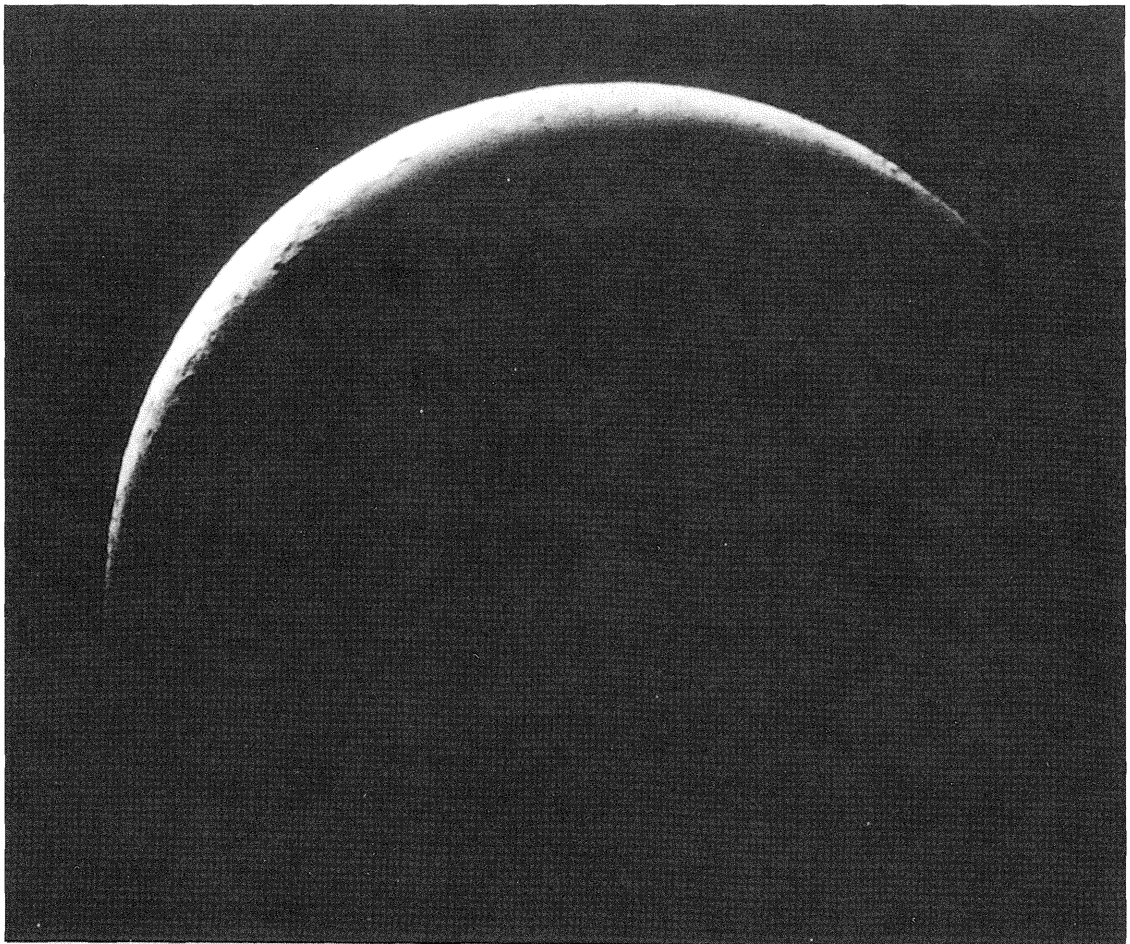
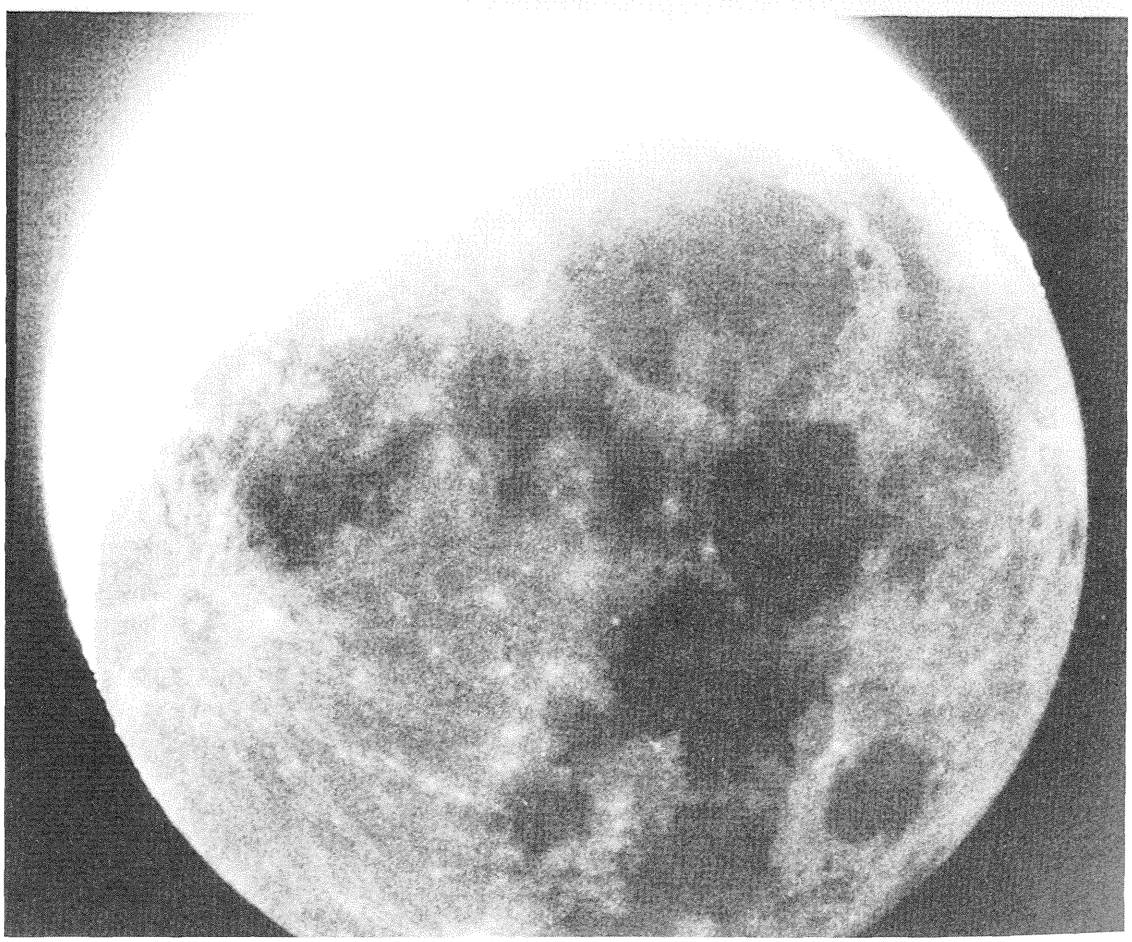




Global Change and the Dark of the Moon

Careful study of this "earthshine" can reveal much about the earth.

by Steven E. Koonin

The lunar crescent, snapped at 1/30 second (top), within a few days of a new moon, is all we usually can see of the moon at this stage. Sometimes, though, the rest of the lunar disk is faintly visible to the naked eye, and with an exposure of 30 seconds, even the features in the dark of the moon can be seen in a photograph.

