

als to study the CMB with orbiting instruments.[3]

Mather had just completed his PhD at Berkeley and joined Patrick Thaddeus's group at the Institute for Space Studies near Columbia University in New York—in offices just upstairs of the restaurant whose exterior was to become famous on televison's *Seinfeld*. "I was planning to do radio-telescope observations of interstellar masers as an escape from the difficulties of my balloon studies of the CMB in Paul Richards' group at Berkeley," recalls Mather. "But Pat called the AO to my attention and encouraged me to write a proposal for a satellite-borne CMB instrument package."

Smoot had been a member of Luis Alvarez's particle-physics group at LBNL since 1970, when he finished his PhD in experimental particle physics under David Frisch at MIT. "But Luie urged us to do the most interesting science we could find, regardless of field," says Smoot. So he built a small differential microwave radiometer and flew it aboard a U2 plane in search of evidence for the predicted temperature differences between different points on the CMB sky.

In response to the 1974 AO, Alvarez, Smoot, and Berkeley colleague Richard Muller submitted a proposal to build a larger and more sophisticated version of Smoot's DMR for a NASA orbiter that would give it access to the whole sky. At several microwave frequencies chosen to minimize and identify foreground emission, the proposed DMR would measure any small difference between the radiant power received by two horn antennae pointing at patches of sky separated by 60°.

Two years later, NASA merged the Mather and Smoot proposals with a similar proposal by Samuel Gulkis (Jet Propulsion Laboratory), thus creating the *COBE* team headed by Mather, with Smoot, Gulkis, and Mather's early collaborators Michael Hauser (Goddard), David Wilkinson (Princeton University), and Rainer Weiss (MIT) in leading positions. Alvarez and Muller had dropped out of the enterprise. At that point, Mather moved to Goddard.

COBE was to carry three observing instruments, to be built at Goddard: Smoot was responsible for the DMR; Mather himself for FIRAS (Far Infrared Absolute Spectrophotometer), an instrument intended to measure the CMB spectrum with great precision over the wavelength range 0.5 mm–1 cm; and Hauser for DIRBE (Diffuse Infrared Background Experiment), which was to map the infrared sky at shorter wavelengths down to a micron, looking for diffuse radiation from early galaxies and studying local foregrounds that obscure the CMB.

"I think it was essential that these very demanding instruments be built in-house" says Mather. "The scientists were in almost daily contact with the engineers." Smoot's deputy at Goddard was Charles Bennett, who went on to head *COBE*'s worthy successor—*WMAP* (the *Wilkinson Microwave Anisotropy Probe*; see PHYSICS TODAY, May 2006, page 16.)

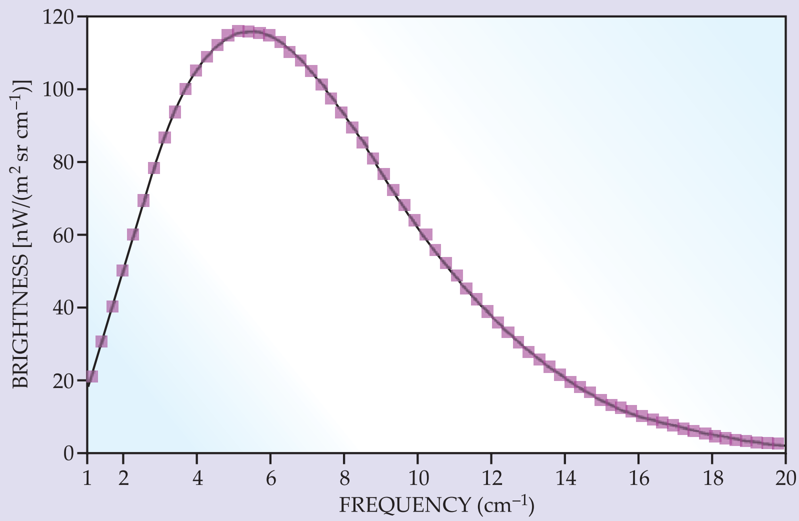


Figure 1. The cosmic microwave background spectrum as measured by the *Cosmic Background Explorer*'s FIRAS spectrometer and presented by John Mather in January 1990, just eight weeks after *COBE*'s launch.[1] Boxes represent conservative estimates of measurement uncertainties. The data show no discernable departure from a perfect blackbody spectrum (the curve) with a best-fit temperature of 2.735 ± 0.06 K.

