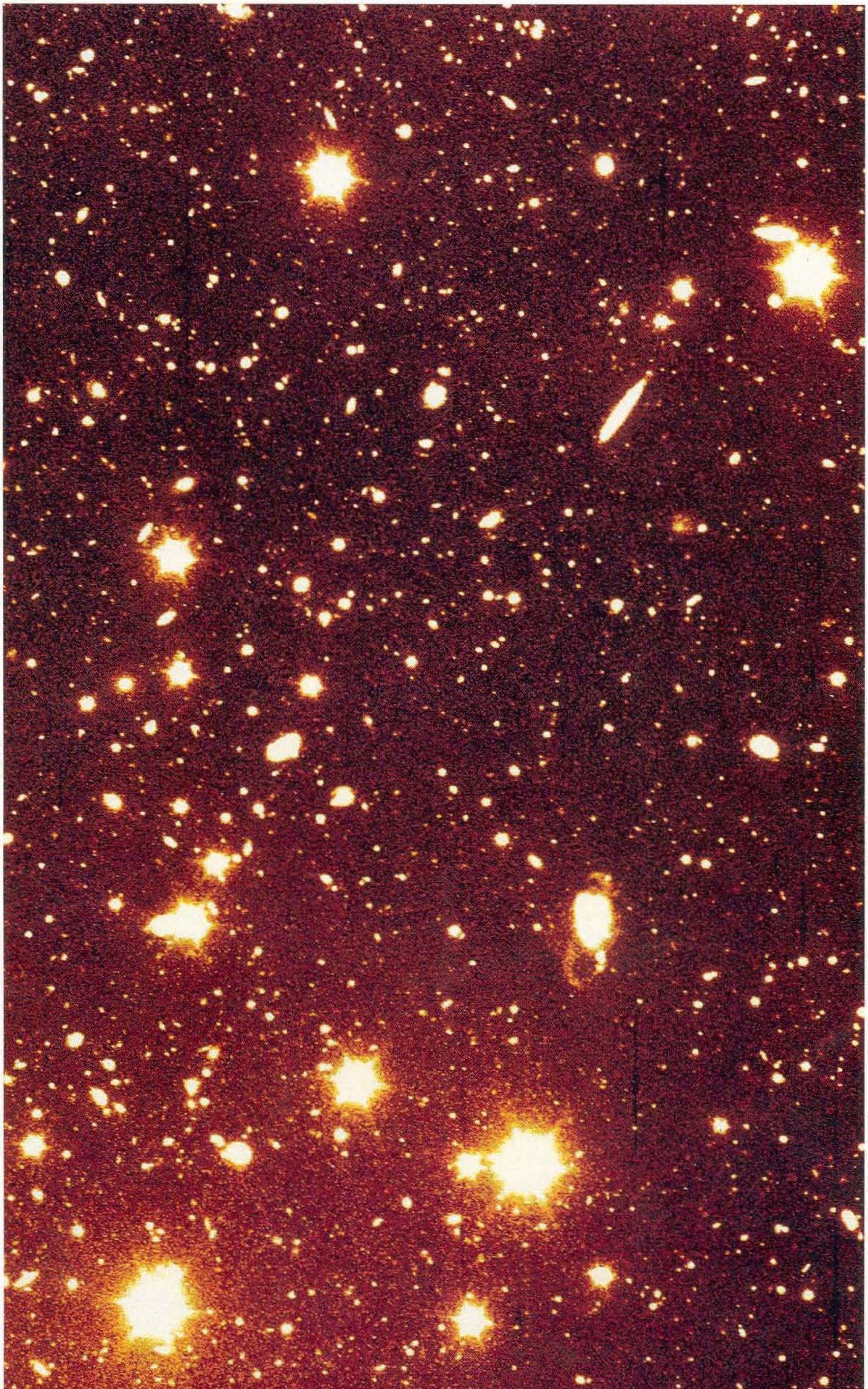


Science with the Keck Telescope

by S. George Djorgovski

By counting galaxies according to their color and apparent brightness in these deep, deep reaches of the universe, we can actually test models of cosmology.

This may be the deepest visible-light image ever obtained—a portion of a field from a visible-light deep-galaxy survey being undertaken at the Keck Telescope by Caltech astronomers. Virtually every dot you see here is a galaxy. The complete image, which covers an area of sky about one-fifteenth that of the full moon, contains about 6,000 galaxies.

Wonderful things are happening in astronomy today, and the Keck Telescope is right in the thick of them. With its 10-meter-diameter primary mirror, it is the largest optical telescope in the world. The Keck is a joint venture between the University of California, Caltech, and the University of Hawaii, and is located in an astronomical preserve on the summit of Mauna Kea, Hawaii. A second Keck Telescope is now under construction there, thanks to the continued generosity of the W. M. Keck Foundation.

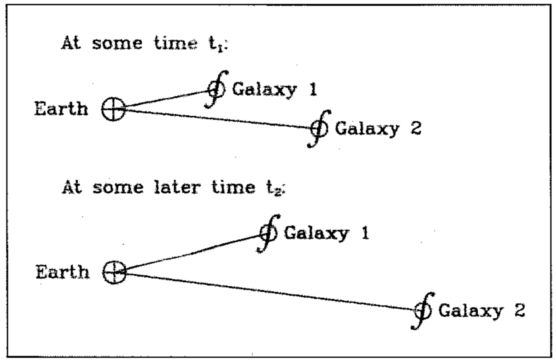
Before I describe what we're doing with the Keck, let's begin with a quick summary of the universe as we know it. Our star the sun, the earth, eight other major planets, and lots of moons, comets, and assorted other things form our solar system. The sun and about a hundred billion other stars, along with some gas and so on, form our galaxy—the Milky Way. Galaxies like to come in groups and clusters—for example, Andromeda, also known as M31; the Milky Way and its satellite galaxies, which include the Magellanic Clouds; and other galaxies form what's called the Local Group. Groups and clusters tend to agglomerate into superclusters, which are the largest structures we know. The center of the Local Supercluster, of which we are a member, is about 50 million light-years away in the Virgo Cluster. (A light-year is the distance that light travels in a year, about 5.88 trillion miles.) The light now reaching us from the outskirts of the Local Supercluster started on its way more than 70 million years ago, when dinosaurs were still walking the earth.

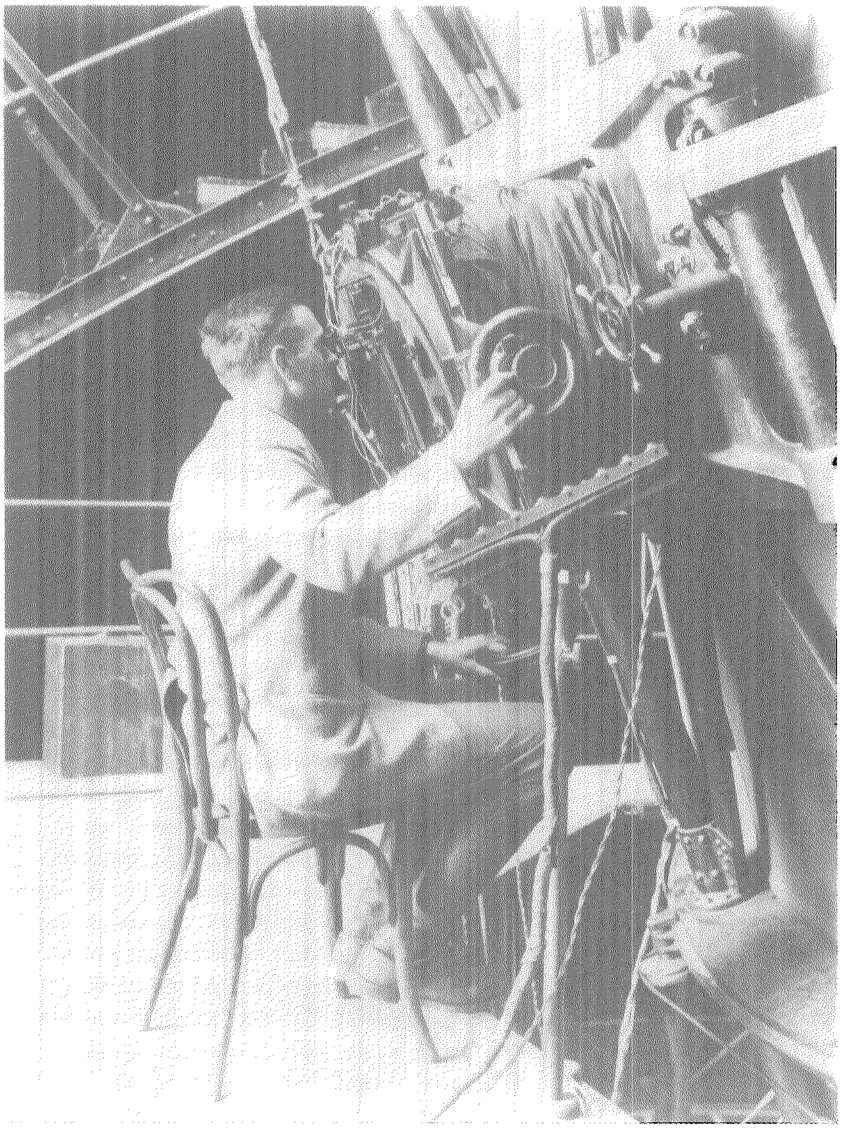
Let me try to illustrate these distances. Imagine that you shrank the earth down to a small grain of sand, about one one-hundredth of an inch in diameter. Then the sun would be an inch across and five feet away, and the solar system would be about a fifth of a mile across. The nearest star would be about 260 miles away, almost all the way to San Francisco, and our galaxy would be six million miles across. The next nearest galaxy would be 40 million miles away. At this point, you begin to lose scale, even with this model—the nearest cluster would be four billion miles away, and the size of the observable universe would be a trillion miles. If you were to ride a taxi across it at five dollars per mile, you could pay off the national debt.