This story is about watching the moon. Of course, people have been doing that for as long as there have been people, and so you might think that there's nothing new to say about moon watching. But a group of us at Caltech have recently revived and improved a 65-year-old program of precise lunar observations that can tell us something about the earth and offer unique insights into the changing global climate.

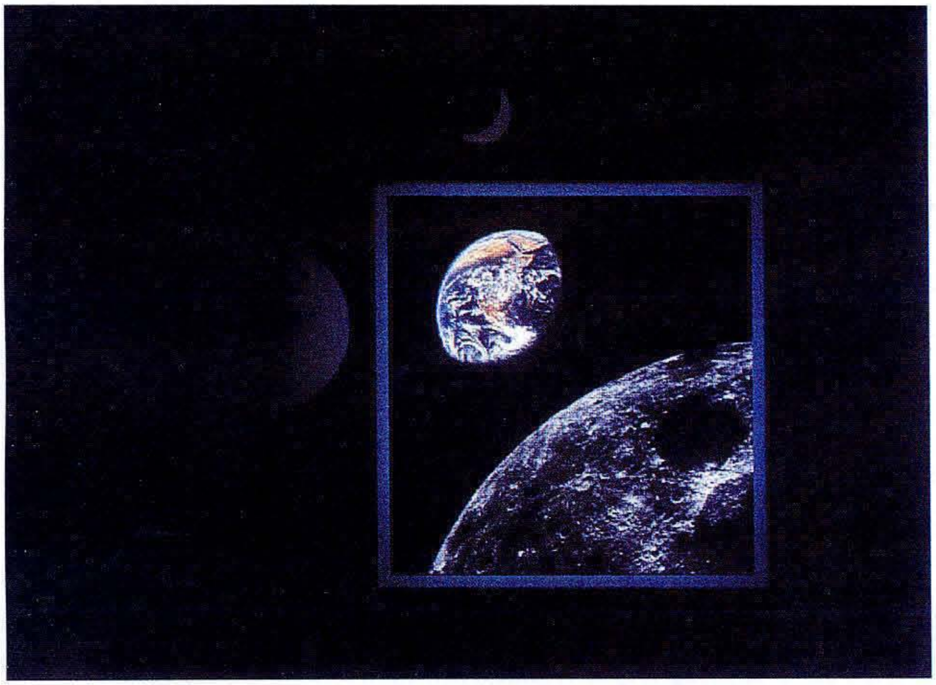
The phenomenon is best understood by considering the lunar image opposite, taken within several days of a new moon. The 1/30-second exposure shows the expected thin crescent. But if the exposure is lengthened to 30 seconds, features on the dark part of the lunar disk become visible. (The crescent, of course, becomes overexposed.) This ghostly glow of the dark of the moon is often visible to the naked eye and was known to the ancients. Various explanations for this light were offered over the centuries, including phosphorescence or translucence of the lunar surface; the great astronomer Tycho Brahe thought that it was light from the planet Venus. However, the correct explanation is generally attributed to Leonardo da Vinci in the 15th century: it is light reflected by the earth.

Careful study of this "earthshine" can reveal much about the earth. But for you to understand how earthshine relates to global change, I'll first need to say something about climate. The first thing to appreciate about the earth's climate system is how complex it is. Of course, there's the atmosphere, whose temperature, humidity, and winds are probably the most familiar manifestation of climate. But the oceans are at least equally important, because they store and transport vast amounts of heat, water, and other chemicals. Snow and ice in the mountains and the polar regions also play a role, as do biological systems both on land and in the ocean. The many interactions among these components result in the delicate balance that determines our climate.

Another important aspect of climate is its great variability. Every few days there are changes due to the weather. Changes over several months are associated with the seasons, and you need only recall that our rainy winter last year ended almost a decade of drought to realize that there is considerable variability from one year to the next. Most, but not all, scientists believe that the rising levels of carbon dioxide in the atmosphere will cause a greenhouse warming over the next several decades, and there is ample proof that the climate has varied substantially on even longer time scales. To go along with this variability in time, there's also great variability with location. Composite satellite images of the cloud cover over the whole globe show that two places with similar climates might have very different weathers on any given day.

So, the answer to the question of whether the climate is changing is "Of course!" But the real questions are: "How is it changing? How fast is it changing? And why is it changing?"

Well, if the climate is changing, what, if anything, should we do about it? The question is sharpened by the realization that human activities can affect the climate system. Examples include the burning of fossil fuels, the destruction of



From the moon, the earth appears to go through phases, just as the moon does to an observer standing on the earth. But these phases are opposite one another. When we see a crescent moon (background), an inhabitant of the moon gazing up at the sky would see a gibbous earth (inset).

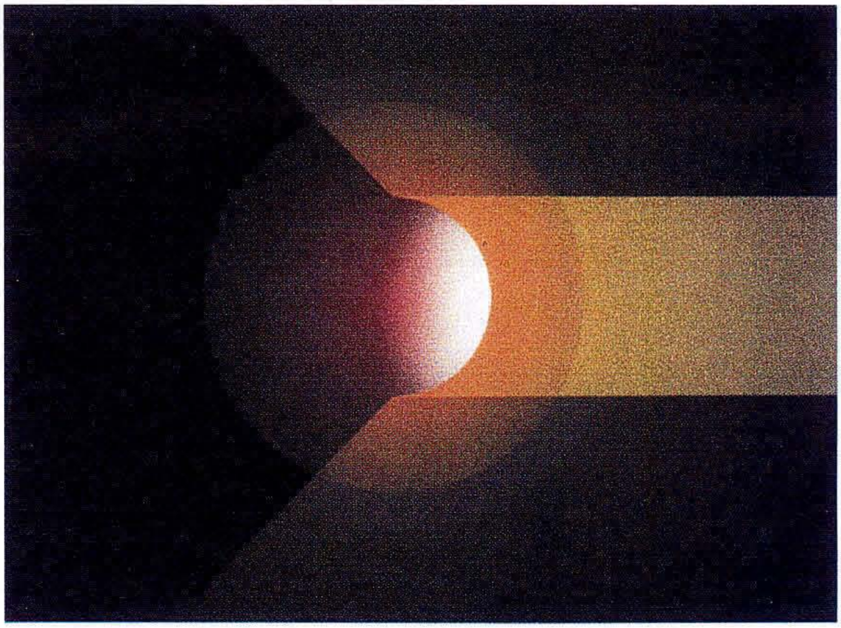
forests, and the use of chlorinated fluorocarbons (CFCs). Many, including the present administration in Washington, advocate far-reaching changes in society, aimed at reducing these activities or diminishing their impact, or, at the very least, adapting to climate change. Such measures, however, must rely on a firm scientific understanding of the climate system, including a clear separation of those changes that are natural from those that are caused by humans, and an assessment of how the system responds when we change something. This scientific understanding rests, in turn, on three kinds of activities.