A moving target

When the *COBE* instruments were first designed, theorists were still vague about the amplitude of the temperature fluctuations one should expect to see. It was widely guessed that the fluctuations would be just an order of magnitude fainter than the part-per-thousand dipole anisotropy. It wasn't clear how worried Big Bang advocates should be when balloon experiments sensitive to anisotropies of a part in 10^4 had seen nothing by 1983.

But with the development of inflationary Big Bang cosmology in the 1980s and the growing conviction that lots of cold, dark (nonbaryonic) matter must have accelerated the evolution of structure from the primordial fluctuations, theoretical predictions began to converge on very shallow CMB fluctuations that would be hard to detect. As theorist Michael Turner put it around the time of *COBE*'s launch, "If the observers haven't found thermal fluctuations by the time their sensitivity gets down to 3 parts in 10^6, we champions of the standard inflationary model will be honor bound to commit ritual suicide."

"We were shooting at a moving target," says Smoot. So he set out in 1983 to convince NASA engineers and administrators, not without difficulty, that the microwave receivers originally intended for the DMR had to be replaced by more sensitive, up-to-date ones that might, in a year's worth of CMB data, detect fluctuations of a few parts per million.

FIRAS presented its own special problems. Whereas the DMR only had to measure the temperature difference, albeit to parts per million, between different patches of sky, FIRAS had to measure absolute spectral brightness with enough precision to detect parts-per-thousand departures from a perfect blackbody spectrum. That required liquid-helium cooling and an on-board temperature-tunable calibrator that came within 0.001% of being a perfect blackbody radiator. FIRAS's microwave observing horn was to alternate between looking at the sky and at the external calibrating blackbody when it was stuffed into the horn like a trumpet mute.

FIRAS was a polarizing Michelson interferometer designed to compare the sky, with 5% spectral resolution, to a tunable internal reference blackbody that didn't have to be nearly as perfect as the external calibrating blackbody. "The purpose of the internal blackbody

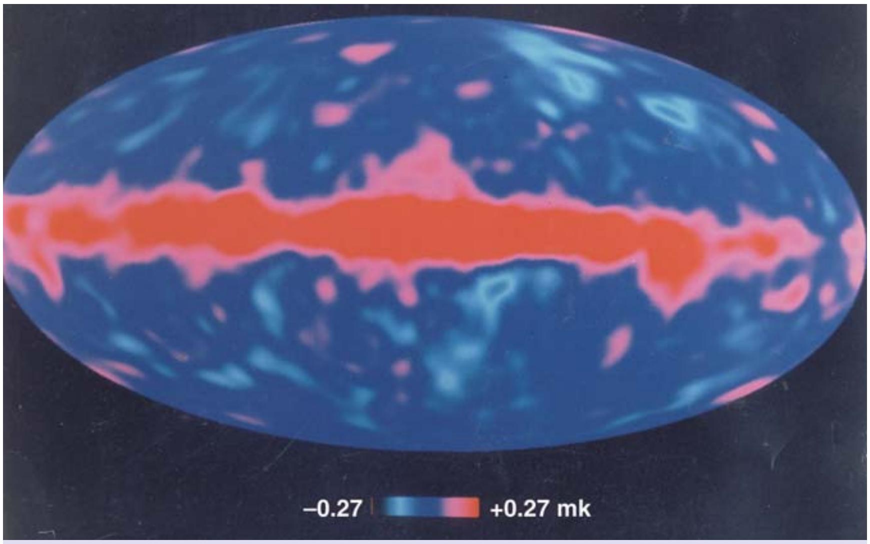


Figure 2. This temperature map of the microwave sky in galactic coordinates, presented by George Smoot in April 1992, offered the first evidence of temperature fluctuations in the cosmic microwave background.[2] The map was made from the first year of observations with the differential microwave radiometer aboard *COBE*. The large dipole anisotropy due to the solar system's motion through the CMB rest frame is already subtracted from the map, but the hot foreground glow from the Milky Way, mostly near the galactic equator, is not. After both subtractions, the root-mean-square temperature fluctuation over the whole sky was found to be 30 microkelvin, a departure from perfect isotropy of only a part in 10^5.

was just to minimize the difference signal," explains Mather, "so we could crank up the gain without wrecking things."

A standing ovation

Just eight weeks after *COBE* was finally launched from Vandenberg Air Force Base in California aboard a Delta rocket in November 1989, the team reported its first result (see PHYSICS TODAY, March 1990, page 17). At the January 1990 meeting of the American Astronomical Society in Washington, DC, Mather presented the CMB spectrum derived from just 9 minutes (accumulated over several weeks) of FIRAS observations of a region of sky near the North Galactic Pole, where foreground microwave radiation from the Milky Way is minimal.[1] When Mather showed the plot reproduced here in figure 1, the packed hall responded with a standing ovation. The precision measurements at 68 wavelengths showed no discernable departure from a perfect blackbody spectrum with a temperature of 2.735 ± 0.06 K.