Observational cosmology—the study of the universe at large—began in the 1920s, when Edwin Hubble, the Pasadena astronomer for whom the Space Telescope is named, discovered that he could see individual stars pulsating in the Andromeda Nebula, as it was then called. Such stars, called Cepheid variables, had been studied in the Milky Way, and their pulsation rate was known to depend upon their brightness. Hubble figured out from the apparent brightness of those within Andromeda that they were very, very distant; they were so faint that, if Andromeda contained them, it must be a galaxy just like our own. Until then, it hadn't been clear what these nebulae were. Were they clouds of gas in the Milky Way? Was the Milky Way the entire universe? Hubble's discovery made the universe much, much larger than people had supposed.

This was a big discovery all right, but it pales beside his next one. Several astronomers, espe-

Below: Edwin Hubble at the Mount Wilson Observatory's 100-inch telescope. Right: As the universe expands, the galaxies within it move away from us. The universe is expanding everywhere at once, so more distant galaxies appear to be moving away faster than nearby ones because there's more of the expanding universe between us and the farther galaxies. Thus measuring the apparent velocity of a galaxy gives its relative distance. (These distances must be calibrated against things whose distances we know, but that's another story.)

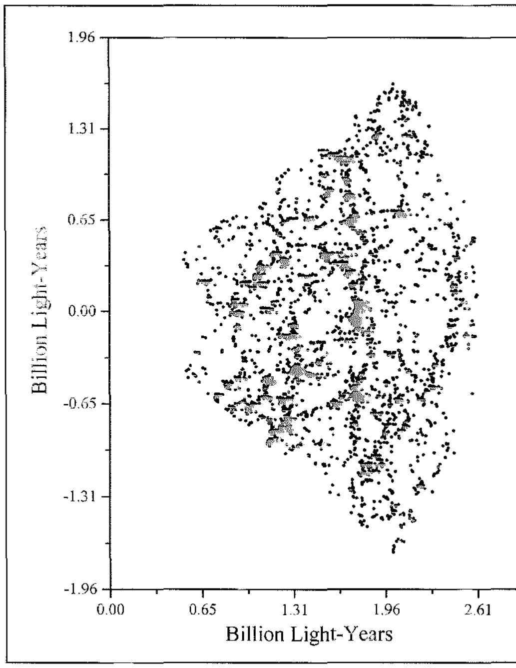




cially Vesto Melvin Slipher, had found that those nebulae were moving away from us at different speeds. Hubble and his colleague Milton Humason, using the 100-inch telescope at the Mount Wilson Observatory, discovered that the farther away a galaxy seemed to be, the faster it was receding. Hubble's interpretation of that observational fact was that the universe as a whole was expanding and carrying the galaxies with it, as shown in the diagram above. If you look at two galaxies, and then look again later, each galaxy's apparent velocity will be its change in distance divided by the time between looks. Galaxy number two—the more distant one—will have moved farther away, relatively speaking, than galaxy one, and so will appear to be moving away faster. You can simulate the expanding universe with the surface of a balloon. As the balloon inflates, every point on its surface gets farther away from every other point, and the farther away they are, the faster they move apart. You can continue this until infinity, or, in the case of the simulation, until the so-called "little bang" comes into play.

One can hardly make a bigger discovery. Some years earlier, Albert Einstein had developed his general theory of relativity, and he had had to introduce a fudge factor in it—the so-called cosmological constant—in order to prevent the universe from expanding. (At that time, everyone assumed it was static.) When Einstein visited Pasadena in the 1930s, Hubble took him to Mount Wilson and showed him the fleeing galaxies. Einstein was very impressed. He later said that the cosmological constant was the big-

Right: This fan-shaped slice of the universe—80 degrees wide by 1.5 degrees thick—contains 3,754 galaxies, and is part of a mapping project by Stephen Shectman and Stephen Landy at the Carnegie Observatories. (We're where the fan's hinge would be.) The entire map to date contains six slices and some 26,000 galaxies. This plot assumes that the Hubble constant (a measure of how fast the universe is expanding) is 50, making the farthest galaxies in the survey 2.6 billion light-years away.



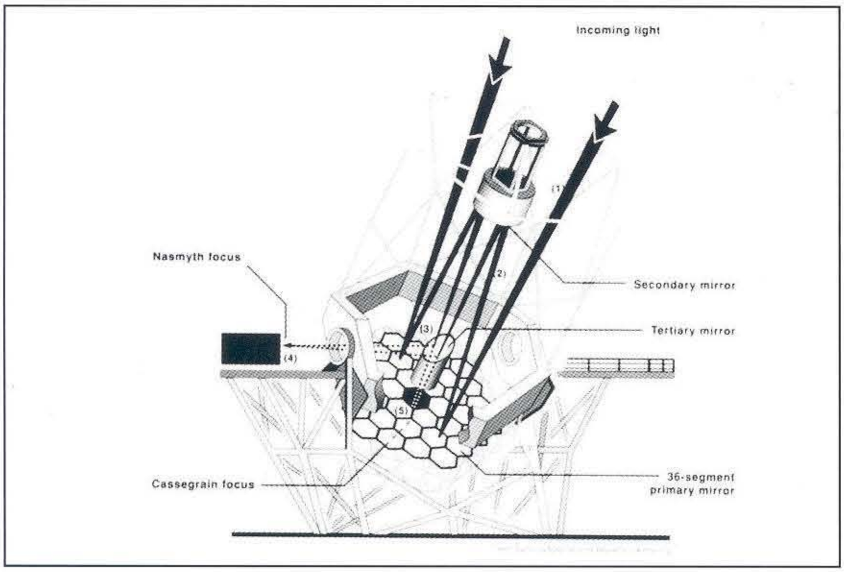
Astronomers measure the relative intensity of light with a perverse system called magnitude, and the reason we do this is twofold: one is to keep physicists out of the field, and the other is to torture astronomy students with homework problems.

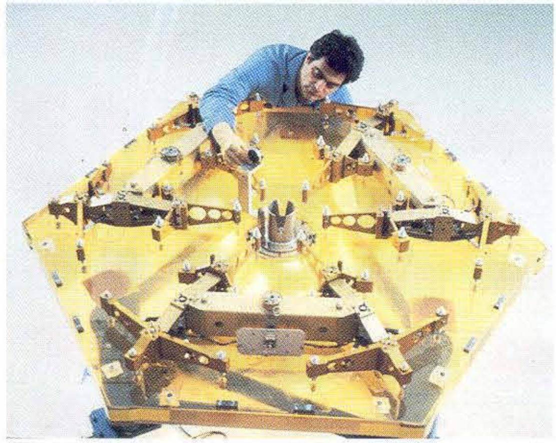
gest blunder of his life. Einstein was a pretty good theoretical physicist, but he failed to make the greatest prediction of his career—that the universe is expanding.

The discovery that the distance to a galaxy is proportional to its apparent velocity is now known as Hubble's law, and it is fundamental to cosmology. We need to measure the distances to galaxies in order to figure out many of their important quantities, such as luminosity, age, diameter, and mass. But distances are very hard to measure. On the other hand, velocities are relatively easy to measure from the so-called Doppler shift, or redshift. As a source of light moves away from us, the light actually stretches, and its wavelength gets longer. Thus its color shifts toward the red—which has longer wavelengths—and, the faster the source is moving, the larger the shift. Starlight can be broken down into patterns of spectroscopic lines—specific wavelengths that are absorbed or emitted by various chemical elements. People have measured these emission and absorption lines in labs here on earth, so we know exactly at what wavelengths the lines occur. Thus, when the light from a distant galaxy displays a known spectral pattern but at a set of wavelengths different from what we have observed in the lab, we can measure how much the light has been shifted. This gives us a proxy for how far away the source is, so that, by measuring the velocities of galaxies one by one, we can start to map the universe. Amazing structures are revealed—filaments composed of many thousands of galaxies enclosing voids a couple of hundred million light-years across. About 100 billion galaxies are estimated to exist in the universe, and that's just a lower limit extrapolated from what we can see.