The first are local observations of the various processes that connect the components of the climate system: for example, the way that plants remove carbon dioxide from the atmosphere, or the way that winds generate ocean currents. The second are computer models that use basic physical laws to describe and predict how the climate system behaves. This task, which is carried out in part using the Intel Touchstone Delta parallel supercomputer here at Caltech, is among the most challenging problems in computational science.

Finally, there are observations to find out what the climate is actually doing. To average out the great variability that I mentioned earlier, these must cover large areas of the globe and extend over many years. Further, they must be very precise, because any significant changes will likely be signaled by subtle shifts in the climate variables. Only when scientific understanding is firmly in hand can we confidently make changes in society and endure the great disruption they will undoubtedly entail. In my opinion, we have reached that point in some cases (for example, in the destruction of stratospheric ozone by CFCs), but are far from that point on many other issues. There is an urgent need for further understanding. The global observations I'm discussing here are one example of the attempt to meet this need.

Watching the planet as a whole is more easily imagined than accomplished, because the earth is large and we are simply too close. To appreciate the problem and its solution, consider how I might watch changes in my own face. The high-tech way would be to set up a video camera, step back, and then watch myself in a monitor. This is analogous to how we've been using artificial satellites for the past 30 years to watch the changing earth. A much easier way, however, is to just look in a mirror. And that brings me back to the moon.

We all learn in school that the moon goes around the earth once every 28 days. The familiar phases of the moon, from new to first quarter to full to last quarter, are caused by the varying visibility of the sunlit side of the moon. Sunlight, however, also illuminates the earth. Most of that sunlight is absorbed by the earth and drives its climate system, but some of it is reflected back into space. In particular, some of the reflected light reaches the moon. If you were standing on the moon and watching the earth, you would see it going through phases opposite to those of the moon: When the moon (as seen from earth) was new, the earth would be full (and you could see half the globe at once); when the



When light from the sun (way out of the picture to the right) reaches the earth, about 70 percent of it is absorbed, warming the planet. Eventually this heat returns to space as infrared radiation from all parts of the globe (the orange glow in this schematic drawing). The other approximately 30 percent (the albedo) is reflected from the sunlit half of the globe. Variations in the albedo change the portion of the sunlight available to warm the earth, and so can provide insights into global change.

It's been a long time since anyone has been on the moon to watch the earthshine, but we can use the moon as an imperfect mirror and see the earthshine reflected back to us on earth as the faint glow of the dark part of the lunar disk.

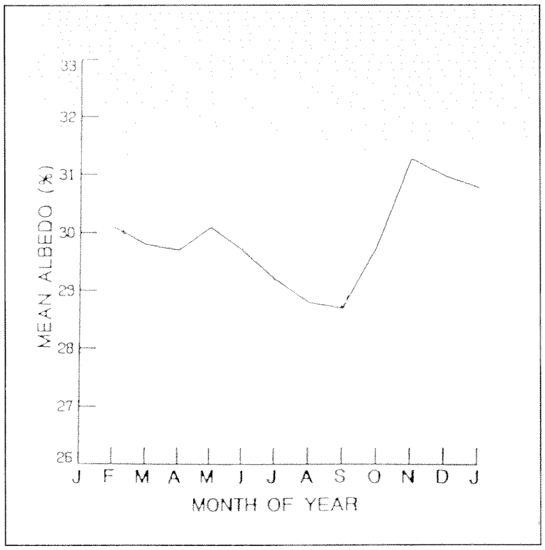
moon was full, the earth would appear as a thin crescent. It's been a long time since anyone has been on the moon to watch the earthshine, but we can use the moon as an imperfect mirror and see the earthshine reflected back to us on earth as the faint glow of the dark part of the lunar disk. The earthshine will be bright and easy to observe near new moon, while it will be dim near the full moon.

To understand how earthshine can be used to monitor the earth's climate, we need to look at what happens when the sun shines on the earth. About 70 percent of the light is absorbed and converted to heat; it is this energy that warms the planet and drives the winds and ocean currents. The heat eventually returns to space as infrared radiation emitted from all parts of the earth. But the 30 percent of the sunlight reflected back into space from the sunlit half of the globe is not available to warm the planet. So the fraction of the sunlight reflected (called the albedo) determines the temperature of the earth. Other things being equal, if the albedo were 29 percent, the earth would be about 2 degrees Fahrenheit warmer, and if it were 31 percent, the earth would be 2 degrees cooler. Since the total greenhouse warming due to doubling the carbon dioxide in the atmosphere is predicted to be between 2.5 and 7 degrees, it's clear that knowing the albedo to a small fraction of a percent would be important.

Of course, it's not that simple. For example, if the albedo were smaller, the earth would be warmer and there might be more water vapor in the atmosphere, leading to more clouds, which would tend to make the albedo larger. Such "feedbacks," where a change in one element causes a second to change, which in turn affects the first element, are a central feature of the climate system and greatly complicate our attempts to understand it. In any event, the albedo is a key parameter of the climate, and the global temperature is very sensitive to it.

The albedo of the entire globe (the fraction of sunlight reflected) depends upon the reflectivity of each part of the earth's surface. The ocean is generally darker than the land, the desert is more reflective than the average land, and snow and ice are the most reflective of all. The presence of clouds can enhance the albedo greatly, and if there were no clouds on the earth, its albedo would be only 17 percent, much less than its true value of 30 percent. The global albedo is therefore highly variable, changing with the weather and the seasons. Since the oceans and continents are not uniformly spread over the earth, it even depends upon which half of the earth is in the sunshine. Volcanic eruptions, such as the recent one from Mt. Pinatubo, also increase the albedo by as much as 0.5 percent, since the dust clouds they loft into the stratosphere linger for several years.

Observations from satellites in orbits several hundred miles high have told us most of what we know about the global albedo. They do this by observing the sunlight reflected from five-mile patches of the earth, one patch at a time. After enough orbits, and with certain assumptions about how the sunlight scatters from the earth, they can deduce the total amount of sunlight



Satellite data produced this monthly plot of the global albedo in 1985, which averages about 30 percent. The variation of about 1 percent is due to the distribution of continents and the changing snow and cloud cover.
Below: French astronomer André Danjon, who performed the first, pre-satellite, quantitative measurements of the earthshine.