"I think much of the response was simply relief that the Big Bang had survived a crucial test," says Mather. Two years earlier, Richards and Japanese collaborators had reported sounding-rocket data yielding a 10% excess at submillimeter wavelengths that would have marred the CMB blackbody spectrum with an unsightly bump. "That was just one of a succession of recent observational assaults on Big Bang theory," recalls Mather, "and it sent the theorists scrambling for fixes. But I didn't believe any of those *ad hoc* theories; they seemed too contrived."

The chairman of the session at which Mather showed the first *COBE* spectrum was the venerable Geoffrey Burbidge, to this day a holdout against Big Bang cosmology (see his article with fellow skeptics Fred Hoyle and Jayant Narlikar in PHYSICS TODAY, April 1999, page 38). Mather recalls that Burbidge, noting the ovation with good-natured disapproval, muttered to him, "They're swallowing this stuff hook, line, and sinker."

Before the liquid-helium cryogen ran out, FIRAS had added 10 more months of observations without seeing any departure from a perfect blackbody spectrum. The final result, with a best-fit temperature of 2.725 ± 0.001 K, was a 50-parts-per-million upper limit on any such departure.

Standard Big Bang theory posits enough photon creation and destruction in the early epoch to guarantee that the cosmos was fully thermalized until about the end of its first year. Mather summarizes the FIRAS result as showing "that there have been no significant injections of energy or entropy since that first year—either before or after decoupling—sufficient to upset the thermal equilibrium of the cosmic radiation field."

Fluctuations at last

In 1977 Smoot and Muller used their U2-borne DMR to make an improved measurement of the one already known CMB anisotropy. But that 0.1% temperature variation across the sky, well fitted by just a dipole moment, wasn't a relic of primordial fluctuations of the kind that *COBE* would be looking for. The dipole variation was taken as Doppler-shift evidence that our galaxy is moving at some 600 km/s—pulled by the Virgo cluster of galaxies—with respect to the CMB's rest frame of reference. The dipole moment's seasonal Doppler modulation turned out to be a valuable calibration signal for *COBE*.

By the end of the first year after *COBE*'s launch, its DMR had scanned the entire sky twice at three microwave frequencies. The analysis team decomposed the resulting all-sky CMB temperature map into spherical harmonics. To find the very shallow CMB temperature fluctuations, one had to subtract off the much larger Doppler dipole moment and foreground emission concentrated in the equatorial band of our own galaxy. The first real evidence would be a discernable quadrupole moment, which would signal temperature differences between points on the CMB sky separated by about 90°. The rather coarse 7° resolution of each of the two DMR antenna horns limited the analysis to spherical-harmonic moments of order less than about 20.

After much agonizing by Smoot, Bennett, and DMR team members Alan Kogut and Ned Wright about instrumental and foreground noise, Smoot was finally ready to announce in April 1992 that "we have a quadrupole!" To a standing-room-only audience at the spring meeting of the American Physical Society in Washington, DC, Smoot showed the all-sky temperature-fluctuation map (figure 2) produced from the first year of DMR observations, and he reported that those data had yielded a root-mean-square cosmic quadrupole amplitude of just 13 ± 4 microkelvin.[2] (See PHYSICS TODAY, June 1992, page 17.) "If our sensitivity had been just half as good as it turned out to be," says Smoot, "we wouldn't have had a convincing first-year result."

The team had, in fact, worried about the surprisingly low value they were getting for the quadrupole amplitude; inflationary Big Bang theory predicted something more like 30 μK. But Smoot and company soon realized that the difference between the measured and theoretical values was within "cosmic variance," the random spread of measured low-order CMB multipoles one would expect from observers at different cosmic vantage points. Indeed the best current value, 9.9 μK from *WMAP*, is even lower. It's still within cosmic variance of standard Big Bang cosmology, but theorists have speculated that it hints at a somehow restrictive cosmic topology at the largest observable distances.

The first-year DMR data yielded an overall rms temperature fluctuation of $30 \pm 5\,\mu$K. That's about 1 part in 10^5. The number depends sensitively on the instrument's angular resolution. *WMAP*, with 35 times finer angular resolution that lets it determine multipole amplitudes out almost to order 1000, finds an all-sky rms temperature fluctuation of about 100 μK. But if one smooths out the *WMAP* data to simulate 7° resolution, one recovers the *COBE* result.