There is another thing I have to introduce, and that's the so-called magnitude scale. Astronomers measure the relative intensity of light with a perverse system called magnitude, and the reason we do this is twofold: one is to keep physicists out of the field, and the other is to torture astronomy students with homework problems. The magnitude scale was introduced by ancient Greeks, who said that the brightest stars are first magnitude, and the faintest ones you can see with the naked eye are sixth magnitude. The system was quantified in the 19th century, and now each magnitude is the fifth root of 100—about two and a half times—dimmer than the preceding one. The faintest objects we can detect with Palomar's 200-inch telescope are about 25th magnitude. (That's equivalent to a 25-watt light bulb—the kind you find in your oven—seen from a million kilometers away.) The Keck Telescope can see objects 20 to 50 times fainter. You need to collect lots of light in order to detect things so very faint, and that's why we need big telescopes. George Ellery Hale, the founding father of Mount Wilson, Palomar, and Caltech always wanted more and more light. Hale would be proud of the Keck Telescope.

The Keck is a revolutionary design. Instead of making one huge mirror, which is no end of pain, Jerry Nelson (BS '65), now a professor at UC Santa Cruz, decided to make 36 smaller pieces of mirror—a much easier job—then cut them into hexagons and combine them to make the surface





Above: The Keck Telescope. Incoming starlight (1) bounces off the primary mirror toward the secondary mirror (2), and thence to the tertiary mirror (3). The light can then go to large instruments on the Nasmyth deck (4), or to smaller instruments behind the primary mirror at the Cassegrain focus (5).

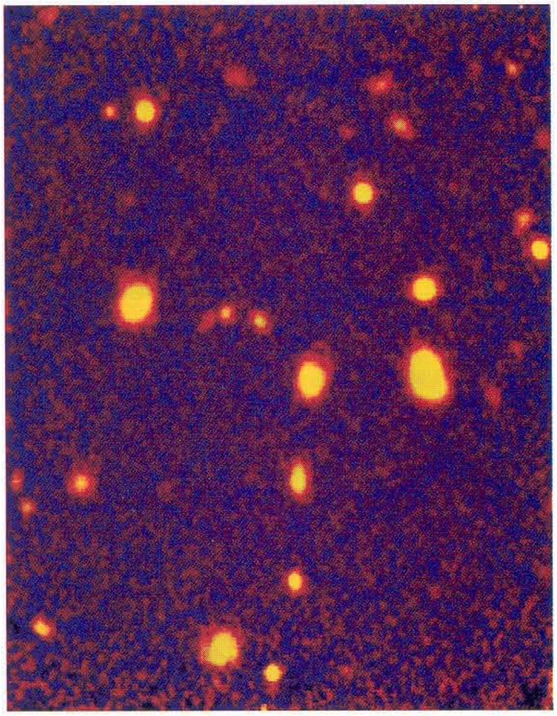
Right: An individual mirror segment before becoming a mirror. Note the complex support structure, which helps it maintain its shape in the telescope.

of a single mirror. Each segment is six feet in diagonal diameter, so a taller person could just sprawl across one. (We do not allow that to happen.) Each segment is precisely polished and bent into exactly the right shape, and sensors at the edges of the segments maintain their relative positions regardless of how the telescope tilts. The mirror is so smooth that if it were the diameter of the earth, its nonuniformities would be less than three feet in height, and the segments would be aligned to within two or three inches. (For a full description of the making and the workings of the Keck Telescope, see *E&S*, Winter '92.)

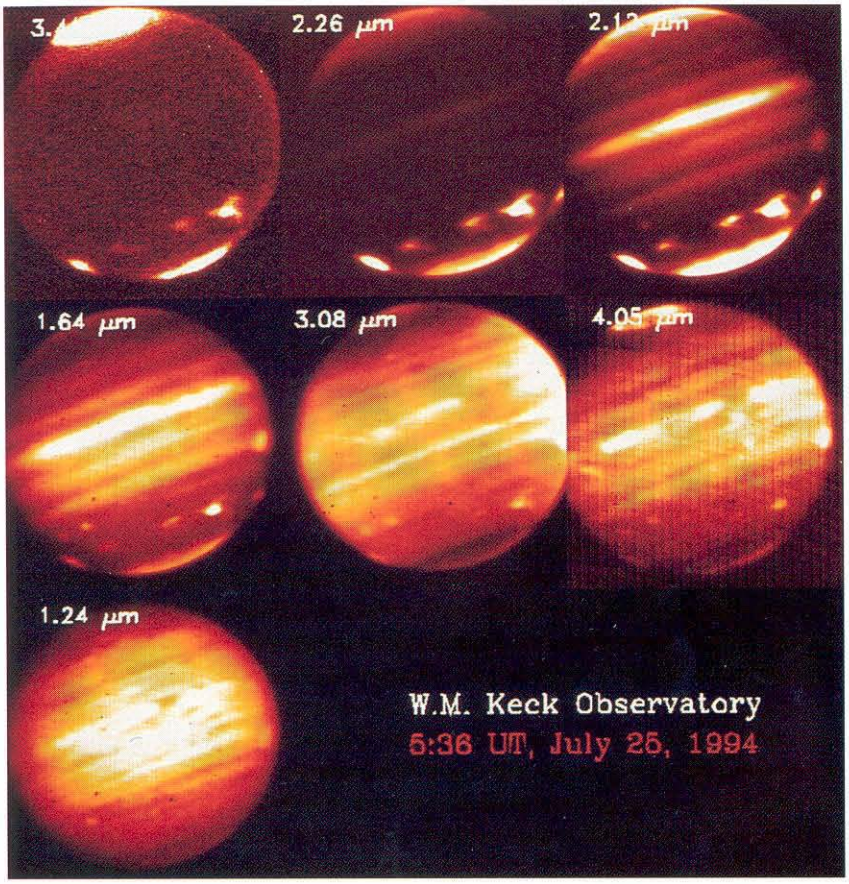
With a big telescope, everything else gets big, too. The light beams are wide due to the mirror's diameter, so the instruments are large. One, called the HIRES (for high-resolution) spectrograph, is the size of a two-car garage. It's so big that we can't hang it from the back of the telescope, like you would a camera. It has to sit on a special platform, called the Nasmyth deck, that we shunt the light to. And big things cost big money. Even observing time is expensive. The cost of building and operating the telescope prorated over its lifetime comes out to roughly a dollar per second every night, whether it's cloudy or not. I once suggested that we install a little meter in the control room, rigged so that if something went wrong the meter would start running, and we could see how much money we're wasting. That's probably not such a good idea, but in any case it's very expensive science.

So what are we doing with the biggest telescope on earth? As you know, the fragmented comet Shoemaker-Levy 9 struck Jupiter as a spectacular firework in July 1994. (See *E&S*, Fall '93.) A collaboration led by Imke de Pater and James Graham, both of UC Berkeley, was standing by with Caltech's Near-Infrared Camera. And wouldn't you know it—it was cloudy and, as the predicted moment of the first impact approached, all present were tearing their hair out. But at the very last instant, the clouds parted, and wonderful data came in. On the opposite page is a picture of the glowing impact sites. The kinetic energy from just one of the larger fragments was equivalent to thousands of global thermonuclear wars in a single go. If one were to hit planet earth, it could ruin your whole day. From this event, astronomers have learned a great deal about the chemistry of Jupiter's atmosphere and the physics of large impacts. Since it's perfectly possible that something big will hit us at some point, this is obviously an important thing to study.

Now let's leap all the way out to the edge of the universe and try to see the faintest objects we can possibly see. That may sound trite, but it's actually very good science. We turn the telescope on some relatively blank patches of sky and look for a long time to collect as much light as we possibly can, and then we classify and count the objects we see. Such surveys have been done with other telescopes at visible wavelengths, but the infrared isn't so well explored. Besides, the bulk of emitted energy from the most distant galaxies has been redshifted to the infrared by the time it gets to us, and the Keck is the world's best telescope for infrared astronomy, so it was an obvious thing to do. We've looked in several



Right: Long, long ago in an infrared galaxy far, far away...



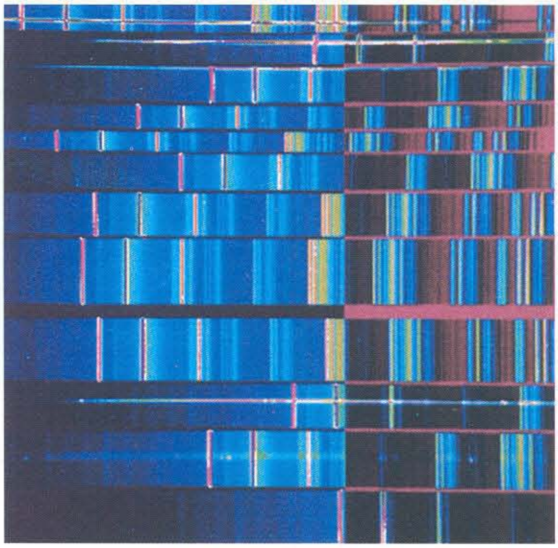
Below: Seven pictures of a battered Jupiter, taken at different wavelengths of infrared light. The five glowing spots in a line in the southern hemisphere are the heat plumes generated by the impacts of (from left) comet fragments H, Q1, R, D and G (which hit one Jupiter day apart in the same spot), and L.