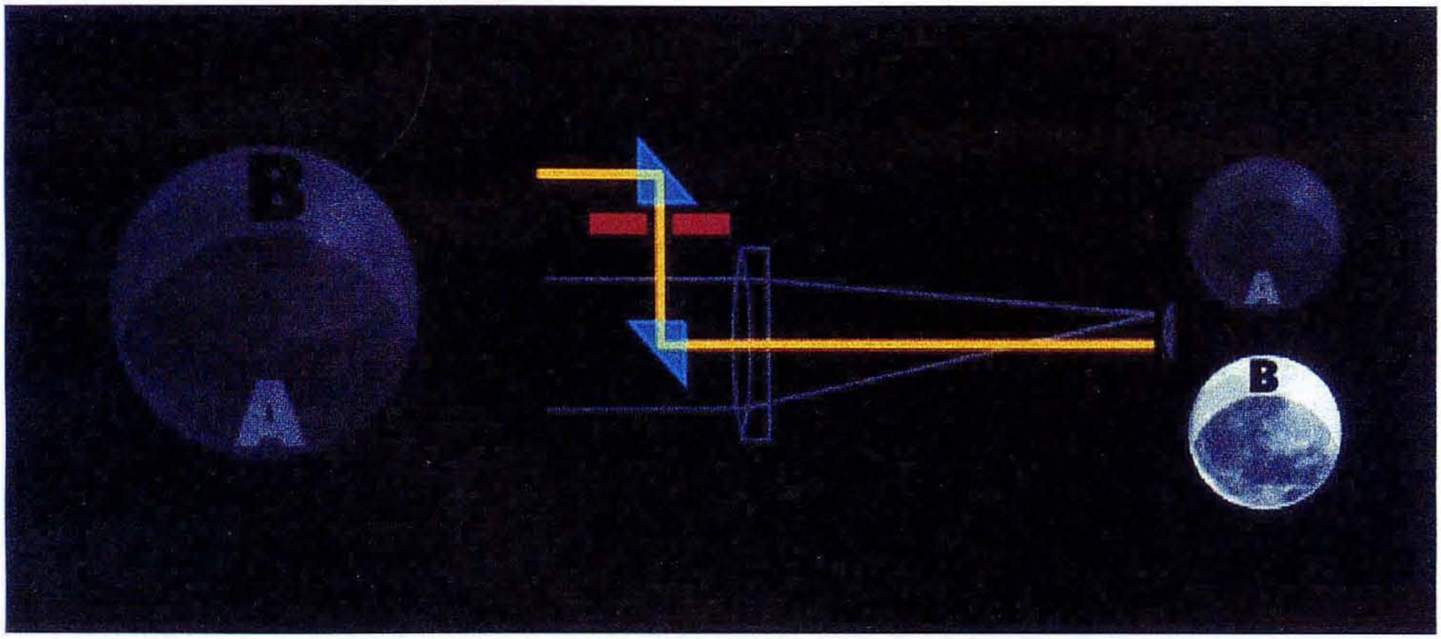
Because earthshine observations are ground-based, they are relatively inexpensive, and, compared to a satellite, the equipment is easy to maintain and upgrade.

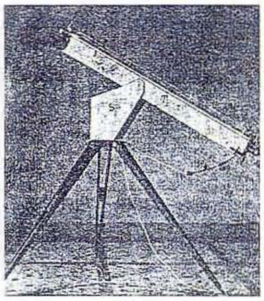
reflected. Above is a plot of the global albedo for each month of 1985 as determined by satellite. You'll notice that it averages about 30 percent, but varies up and down by about 1 percent during the year, with a minimum in August/September and a maximum in November. This variation is due to the way in which the continents are distributed on the earth (there is much more land in the northern hemisphere) and to the way in which the snow cover changes during the year. Of course, if we were to look at the results for 1986, the details would be different, but the overall features that I just mentioned would be similar.

Satellites are marvelous devices, and many people work very hard to produce and analyze the wealth of data they provide. But satellites are not perfect. They cannot cover large areas of the globe simultaneously (just patch by patch), nor can they do it continuously; any one satellite sees a given point on the earth only infrequently. Further, there are uncertainties in how to relate the light that the satellite detects to what is actually scattered from a given patch of the earth. It's also not so easy to keep a precision instrument calibrated in space. As a result, two different satellite systems will typically differ by 0.7 percent in the monthly average albedo. That may not sound like much, but it's worth about 1.5 degrees in the global temperature, a non-negligible fraction of the expected greenhouse warming. Satellites are also expensive—typically costing hundreds of millions of dollars—and they can break; at this moment there is no satellite doing precision monitoring of the earth's albedo. And finally, we have good satellite data for only two or three decades at best.

Earthshine observations can complement the satellite observations in interesting ways. By observing close to the new moon, you can cover almost half the globe at once, and with sites spaced around the globe, this could be done during more than half of each lunar month. Earthshine observations are self-calibrating, as I'll explain shortly, and should be able to detect changes in the albedo as small as 0.2 percent. Because earthshine observations are ground-based, they are relatively inexpensive, and, compared to a satellite, the equipment is easy to maintain and upgrade.

Another advantage is the existence of a historical record of observations extending back over 65 years, which should give us a long interval over which to assess climate change. André Danjon, a French astronomer, devised the method that allows a quantitative measurement of the earthshine. Danjon was a major figure in French astronomy, finishing his career as director of the Paris Observatory before his death in 1967. He was noted for inventing several types of astronomical instruments and for his precise photometry (studies of variations in brightness) of the planets and stars. Danjon's method for measuring the earthshine is quite elegant. He selected two spots nearly diametrically opposite on the lunar disk. They were chosen to have similar optical properties (both are bright highland regions) and are quite clearly described in his papers. We can call one of these spots region A and the other region B. At some time early in





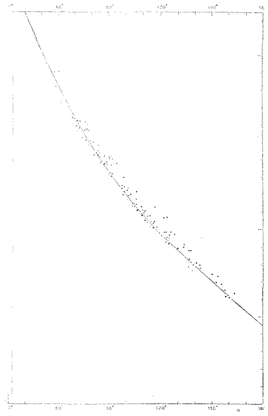
Danjon's photometer (left) employed an elegant system for determining the brightness of the dark of the moon relative to its sunlit crescent. Two spots, A and B, were selected on opposite sides of the lunar disk; at any point in the lunar month, one spot would be bright in sunlight and the other dimly illuminated by earthshine. The photometer's eyepiece showed two adjacent lunar images, one of which had passed through a simple telescopic lens, and the other through a series of prisms (blue) and a diaphragm (red). This diaphragm, shaped like a cat's eye, could be adjusted to reduce the brightness until both spots looked the same. The amount of adjustment provided an accurate measure of the relative brightness of the two spots.

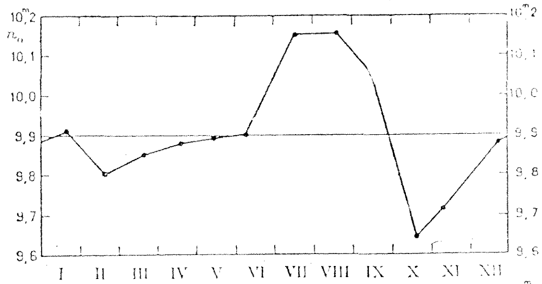
the lunar month, one of these two spots (say, A) will be in the earthshine, and the other, B, will be in the sunshine. Of course, later in the month the role of the two spots will be reversed.