In addition to the spherical-harmonic analysis, the *COBE* group produced a two-point correlation function meant to show how measured temperature differences between points on the sky depend on the angular distance between them. The correlation function not only strengthened the case for the temperature fluctuations; it also yielded the first significant evidence in support of the inflation-theoretic expectation that the power spectrum of primordial quantum fluctuations that grew into the CMB fluctuations was very nearly independent of spatial scale. "Therefore," says theorist Paul Steinhardt (Princeton), "*COBE*'s snapshot from the moment of decoupling could be interpreted as a direct image of the cosmos an instant after the Big Bang."

DIRBE's principal result revealed an aspect of the cosmos at a much later epoch. "It was *COBE*'s most unexpected finding," says Mather. Hauser's team found a diffuse infrared background indicative of a very dusty universe some two to three billion years after the Big Bang.[4] That background has since been largely resolved into emission from early galaxies whose intense star formation and high dust content make them ultraluminous in the infrared.

Because the DMR, unlike FIRAS and DIRBE, did not need active cooling, it continued to observe the CMB for another three years after the liquid helium was used up. CMB temperature fluctuations on the all-sky map showed up with increasing clarity. "We even thought briefly about naming prominent hot and cold spots after great scientists of the past," says Smoot. Analysis of the additional DMR data yielded ever stronger evidence for the inflationary Big-Bang scenario, in which the gravitational clustering of ordinary matter that eventually formed large accumulations of galaxies was dominated by some still unidentified form of cold dark matter.

In 1998, four years after *COBE* stopped taking CMB data, observations of the redshifts of distant supernovae revealed that the dark matter was, in fact, playing second fiddle to an even more mysterious dark energy. By the end of the decade, much-improved balloon experiments by Richards and others were finding the first of the predicted "acoustic peaks" in the CMB's fluctuation power spectrum (see PHYSICS TODAY July 2000, page 17). *COBE*'s successor, the *Microwave Anisotropy Probe*, launched in 2001, was renamed in honor of Wilkinson after his death a year later. He had been a founding member of the *WMAP* and *COBE* collaborations (see his obituary in PHYSICS TODAY, May 2003, page 76). *WMAP*'s exquisitely precise measurements of the CMB temperature fluctuations out to small angular scales are central to the present robust "concordance model" of a cosmos whose mass–energy content is about 70% dark energy and 25% dark matter. The remaining 5% is all we really know about.

"*COBE* verified the key Big Bang assumption that gravity sufficed to transform the universe from near homogeneity to its present lumpy condition in less than 14 billion years," says Steinhardt. "Had the results been different, we might have had to invoke new long-range forces that violate general relativity."

The laureates

Born in Virginia in 1946, Mather grew up in the town of Sussex in northwestern New Jersey, where his father was a cattle researcher at an experimental station of Rutgers University. "That's just 50 miles from where Penzias and Wilson discovered the CMB," Mather points out. By coincidence, the external examiner for his senior honors-physics project in 1968 at Swarthmore College was Wilkinson, a professor at nearby Princeton.

Mather thought about going to Princeton for graduate school. "But word that girls were scarce at Princeton and a photo of a friend in short sleeves on the Berkeley campus in January convinced me to choose Cal," he recalls. That choice was reinforced by a summer job in particle physics at LBNL after he graduated from Swarthmore. "I started out wanting to be the next Richard Feynman," he says. "But that job was taken."

Mather is the first NASA civil servant to win a Nobel prize. He is now the chief scientist of NASA's *James Webb Space Telescope* project. The *JWST*, successor to the *Hubble*, is scheduled for a 2013 launch into the L2 Lagrange point 1.5 million kilometers antisunward from Earth. "Its infrared capabilities will let us peer through dusty stellar nurseries and study the details of star formation." says Mather. "We also hope to see the first generation of supernovae."

Smoot was born in 1945 in northern Florida, in a town with the unlikely name of Yukon. Perhaps it presaged his later sojourns in colder climes: elementary school in Alaska and a 1991 trip to his Berkeley group's radio dish at the South Pole to measure galactic-foreground emission at wavelengths longer than *COBE* could see.

His undergraduate degree, as well as his PhD, is from MIT. "I'm often asked," says Smoot, "whether I'm the eponymous Smoot after whom the body-length unit of measure marked off in paint along the Harvard Bridge is named. The answer is no. *That* Smoot was my older and considerably shorter cousin Oliver."