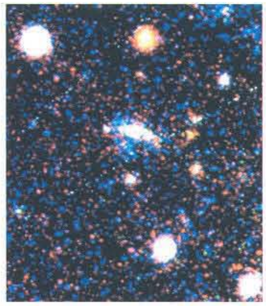
widely separated directions, to try to choose random, representative samples of the universe. One such sample is the photo at left, which is probably the deepest infrared image of the sky ever obtained. It's a very tiny portion of sky—less than an arc minute in angular diameter. There may be a couple of stars in it, but most of the objects you see are very distant galaxies. We don't know how far away they are yet, but we're certainly going to try to find out.

This survey is the work of a number of Caltech people: Roger Blandford, the Tolman Professor of Theoretical Astrophysics; Professor of Astronomy Judith Cohen (MS '69, PhD '71); Gerry Neugebauer (PhD '60), the Hughes Professor and professor of physics; Professor of Physics Tom Soifer (BS '68); me; Member of the Professional Staff Keith Matthews (BS '62); and grad students David Hogg, James Larkin, and Mike Pahre. (These folks also provided most of the pictures I'll show you.) It has probed the very faintest limits ever reached. Its dimmest infrared observations, translated into visible light, would be about 28th or 29th magnitude—much fainter than that 25-watt light bulb a million kilometers away.

By counting galaxies according to their color and apparent brightness in these deep, deep reaches of the universe, we can actually test models of cosmology. Such counts can help answer two important questions: First, will the universe expand forever, or will it ultimately recollapse? A universe dense enough to recollapse will expand more slowly, due to its greater gravity; thus, it will occupy a smaller volume, and contain fewer galaxies to be counted. Second, how do galaxies evolve? Looking billions of light-years away is equivalent to looking billions of years back into the past—we see the galaxies as they were when they emitted that light billions of years ago. Galaxies were generally brighter in the past, because they were then in an intense period of star formation and so were full of hot, young stars; the more star formation was going on, the brighter they were. Brighter objects can be seen at larger distances, so we can see more of them. Thus, the earlier galaxies evolved in the history of the universe, the more of them we should see at great distances. On the other hand, galaxies can collide and merge, so their numbers can decrease over intermediate timescales.

Detailed modeling of the galaxy counts we observe can be used to disentangle these effects. As we look in a given wavelength at ever more distant galaxies, we see light that was originally emitted from them at ever shorter wavelengths, due to the cosmological redshift. The effects of star formation are more prominent at the shorter





Above: This swatch of Madras plaid is actually a false-color LRIS multi-slit spectrum. Each horizontal band is a section of the spectrum from a different piece of the sky. The vertical stripes are the background spectrum from the night sky, and the thin horizontal streaks in the top three bands and in the second and third bands from the bottom are the spectra of faint, distant galaxies. The little beads on each streak are the galaxy's individual emission lines, which can be used to measure the galaxy's redshift.

Right: 4C41.17 is the distorted horizontal blob in the center of the photo.

(bluer) wavelengths, since luminous, massive young stars are blue. Thus, counting galaxies seen in visible light is a process very much influenced by their star-formation histories, perhaps confusingly so—it may be hard to distinguish star-forming dwarf galaxies that are relatively nearby from quiescent giants far away. An added complication is that the bluer wavelengths are more sensitive to absorption by interstellar dust.

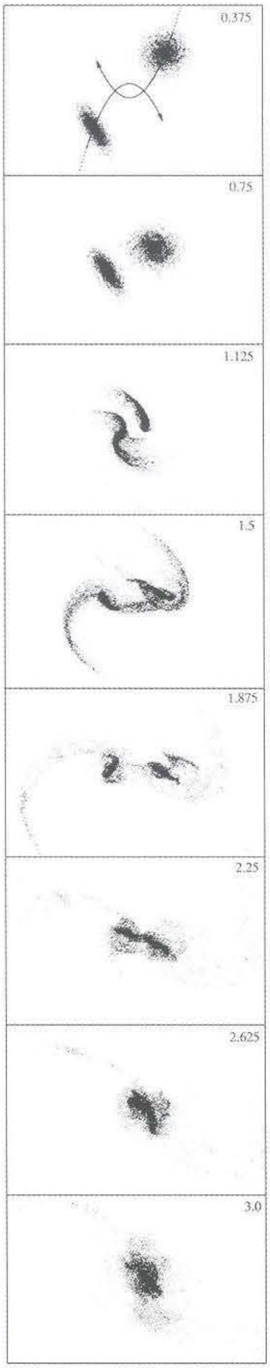
Counting galaxies in the near-infrared largely bypasses these problems, but the only way to really be sure of what you're seeing is to take spectra. The spectral fingerprints of various classes of galaxies are quite distinctive, and, of course, their redshifts tell you their distances. However, you have to collect a lot more light to get a spectrum than you need to take a picture. And since the whole point of the survey is to look at as much of the sky as quickly as possible, we're using the Keck to take pictures, from which we select specific galaxies for follow-up spectral studies. We do the spectrographic work using the Low-Resolution Imaging Spectrograph (LRIS), an instrument that Cohen and Professor of Astronomy, Emeritus, J. Beverley Oke built at Caltech for the Keck.

It is, however, still useful to do deep galaxy surveys in visible light, as it complements the information that's obtained in the infrared. Such a survey is being done by Professor of Astronomy Shrinivas Kulkarni and Cohen, along with grad students Hogg and Lin Yan, and then-postdoc Ian Smail, now in England. The photo at the beginning of this article is a segment of one of their survey pictures, which they obtained by using the LRIS in its imaging mode. (With the LRIS, one gets either pictures or spectra, so, again, specific galaxies are selected from the images for later spectral analysis.) These are probably the deepest visible-light images ever obtained, and, again, virtually every one of the little blobs of light is a galaxy that's probably billions of light-years away.

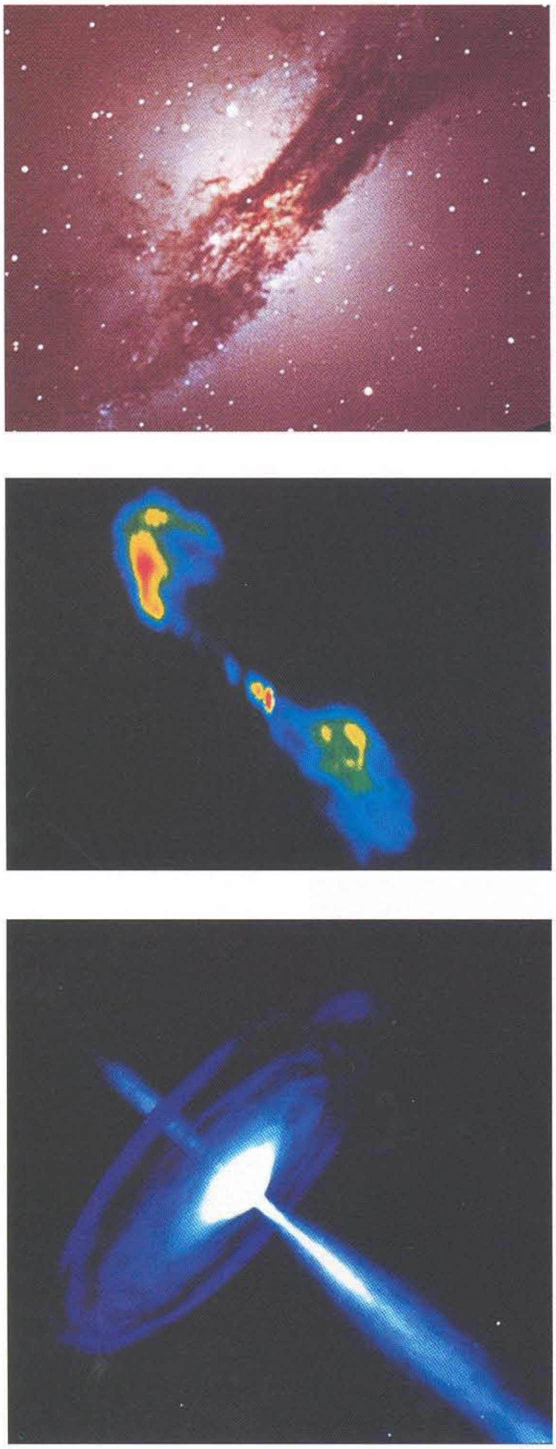
Just counting galaxies is interesting, but we really want to know how far away they are. We've now started a project to measure their redshifts, using the LRIS in a multislit mode where, instead of measuring distances to galaxies one by one, we put a mask in the instrument that selects 20 or 30 faint galaxies at once. A team of astronomers at UC Santa Cruz plans to build an instrument dedicated to this purpose that will take roughly 100 spectra at once. As far as we can tell, the universe is pretty much homogeneous—that is, it's the same in all directions—up to very large scales. There is clustering of galaxies, even very faint galaxies, but the deeper into space you look, the weaker it gets. One reason for this is that large-scale structures need time to grow—it takes a while for galaxies to fall together—so the clustering signal gets fainter the further back you look. The origins of large-scale structure and clustering of galaxies are fascinating problems, and that's one of the things we're trying to address in this deep-sky survey.