Danjon developed a "cat's-eye" photometer to make his measurements. The device presented two adjacent images of the moon in the eyepiece. One of these passed through an ordinary telescope arrangement. The other image was produced similarly, but first passed through some prisms and a diaphragm shaped like a cat's eye, which could be adjusted to reduce the brightness of the image. In the eyepiece spot A of the first image would appear next to spot B of the second image. If Danjon then adjusted the diaphragm until the two spots appeared to be equally bright, he could determine the brightness of the earthshine relative to the light from the bright crescent. This gives the technique the advantage of self-calibration; that is, the earthshine is compared to a "standard candle"—the sunlit part of the moon.

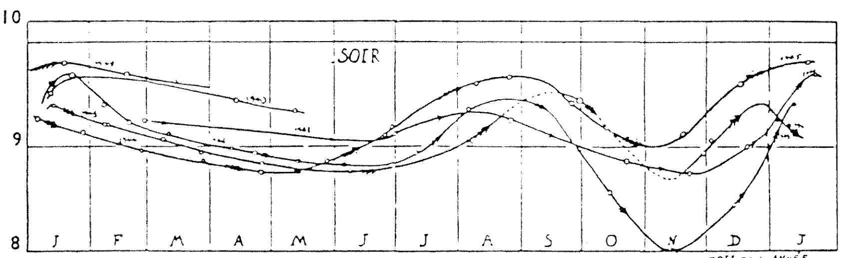
It also neatly solves another problem. Precision astronomical observations from the ground generally suffer from the fact that the light has to pass through the atmosphere where it can be absorbed or distorted, as in the familiar twinkling of the stars. But, since the light from both spots takes almost the same path through the atmosphere, both images suffer the same distortion, which then doesn't matter when they're compared. Danjon estimated that, with his trained eye, he could determine the ratio of the light from the two spots to an accuracy of 5 percent.

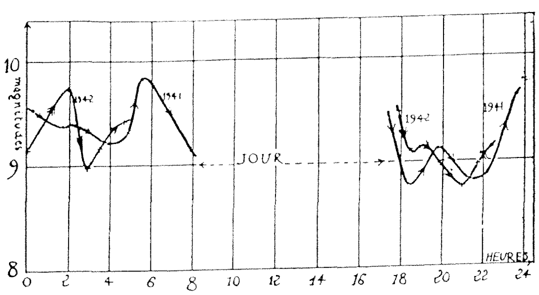
Danjon's photometer was packaged in a portable device, easily set up and operated on a

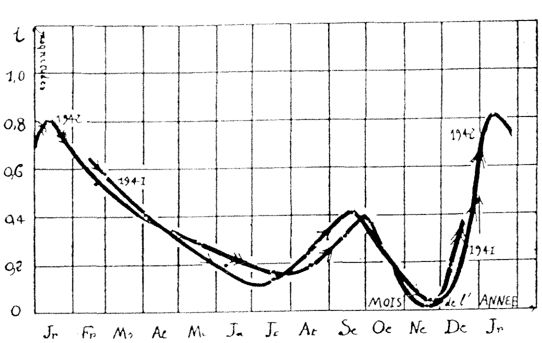




Dubois and Danjon observed and plotted earthshine variations, beginning in 1927 and continuing until 1960, showing (from top) how it changed with lunar phase (brightest near new moon), with season (in 1929; Roman numerals represent months; numbers along vertical axis refer to astronomical magnitudes), with season again in the 1940s, with time of day (hours along bottom), and with color by month (the vertical axis is the color index in astronomical magnitudes).





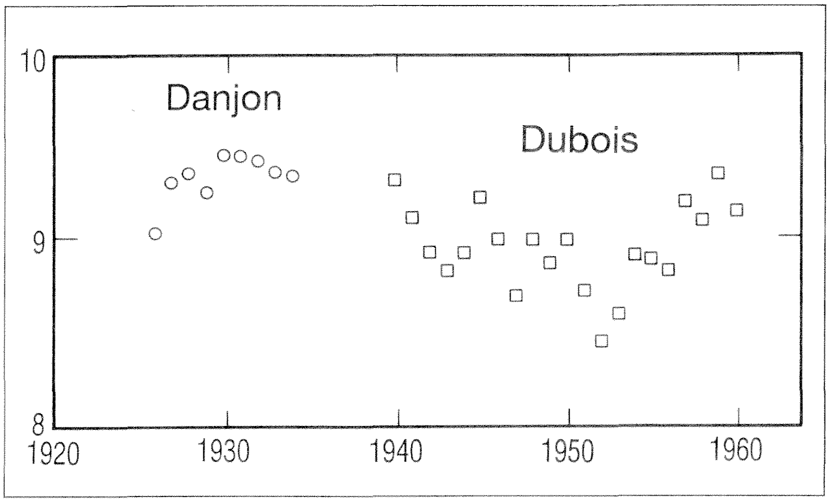


The old French observations qualitatively established many important features of the earthshine.

tripod. He used it to make some 200 earthshine observations in southern France from 1927 to 1931. His program was pursued and extended by J. E. Dubois, who made many observations from 1940 to 1960. One might imagine that Dubois took a considerable risk running around the countryside of occupied Bordeaux pointing this funny-looking contraption at the night sky. But, in fact, he claimed that the wartime blackouts actually made his work easier by darkening the sky.

The old French observations qualitatively established many important features of the earthshine. They mapped out how the phenomenon varies with the lunar phase (as I mentioned earlier, it's brightest near new moon and dimmest near full moon), and showed that it depended upon the weather. For example, one of the papers remarks that the earthshine was particularly bright one night due to the clouds of a large storm in the North Atlantic. They were also able to map out how the earthshine varied with season, which is quite similar to the variation in the albedo seen in satellite measurements. (Remember, this was done about 25 years before the first satellite was launched!) They also showed that the earthshine varies from one year to the next and even showed that it varies with time of day, as different parts of the earth reflect sunlight up to the moon. Finally, they studied the color of the earthshine and found that it's relatively blue, as might be expected of the light from our "blue planet." They also found that the color varies with the season and with the time of day.

Many of the details of the old French measure-



Don Huffman's analysis of the Danjon/Dubois data shows large fluctuations, particularly over the latter two decades. This phenomenon is not yet understood.

One might imagine that Dubois took a considerable risk running around the countryside of occupied Bordeaux pointing this funny-looking contraption at the night sky.

ments have been recovered by Don Huffman, professor of physics at the University of Arizona. Huffman has achieved great notoriety in recent years in figuring out how to make large quantities of "Buckyballs," a new family of large, all-carbon molecules. But earthshine is sort of a hobby for him. He has been to France several times since 1989 to interview Dubois's widow, examine the old notebooks, and inspect the instrument that Dubois used. Huffman's analysis of the Danjon/Dubois record shows large fluctuations over two decades, a phenomenon not yet understood. Don has also reproduced the old French instrument and trained himself in the observing techniques; he's making regular earthshine measurements from the Arizona desert to extend and understand this 65-year time series. This still leaves a gap of some 30 years; we would love to find someone who was making earthshine observations during that period.