A casual remark by Smoot at the press conference following the 1992 announcement of CMB fluctuations made him a media celebrity. Asked about the significance of the fluctuations for nonscientists, he answered, "If you're religious, this is like seeing God." Not long thereafter he attended an astrophysics meeting in England that happened to coincide with a major meeting of Anglican bishops. "Somehow in this ecclesiastical context I found myself on the BBC and front pages for two weeks."

Smoot is now a member of the *Planck* team. The European Space Agency's *Planck* observatory, much anticipated as *WMAP*'s successor, is scheduled for launch sometime next year. Like the Webb telescope, it is headed for the vicinity of L2. With finer angular resolution than *WMAP*, *Planck* should be able to measure CMB multipoles of order 2000. That's fine enough to reveal the CMB seeds of large galaxy clusters.

Bertram Schwarzschild

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4. M. G. Hauser et al., *Astrophys. J.* **508**, 25 (1998).

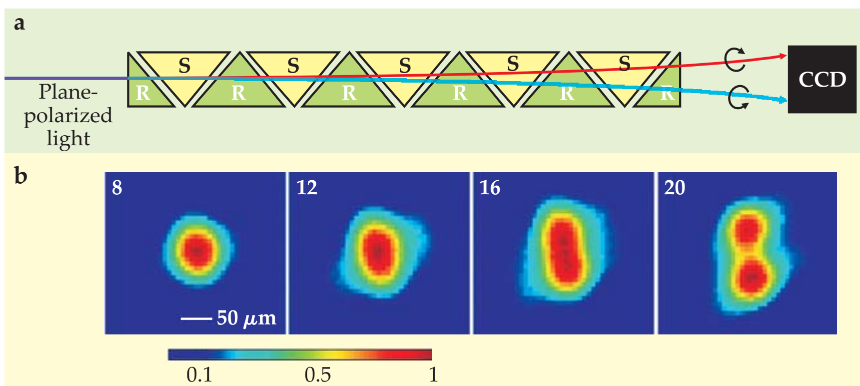
New angles to refraction and reflection in chiral liquids

A new experiment demonstrates one exception to a well-known rule: The angle of incidence is not always equal to the angle of reflection.

Augustin-Jean Fresnel predicted in 1822 that a light beam would split into two beams as it enters a chiral liquid—that is, one containing molecules that lack mirror symmetry. The splitting in a chiral liquid occurs because right-handed circularly polarized light and left-handed circularly polarized light travel at different speeds and hence see different indexes of refraction. Fresnel proposed an experiment to measure the angular splitting in a chiral solution, but the angle of splitting, on the order of microradians, is too small for Fresnel to have detected it. He did, however, observe the double image produced by light that had traversed a quartz crystal, which is birefringent because of its anisotropy. He used the effect to prove the existence of circularly polarized light.

Recently, Ambarish Ghosh and Peer Fischer of the Rowland Institute at Harvard University used a scheme similar to Fresnel's to measure the tiny angle of splitting between the two directions of polarization in a chiral liquid. Fischer said they were surprised that no one seems to have measured this angle before them. Perhaps, he thought, that's because previous research had focused on phase differences rather than beam positions.

One easily observable consequence of the accumulated phase difference between the two circularly polarized components is the rotation of polarization of plane-polarized light. Plane-polarized light is a coherent superposition of equal contributions of right- and left-handed circularly polarized light. Because one of the components travels more slowly than the other in a chiral liquid, a phase difference develops, causing the polarization vector of the superposition to rotate.



Beam splitting by chiral molecules. (a) Cuvettes filled with a solution of left-handed, or sinister (S), chiral molecules alternate with cuvettes of right-handed, or rectus (R), molecules. The net result of the arrangement is to increase the divergence of the right- and left-handed circularly polarized components of the incident plane-polarized light. **(b)** The splitting increases with the number of cuvettes (shown in the upper left of each image) until the two distinct beams are resolved. Color scale indicates intensity. (Adapted from ref. 1.)

Researchers today routinely use optical rotation to measure the concentration or the handedness of chiral molecules in solution. Much of organic stereochemistry is concerned with chiral molecules. Most drugs are chiral and are now marketed as single enantiomers—that is, molecules with the same chirality—because the mirror image can have a different effect on the human body.

To image the angular splitting, Ghosh and Fischer sent a plane-polarized light beam through a series of prismatic containers (cuvettes) filled in an alternating pattern with left-handed and right-handed enantiomers (see panel a of the figure). Because the angles at which the rays enter and leave a cuvette change along with the type of enantiomer filling that cuvette, the component rays diverge further at each interface. Panel b shows the image of the beams on a CCD camera after the