We can also study individual galaxies that we know are far away. At left is an infrared image from the very first science run with the Keck, of a radio galaxy—a galaxy that's also a copious emitter of radio waves—called 4C41.17. At the time, it was the most distant galaxy known. It has a redshift of 3.80. Because an object's redshift is a proxy for its distance, and because light takes a very long time indeed to reach us from such far-off galaxies, this redshift is equivalent to a look-back time of 88 percent of the age of the universe. In other words, we're seeing 4C41.17 as it was when the universe was a mere 12 percent of its present age. We don't know how old the universe is—that's one of the biggest questions in cosmology today—but if we assume that the universe is about 15 billion years old, which is our best guess at the moment, then the light from this galaxy started toward us 12 billion years ago. This light was already about two-thirds of the way here when the solar system formed. It's therefore possible that we are seeing light emitted from what was then a very young galaxy still in the process of formation.

At this point, you might well ask how we know that the universe is still expanding, if our data are 12 billion years old? What's happening



Left: Two spiral galaxies approaching each other on parabolic trajectories (arrows) distort, form a bridge, and eventually merge. The number in each frame shows the time elapsed since the beginning of the simulation, in units of 250 million years.



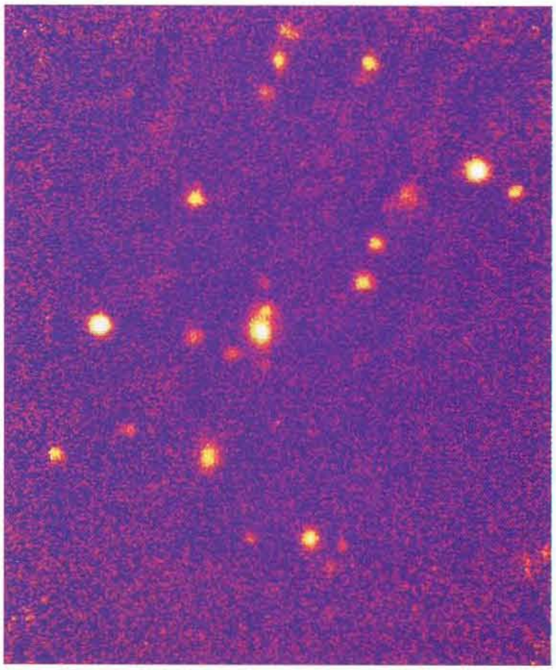
Left: Radio galaxy Centaurus A as seen in visible light (top) and at radio wavelengths (middle). The dark band across the center of the top photo is a thick cloud of dust that we assume is the byproduct of a galactic collision. The two views are at the same orientation, but not the same scale. If we were close enough for a better view, the galaxy and its plasma jets might look like the bottom picture.

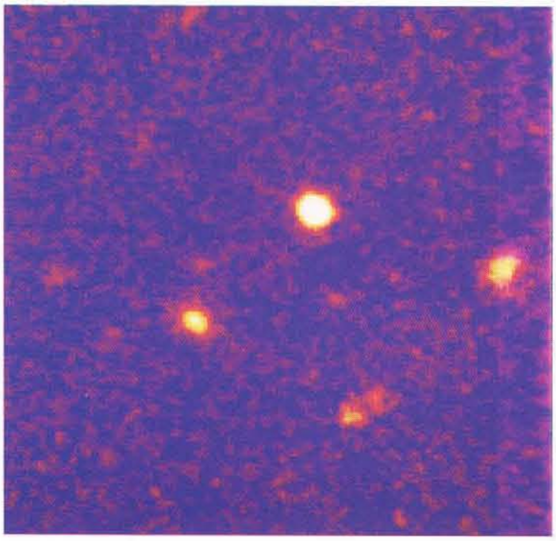
back there now? And the answer is, we have to wait another 12 billion years and look again to find out. It's a good Caltech thesis—or maybe a good tenure project, I don't know.

Since the universe is expanding in every direction, it may come as a surprise that galaxies like to collide. At far left is a numerical simulation of two galaxies that should pass by each other, but no—they distort each other tidally, bash together, collapse, and make a single object, while vast masses of gas sink right smack into the galactic core. Such collisions, and even near misses, may be what creates radio galaxies and quasars, which are also strong sources of radio waves.

Radio galaxies often appear misshapen in visible light, but they look even stranger at radio wavelengths. They tend to have a small, bright core right in the middle, flanked by two huge blobs of plasma—charged particles, like electrons—spurting out in opposite directions. Most of the galaxy's radiated energy comes from the plasma blobs. What we believe is going on, and those of you who bought Kip Thorne's book, *Black Holes & Time Warps*, may recognize the illustration, is that the radio galaxy has a massive black hole in its belly. Gas stirred up by the collision spirals in toward the black hole, forming a disk because it has too much angular momentum to fall straight in. The spiraling gas gets ionized and accelerated into fast jets of plasma that, perhaps guided by a magnetic field, shoot out perpendicular to the disk to become the radio lobes.

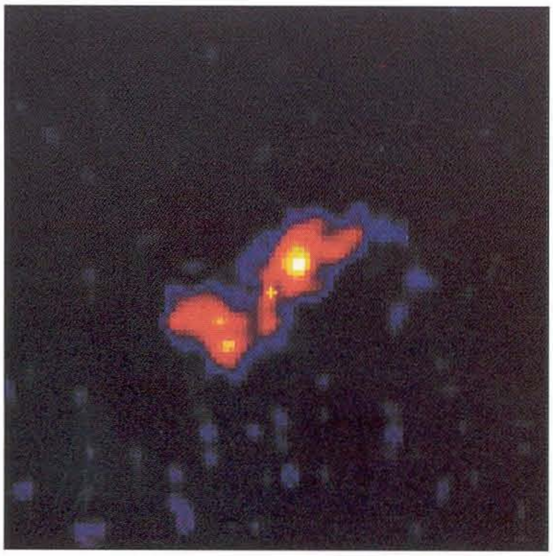
Quasars emit the radiant energy of a galaxy from an object roughly the size of the solar system. Their redshifts reveal them to be the most





B3 1253+432 (left) is unprepossessing to the eye, being the faint red object above the left-hand point of the diamond, but a plot of its spectrum (below) shows something more exotic. One axis of this plot is velocity, and the other is spatial distribution. If everything associated with the galaxy were receding from us at the same speed, all the data would plot to a straight line. Instead, we see two lobes of gas being ejected from the galactic core (white cross) in opposite directions. One lobe is coming toward us, the other is heading away from us. The colors indicate the signals' intensity, which provides information about the mass and excitation states of the gas.

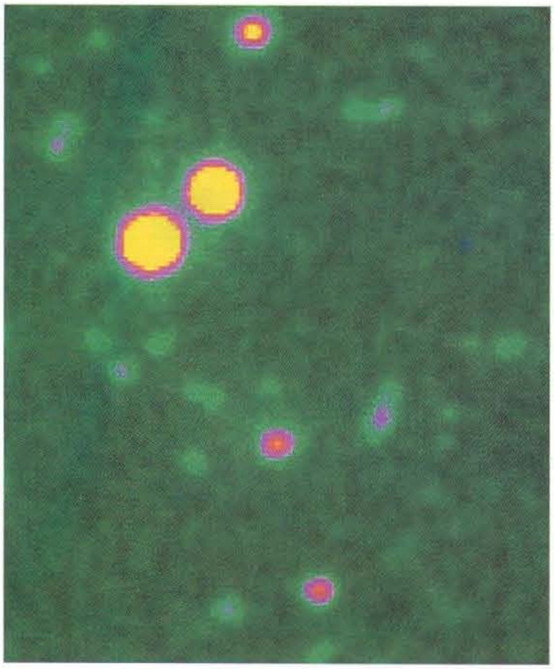
Right: The bright yellow spot at the center of this image is 3C324. The cluster of elliptical galaxies surrounding it include the two red spots just below it and the red spot just above it.