The French observations stopped in 1960 for several reasons. Professional astronomers were getting bored with the moon and moved on to more glamorous objects such as quasars. In fact, Danjon closes one of his papers with a charming apology for spending his time on earthshine, saying that, while it might not be the most fashionable astronomy, it probably has something to do with the earth's climate. Moreover, Danjon determined the average albedo to be 36 percent. Because this is much greater than the 30 percent later measured by satellites, his work has been dismissed with some vague mention of problems with the observations or method.

That discrepancy persisted until 1991, when my part of the story starts. During that summer I was a member of a government committee looking into what use a fleet of small satellites might have in studying global change. One of the suggestions was to study the albedo. At some point in the discussion, someone noted that the way the earth's albedo was first determined was through observations of earthshine. A fellow committee member (Gordon MacDonald of UC San Diego) and I thought that sounded pretty interesting. So we set off searching libraries all across the United States and Europe, using phones, fax, and the Internet. We soon dug up the old French references and learned the historical details I've just recounted. But we also realized that the old analyses had not accounted for a peculiar property of the lunar reflectivity called the opposition effect.

The point is that the sunlight is reflected from the bright lunar crescent by an angle that changes with the lunar phase. The earthshine, however, is always reflected straight back from the moon in the direction of the earth. So, to compare the intensity of the earthshine to the sunshine, you need to know how the quality of the lunar mirror (its reflectivity) changes with the angle. Danjon measured this by studying how the brightness of his two spots varied during the lunar month, when they were in the sunshine. His data trace out a smooth variation with angle, as shown by the blue curve in the middle figure on the following page. Unfortunately, Danjon measured the lunar reflectivity only to within 11 degrees of the full moon, in part because the 6-degree tilt of the moon's orbit prevented him

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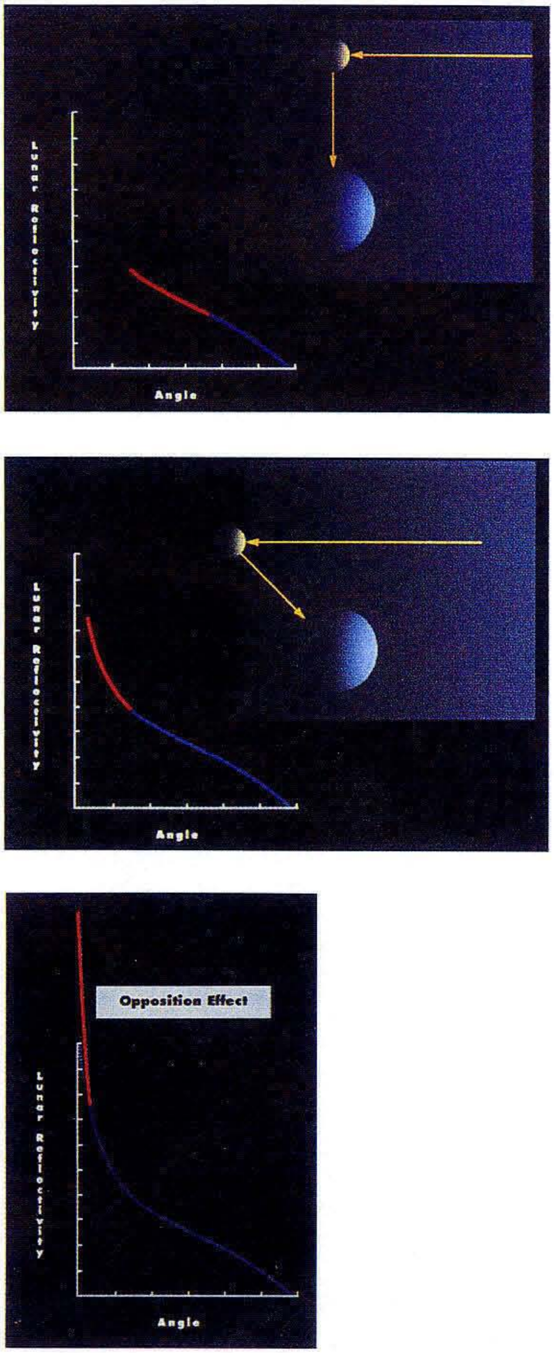
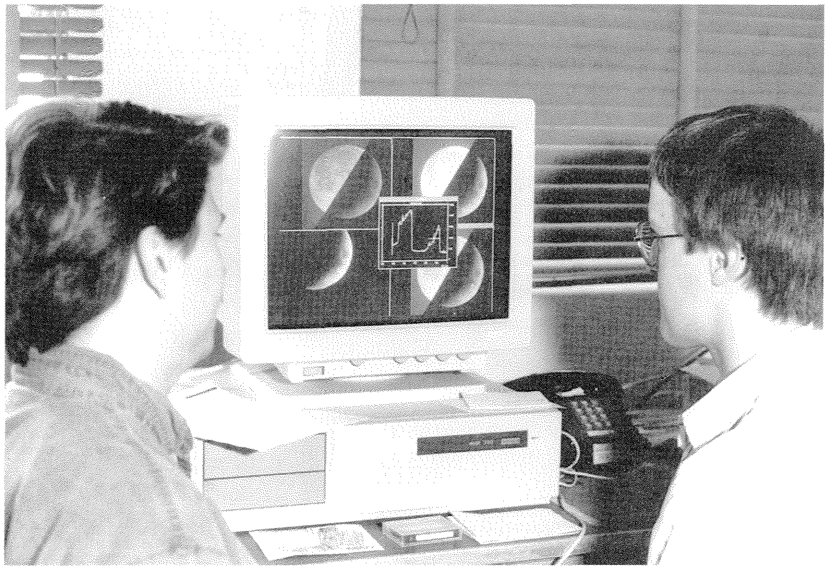


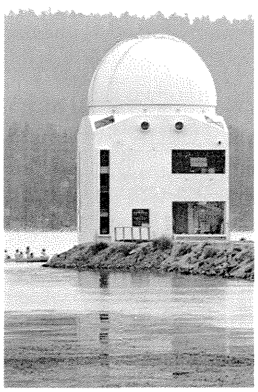
A phenomenon called the opposition effect complicates the comparison of the intensity of sunshine with earthshine. It refers to the fact that, while the sunlight reflects through an angle that varies with the lunar phase, the earthshine is always reflected straight back to the earth. The reflectivity is least just after new moon (top). Danjon expected a smooth curve upward as the angle of reflected sunlight decreased (center), but failed to account for the opposition peak near full moon, which causes the curve to rise dramatically near the axis (bottom). Modern corrections of Danjon's underestimate of the reflectivity of the moon bring his figures for average albedo into line with current observations.

from seeing an exactly full moon. But he made what seems like a quite reasonable estimate of the reflectivity for earthshine. More modern measurements of the variation of the moon's brightness near lunar eclipses (when the sunlight is reflected almost exactly straight back) show that the lunar reflectivity rises dramatically (the opposition peak) within a few degrees of back-reflection, as shown by the red curve in the bottom figure. As a result, the moon is a much better mirror for earthshine than Danjon had estimated. (It is this same opposition effect that makes the full moon much brighter than one would have guessed.) When the correct lunar reflectivity is used, Danjon's average albedo of 36 percent becomes just about 30 percent, in accord with the satellite values.