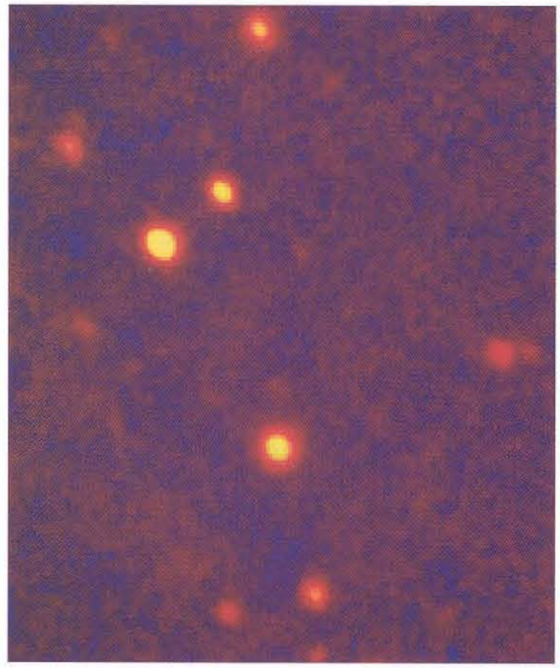


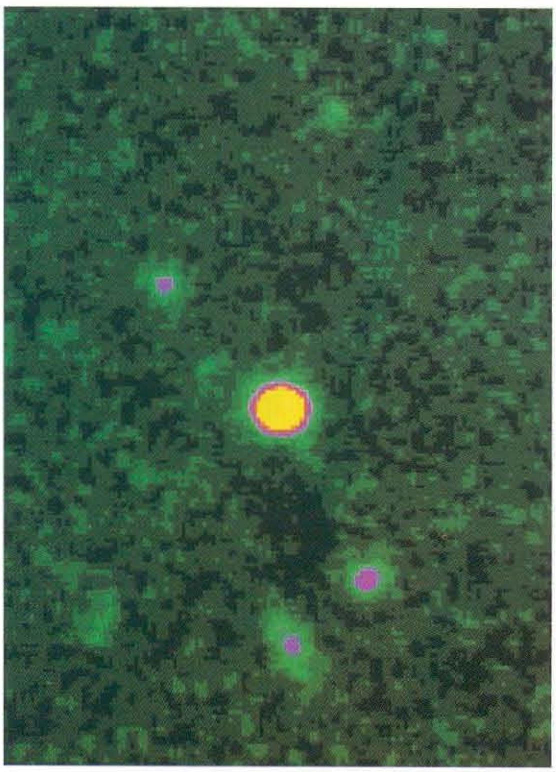
distant known objects in the universe, and they thus give us hints about galaxy formation in the very earliest days of the universe that we can see. Most people believe that there's a quasar hidden in every radio galaxy, and whether we see the quasar or not depends on our viewing angle. This is fine, because when the quasar is obscured, we can study the radio galaxy, which the quasar would otherwise outshine.

High-redshift radio galaxies may look peculiar, but at least we can see them—they're the most distant galaxies known. They give us some glimpse of what galaxies in the early universe might look like. This thing at left, known by the romantic name of B3 1253+432, has a redshift of 2.33, which means that the look-back time is 80 percent of the way to the Big Bang. B3 1253+432 doesn't look too impressive, but its spectrum showed something truly spectacular, as shown in the lower image. This galaxy seems to be ejecting vast masses of ionized hydrogen at speeds of a couple thousand kilometers per second, which is about as fast as we've ever seen. We don't understand such phenomena very well, but it shows you the power of the Keck, both in infrared imaging and in optical spectroscopy, to study such systems.

Above is another radio galaxy, also known from previous studies, called 3C324. It has a redshift of 1.21, which is a look-back time of about 65 percent of the way to the Big Bang. Mark Dickinson from the Space Telescope Science Institute, Hy Spinrad from Berkeley, and colleagues used the Keck to find that 3C324 is surrounded by what appears to be a cluster of







Above: The brightest two objects in the middle of this photo are a pair of quasars as seen in visible light.
Right: Some of the objects around the quasar pair weren't very bright in visible light, but stand out more prominently in this infrared image. These infrared-bright galaxies could be elliptical galaxies in a cluster associated with the quasar pair.

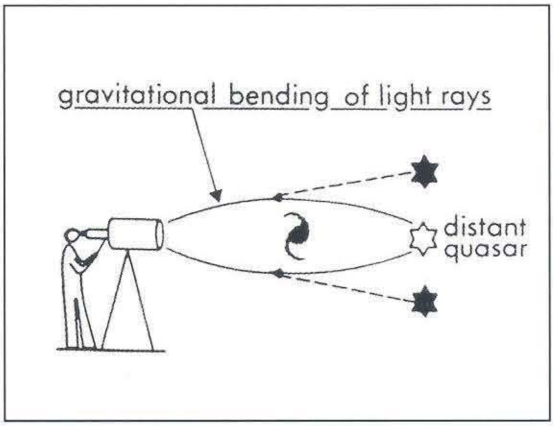
Left: Quasar Parkes 1614+051 is the large yellow blob in the center of this picture. The red dot above and to the left of the quasar is a previously discovered active galaxy. The green dot midway between the two, however, is a newfound companion galaxy. Analysis of its spectral data is still under way, but preliminary results hint that the companion galaxy is at the same distance as the quasar and the active galaxy, indicating that they may all belong to a compact group of galaxies.

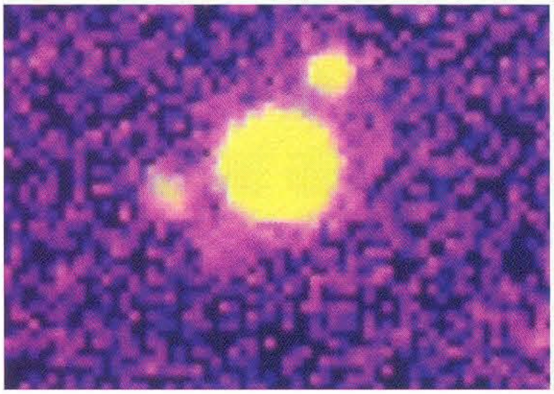
relatively normal elliptical galaxies. This is a major find, because it will probably prove to be one of the most distant clusters known. The researchers recently obtained spectra of it with the Keck, and have measured some of the distances, but the work hasn't been published yet.

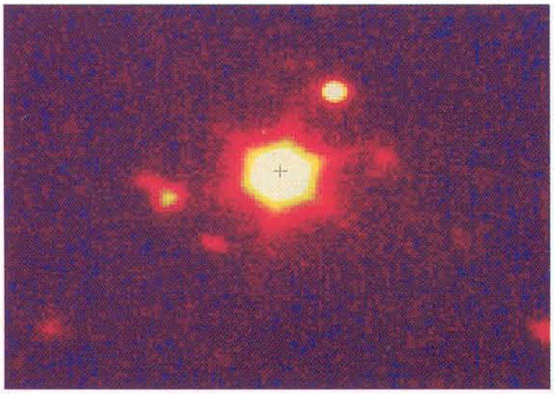
We're also studying several known pairs of quasars. We're doing this for two reasons. One is to better understand what makes quasars "quase"—in order to produce a quasar's stupendous amount of energy, a great deal of material would have to be dumped into that black hole. The other is that, since galaxies like to cluster, wherever we see a quasar pair, there may be other, relatively normal galaxies lurking nearby. The pictures above show two separate quasars at a redshift of 1.35—68 percent of the look-back time—and they also seem to be surrounded by a cluster of normal, reddish-colored galaxies. We would dearly like to measure the distances to the red galaxies, but we simply haven't had the chance to do so yet. This could be the most distant cluster known, if it pans out. Clusters of galaxies are good because they give you a whole selection of galaxies at the same distance, which you can compare to clusters nearby. This can tell you a lot about the way in which galaxies evolve.

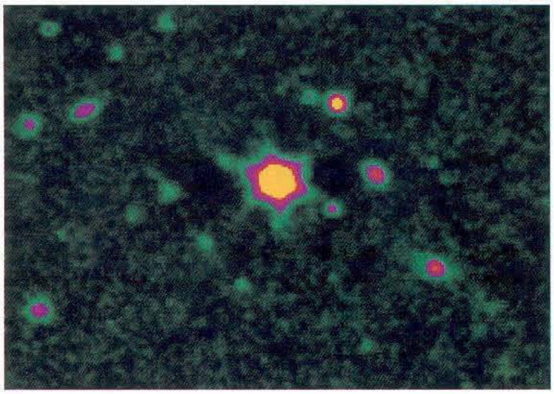
Another known quasar, called Parkes 1614+051, sits next to an active galaxy (an otherwise normal galaxy that has a brighter-than-normal core) at the same distance. They have a redshift of 3.21, or a look-back time of 86 percent of the way to the Big Bang. This might be a whole compact group of galaxies, perhaps still forming.

Below: Gravitational lensing can cause an observer to see two images of a single distant quasar. (You can see this was drawn especially for the Keck Telescope.)









Top: The thing that looks like a water molecule is a quasar pair named UM 425. One quasar is the oxygen atom; the other quasar is the right-hand hydrogen atom. This is the view from the European Southern Observatory's 3.6-meter telescope at optical wavelengths.

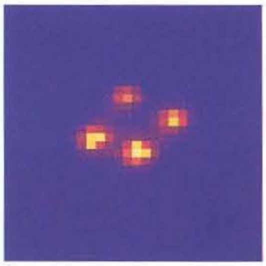
Middle: The 10-meter Keck's-eye view of the same quasar pair, also at optical wavelengths, unveils two fainter companions, one of which was sort of visible before (but only if you knew to look for it).

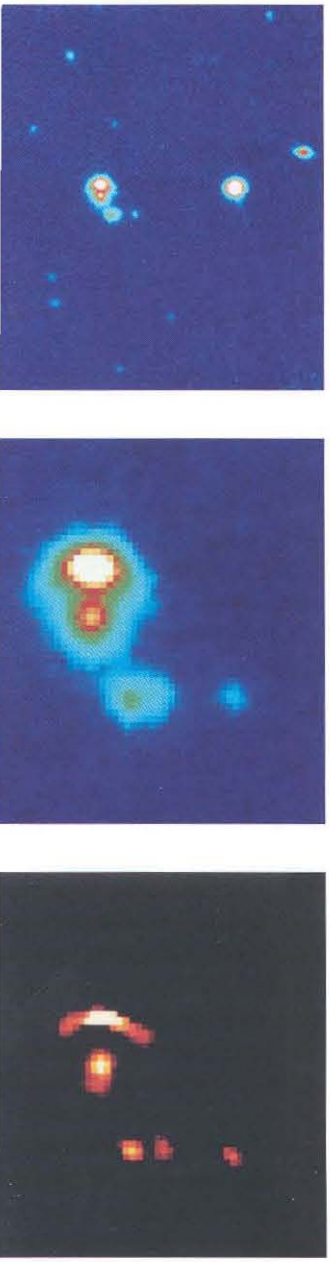
Bottom: In the Keck's infrared view, the pair on the left side becomes a threesome, the big quasar acquires two close attendants, and the little quasar gets a buddy of its own. Note that the brighter light sources morph into six-sided objects in the Keck images—an inheritance of the telescope's hexagonal mirror segments. Thus every star is a Star of David at the Keck.

Here's an example of just how much better you can study such systems with the Keck. The top left picture is of UM 425, a known quasar pair at a redshift of 1.46, taken with the European Southern Observatory's 3.6-meter telescope. Below it is the same pair as seen by the Keck. The Keck has revealed a lot of features that couldn't be seen before. We've taken these quasars' spectra, and they're noticeably different, so the quasars are probably interacting, perhaps in a compact group of galaxies. The real surprise came when we took an infrared image (bottom), revealing a whole set of new infrared galaxies that are probably at redshifts similar to that of the two quasars—70 percent of the look-back time to the Big Bang. The sharpness of these images is unprecedented.

Another strange astrophysical phenomenon we can look at is gravitational lensing. One of the consequences of Einstein's theory of general relativity is that a gravitational field will bend the paths of light rays; indeed, that's how the theory was originally tested. Now, suppose there's a distant quasar in the background, and there's a galaxy, or a cluster of galaxies, in the foreground. As shown in the diagram above, the light rays from the quasar will be bent by the foreground gravitational field, and instead of missing the earth, will fall into the telescope. The observer can extrapolate the diverging light rays backward, and should see two images instead of one. (Actually, it wouldn't have to be two images—depending on the geometry of the situation, it could be four images, or five, or segments of a ring, or even a complete ring.) The

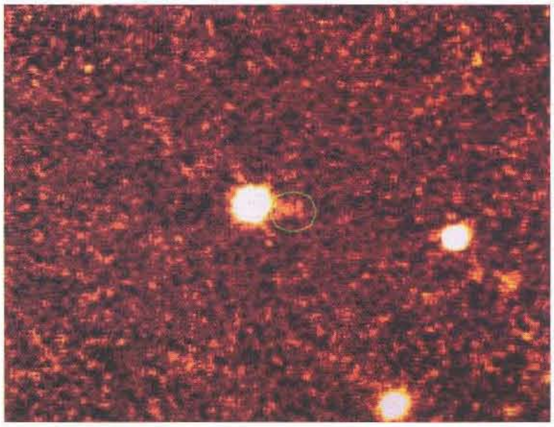
Below: The Cloverleaf lens, as see by the Keck.





Left: An early picture from the Keck's NIRC (top) resolved IRAS 10214+4724 into a multiple source, seen better in this zoom-in (center). A newer NIRC image (bottom) dissects the object into a point source and an arc—a telltale mark of a gravitational lens. The seeing in the two images has sharpened from 0.8 to 0.4 arc seconds due to improvements in mirror alignment.

Below: BRI 1202-0725, as seen by the NIRC. The green circle marks the faint foreground galaxy that's imprinting absorption lines on the quasar's spectrum.



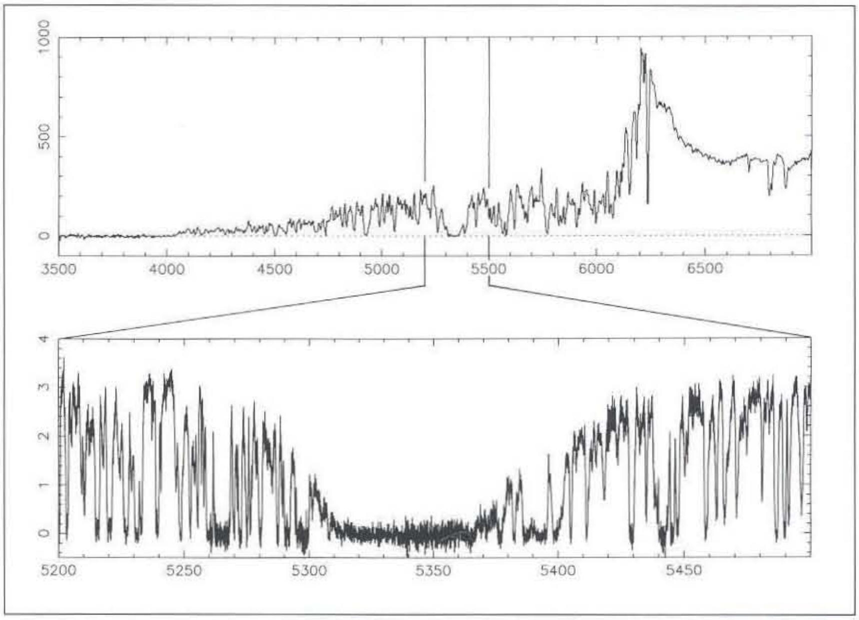
first extragalactic example of this phenomenon was discovered in 1979, but it was actually predicted in the 1930s by an eccentric genius at Caltech, Fritz Zwicky, who made many other fundamental discoveries and predictions.

The Keck turns out to be a wonderful machine to check on gravitational lenses. Having a large telescope that gathers lots of light is good, but there's another important factor, and that's image quality. Images are blurred by the earth's atmosphere, most of which lies at altitudes below the Keck; therefore, the telescope's image quality is superb. This image shows a previously known lens called the Cloverleaf, for obvious reasons. The Cloverleaf is about an arc second wide. Typical seeing at Palomar, which is about as good as you're going to get anywhere in the continental United States, is one or two arc seconds, so you'd just see a little square blob. The Keck can distinguish between objects that are 0.3 arc seconds apart, which is fantastic. To give you an idea, 0.3 arc seconds is roughly what a dime would look like from five miles away.

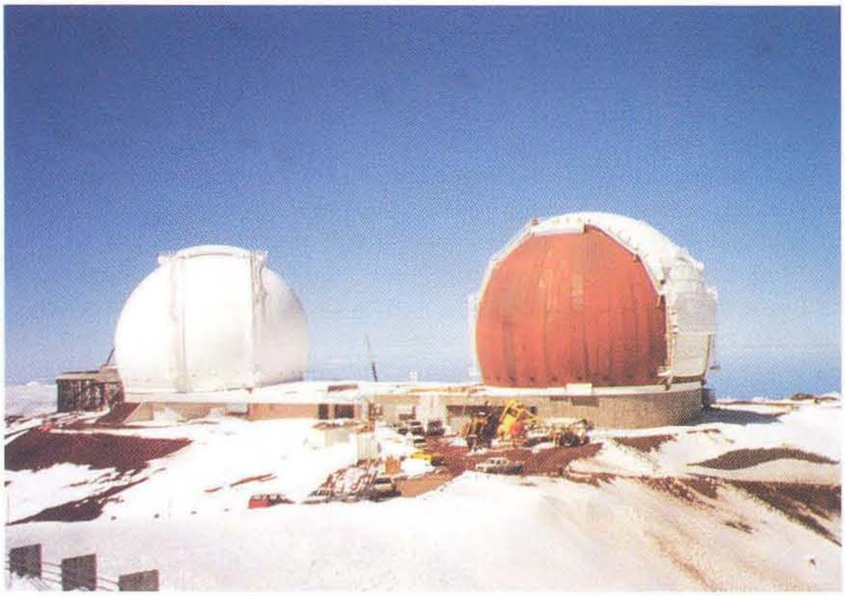
But the important thing about gravitational lenses is that they really *are* lenses. Because you can use a gravitational lens to help you see farther than you could otherwise, you can think of it as an attachment you put in front of the telescope. (And if you thought that a hundred million dollars was expensive for a telescope, think how much it would cost to buy a cluster of galaxies!) So using gravitational telescopes in combination with the power of the Keck can teach us about ever more distant galaxies.