The realization that there probably wasn't anything wrong with the old observations and that earthshine could be a good quantitative measure of the earth's albedo motivates our modern observational program. Since I'm a theorist, my first urge was to rush to a computer and start modeling. And, being a professor, I couldn't resist the opportunity to educate someone else. So I enlisted two research fellows with a background not in planetary sciences or something germane, but, of course, in theoretical nuclear physics: Edwin Kolbe, who's visiting Caltech from Germany, and Ming Chu, BS '83, PhD '87. We three amateurs in the climate business soon had the first modern model of the earthshine working. This involves the well-known motions of the earth around the sun and the moon around the earth, but also the much more uncertain way



Research Fellow Edwin Kolbe (right) and grad student Jason Maron analyze the corrected lunar images taken at Caltech's Big Bear Solar Observatory (below).



in which the sunlight reflects from each patch of the earth. To know this, we needed to know the instantaneous cloud and ice cover over the whole globe for at least a year. Since that's pretty hard to come by, even with satellites, we used the results from one of the most advanced climate models developed by the European Center for Medium Range Weather Forecasting.

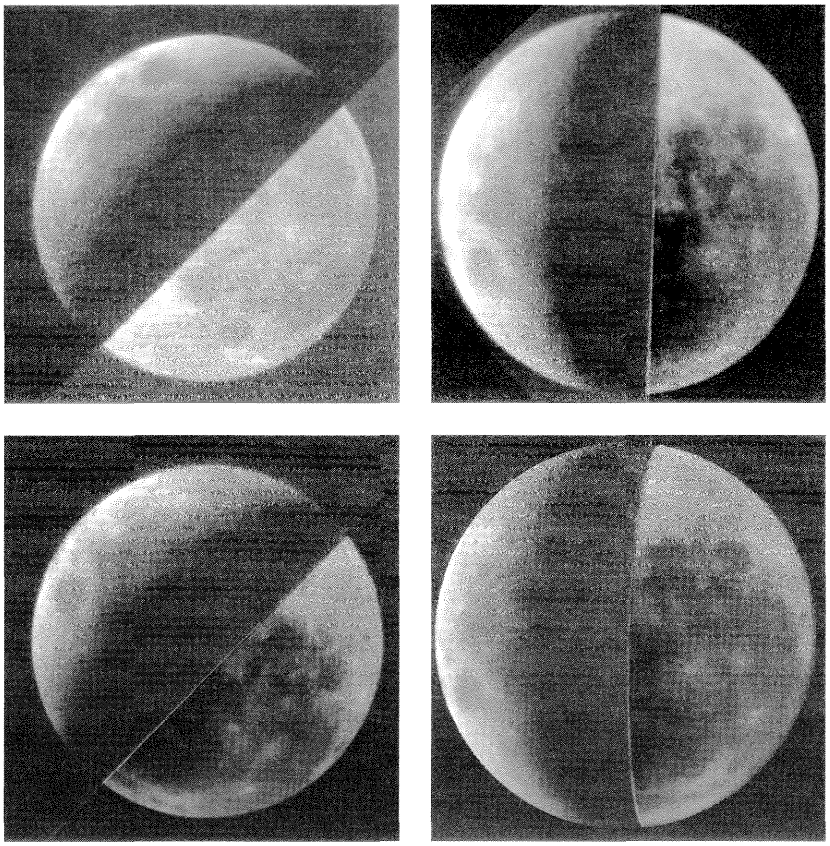
Our modeling confirmed the suspicion that earthshine was an excellent indicator of the earth's albedo. It also showed that we could determine the albedo with an accuracy of 0.2 percent (somewhat better than the satellite measurements) if we could measure the earthshine intensity to 1 percent. Danjon and Dubois had achieved a precision of 5 percent by eye, and, of course, technology has improved in the intervening decades.

At that point it was time to get professional, and so I interested my colleague, Professor of Astrophysics Hal Zirin, in the project. With funding from the Department of Energy's Western Center for Global and Environmental Change, we started taking regular pictures of the moon last May at Caltech's Big Bear Solar Observatory, of which Hal is the director. Rich Goeden, member of the professional staff, constructed the hardware, including a 6-inch telescope mounted on the solar drive, which uses a magical chip called a charge-coupled device (CCD) to produce digital images. Glenn Eychaner, BS '90, a Big Bear observer, and Research Fellow Jo Bruls have rearranged their lives according to the lunar cycle to take the pictures.

We use a modern version of the Danjon technique, in which a neutral-density filter dims the sunlit crescent, as seen on the monitor above. This allows both the earthshine and the sunshine to be recorded simultaneously. The images come out of the CCD camera as square arrays, 512 pixels on a side. Each of these pixels contains a number giving the brightness of that spot of the image. You might note in the raw picture on page 2 the variation of the sunlight across the crescent in contrast with the uniform brightness of the earthshine; this is a consequence of the opposition effect I described earlier.

The analysis of the images is being carried out by Edwin Kolbe and Jason Maron, a first-year graduate student, also in physics. To reach our goal of 1-percent precision on the earthshine measurement, the raw images have to be corrected in several ways. One of the most important corrections arises from the moonshine being about 10,000 times brighter than the earthshine, so that even a tiny bit of moonlight scattering in the atmosphere or the telescope can overwhelm what we're looking for. So we subtract this background.

A second problem is defining the comparison spots on the moon. Danjon's spots are not well-enough described for our precision work, and, because we have the whole lunar disk in our images, we're free to pick our own and as many pairs as we like. To find the spots with precision, we first scale the lunar image to a standard size, since the apparent size of the moon varies by 20 percent during the lunar month. Then we rotate it to a standard orientation. We can then let the computer find precisely the areas that we want.



This CCD image taken at Big Bear has been corrected in several ways. At top left a neutral-density filter dims the sunlit crescent; at lower left the background of scattered moonlight has been subtracted and the image inverted; at top right, the moon has been scaled to a standard size (it varies up to 20 percent over a month) and rotated to a standard orientation, in order to precisely locate the pairs of comparison spots; and at lower right, the image has been "delibrated" to correct for the moon's slightly changing face due to its elliptical orbit.

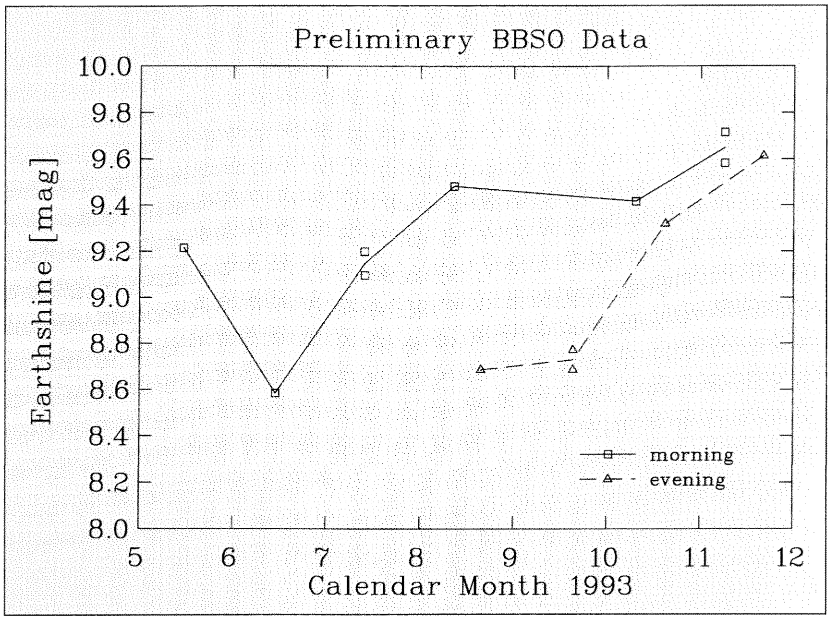
Another important correction is the lunar libration. Because the moon's orbit around the earth is elliptical rather than circular, it does not always present exactly the same face to the earth. Rather, it appears to swing back and forth, or librate, during the lunar month. Of course, the libration affects our spot finding, so we must "delibrate" the images using the known orientation of the moon. The libration also affects the brightness of our sunlit spot by changing the angle at which it's illuminated.

Finally, there is the issue of the lunar reflectivity. We need to know how the lunar reflectivity varies with angle for all of our spots. Since we've been unable to locate modern digital data, we're doing it ourselves by taking precision images at all lunar phases. Fortunately, Big Bear was cloud-free during the lunar eclipse last November 28, which allowed Glenn and Jo to take many pictures to catch the opposition peak I described earlier.

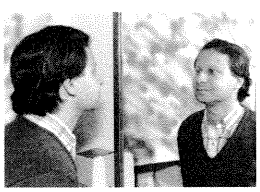
After applying these corrections and several others, we've been able to determine the relative variation in the earthshine (and hence in the albedo) since last May. The plot on the opposite page shows the brightness of the earthshine in astronomical magnitudes, measured each month when the moon's phase was plus or minus 120 degrees (that is, about a third of the way before or after new moon). While we would still term these data preliminary, several features are already evident. First, on several dates you see two points plotted. These were taken within two hours of each other, and so give some measure of the hourly variation in the earthshine. Second, you can see significant variations from month to month of a size comparable to that expected from the French work. Finally, there are clear differences between morning and evening observations. These are to be expected because observations in the evening (just after a new moon) sample the hemisphere to the west of us (the Pacific Ocean), while those in the morning (in the waning days of an old moon) sample the Americas and the Atlantic.

Although these data give you a feel for what we'll be able to do, they need further study before we can have complete confidence in them. We're really just six months into this program, and we're funded to continue for another 18 months. There will be more intensive earthshine observations at other lunar phases, as well as campaigns to map out the hourly and color variation.

The color of the earthshine, or more technically its spectrum, is also the subject of a more speculative activity that we're engaged in, still using the moon as mirror in which to view the



Corrected data from Big Bear Solar Observatory show the brightness of earthshine in astronomical magnitudes measured about a third of the way before or after new moon. Hourly variations are indicated by two boxes in one place; expected differences between morning and evening observations are due to sampling from different hemispheres. Strong monthly variations are similar to the French data on page 8.
Below: Steve Koonin monitors facial change in his own mirror.



earth. Everyone has probably seen that familiar demonstration in which light from the sun is broken into its component colors when passed through a prism. It's interesting to ask what happens to those colors when the light is reflected by the earth. The sunlight passes through the atmosphere and is either absorbed or reflected by the earth or from the clouds. During the course of that passage, light at particular wavelengths, or colors, is removed, the precise colors depending upon the various chemicals in the atmosphere. Carbon dioxide, for example, will have one particular pattern, water vapor another, and so on. These patterns will also depend upon the temperatures of the absorbing molecules. So, by measuring the spectrum of the earthshine, we might be able to monitor, on a global scale, the concentration and temperatures of various chemicals in the atmosphere.

Frank Very, an American astronomer, was, to our knowledge, the last to attempt to take a spectrum of the earthshine. He published a paper on it in 1914 with inconclusive results. Surprisingly, there have been few, if any, high-resolution spectral measurements of the whole earth from satellites, although there are plans to orbit at least one device capable of such measurements in a few years—at considerable expense, of course.

We had the feeling that it shouldn't be too difficult to take a spectrum of the earthshine since, after all, the light is bright enough to see and astronomical instrumentation has improved markedly since Very's time. So we enlisted Jim McCarthy, assistant professor of astronomy, and made two attempts last summer to take a spectrum of the earthshine using Jim's echelle spectrograph installed on the 60-inch telescope on Palomar Mountain. Unfortunately, we were hampered by scattered light, but we've got time this spring to try again more systematically under better conditions. Should we be successful in getting a spectrum and demonstrating that it varies from day to day or with the seasons, it could provide a different and very interesting way of assessing the changing global climate.

So, in the end, why are we doing all of this watching of the moon? I think there are at least three reasons. First, we hope to demonstrate that earthshine observations can be carried out with sufficient precision that they can usefully complement satellite observations. Certainly our modeling indicates that this is possible, but there's nothing like actually doing it to convince the skeptics. Second, we hope to establish firm benchmarks against which future observations can be compared to assess global change. Thus, if someone measures the earthshine 10 or 20 years from now, they'll have our precise and well-documented observations against which to judge changes. We might also try to calibrate Huffman's observations to tie back to the Danjon/Dubois work in order to obtain a 65-year record of global change.

And finally, a very important reason is that it's just plain fun to be working on a small, interdisciplinary project that might contribute a bit to one of the major issues facing society. I hope this presentation will let you share a bit of the amazing feeling I get when I look up at the crescent moon and realize that I'm watching the earth. □

Steve Koonin's "real" research is centered on the structure and interaction of atomic nuclei. He spent his undergraduate years at Caltech (BS '72), earned his PhD at MIT in 1975, and then promptly returned to Caltech as assistant professor. He was appointed associate professor in 1978 and professor of theoretical physics in 1981. When he's not moongazing, Koonin has also developed an innovative course in computational physics, led the Caltech denunciation of cold-fusion claims in 1989, and was chairman of the faculty in 1989–91. This article was adapted from Koonin's January Watson Lecture. The graphics were originally developed for the lecture by Wayne Waller in Caltech's new Media Integration Laboratory, part of the Campus Computing Organization.