This leads us to what was once believed to be the most luminous object in the universe. It's called IRAS 10214+4724, but nobody knew what it was, or why it appeared to be as bright as 50,000 Milky Way galaxies—500 trillion times more luminous than our sun. One of the first images from the Keck Near-Infrared Camera resolved it into a nice set of components, including something that kind of looked like an arc. When people saw this, they began to mumble, "gravitational lens, gravitational lens." Recently, James Graham and his collaborators obtained superb images, including the one at bottom left, with the Near-Infrared Camera, which indeed shows a point source and an arc. So this object, which launched dozens of papers proposing theories to explain how it could be so fantastically luminous, turns out to be yet another gravitational lens. Subsequent observations by the Hubble Space Telescope have confirmed the Keck result.

The infrared sky is a whole new sky—a lot of wonderful new stuff is showing up. A year or so ago, we looked at the second most distant quasar known, BRI 1202-0725, with the Near-Infrared Camera, and a faint infrared galaxy showed up nearby. Last winter Wallace Sargent, the Bowen Professor of Astronomy, and postdocs Limin Lu and Donna Womble obtained the quasar's spectrum and discovered that it shows absorption lines due to a foreground galaxy at a redshift of 4.4. The infrared galaxy could well be that absorber—it's faint enough to be that distant. A group at the European Southern Observatory recently obtained more data and essentially proposed the same thing. If confirmed, this infrared galaxy would then be the most distant galaxy



Right: The upper spectrum, of quasar Q 0000-263, was gathered at the five-meter Hale Telescope at Palomar in 50 minutes. (Data from Sargent, Steidel, and Boksenberg, 1989.) The lower one, of the same quasar, took the Keck HIRES only four times longer to collect but has a 45-fold increase in resolution.



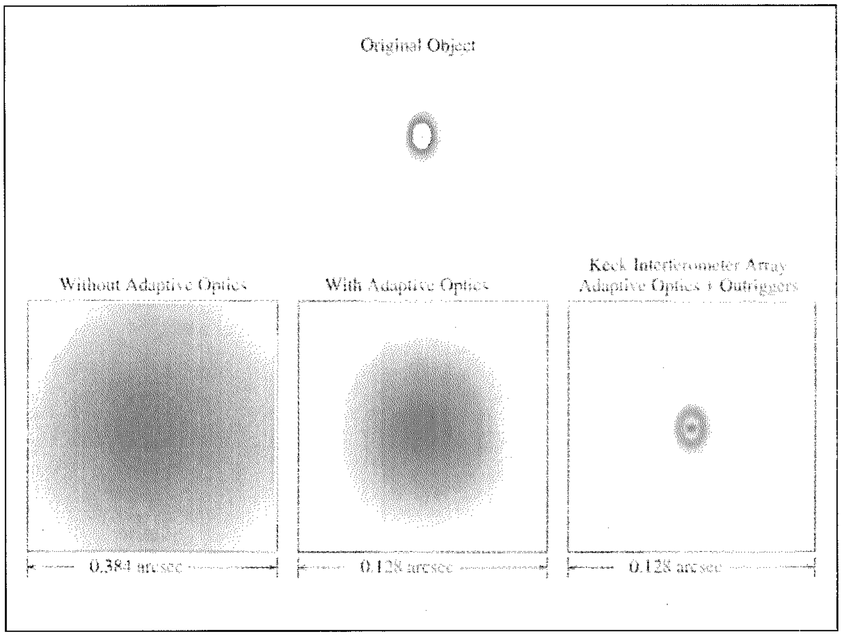
Below: Kecks I (white dome) and II (primer-red dome). I used to tell visitors that the infrared telescope lived in a special red dome, but it's since been painted white.

known, other than the quasars themselves.

There's a great deal of work being done on quasar absorption lines at the Keck. If you look toward a quasar, your line of sight might pass through a cloud of gas, which might be associated with a galaxy. Then, superimposed on the quasar's spectrum, you would see absorptions due to that gas. Multiply this by the many thousands of gas clouds that lie between you and a far distant quasar, and you have one humongously complex spectrum. The Keck Telescope coupled with the HIRES instrument is now the preeminent tool for studying intergalactic gas, because the Keck's great light-gathering power and the HIRES's superior spectrographic capability provide much more detailed spectra per unit of observing time.

What of the future? Eighty-five meters away from the Keck Telescope stands Keck II, which is almost finished. It should see first light this winter, and we hope to start doing science with it next autumn, or maybe even sooner. It was built under budget and ahead of schedule. The second Keck will be optimized for infrared astronomy, which means doing some extra little things, like coating the mirrors with silver rather than aluminum to make them more reflective to infrared light.

Of course, it's nice to have two telescopes instead of one, but the plan is to combine light from the two Kecks in an interferometer. The idea is to observe an object with both telescopes at once and combine the light into one signal with a precision of a few parts in a hundred billion or so—a small fraction of a wavelength.



What adaptive optics can do for you. In this simulation, the object being observed (top, center) is a protoplanetary disk—an embryonic solar system. The disk, which we're seeing face-on, surrounds a young, sunlike star 140 parsecs away from us. The star's light has swept away all the gas and dust out to the radius of Earth's orbit, allowing the star to shine forth from the cleared area while planets continue to form in the remaining part of the disk. The bottom left panel shows how this star might look to the Keck in its current state. The center panel shows how adaptive optics should sharpen the image, and the right panel shows what one might see with two Kecks and four small telescopes. (Such outrigger telescopes would provide additional information over baselines other than the one connecting the two Kecks.)

This doesn't mean you see any deeper, because you only get as much light as hits the two mirrors, but you achieve an ability to discriminate angular separations between objects that's equivalent to having an 85-meter-diameter telescope—the distance between the two mirrors. And seeing objects that are very close together can be used to confirm that planets exist around other stars and that our solar system is not unique, which is one of the major goals in astrophysics today. This is why the NASA planetary community has become a partner in the second Keck.

But there's something else we have to do before we can start doing interferometry. Light gets smeared and blurred as it passes through the earth's turbulent atmosphere, so we can't see quite as far or as sharply as we would if the atmosphere weren't in the way. Many people are working on a new technology, called adaptive optics, that allows us to probe the atmosphere by using a bright star next to the object we're studying. (If there isn't a star handy, some other observatories shine a laser beam skyward. Roughly 100 kilometers up, in the upper troposphere, the beam reflects from a sodium layer—detritus from meteors that burned up in the atmosphere—and generates a fake "star." Although still visible to the telescope after a 200-kilometer round trip, the outgoing beam can't be seen by anyone standing even a few hundred feet from the dome.) We know that the light from the bright star (or the laser) starts out with its rays perfectly parallel, so we can measure how the light was distorted by the atmosphere. This information is sent to a small adjustable mirror that moves to compensate for the distortion and take out the blur. In other words, adaptive-optics technology untwinkles the stars and makes them as sharp and steady as seen by the Hubble Space Telescope. We're just beginning to design an adaptive-optics system for Keck II, and we hope eventually to have one for Keck I as well. Then we will be able to combine the light in interferometer fashion to achieve the best possible resolution the telescopes are capable of. The farther apart you put your telescopes, the more difficult it gets to do interferometry. We don't really know how hard it will be to make it work over an 85-meter baseline. It's going to take a great deal of hard work, but there are no insurmountable technical obstacles.

The simulation at left shows what one might expect to see with one Keck and adaptive optics (left box), and with two Kecks and adaptive optics (center box). (If we were to then add four smaller telescopes, and observe for a few nights to gather more light, we might see something like what's shown in the right box.) Once the adaptive optics are working, the Keck will be competitive with the Space Telescope in sharpness of vision, at least at infrared wavelengths (which the Space Telescope does not observe), and probably at a very minor fraction of the cost of the Space Telescope. This is where the future lies, I think—in the adaptive-optics revolution, in removing the detrimental effects of the earth's atmosphere. It's much cheaper than putting telescopes on the moon, and who knows what wonderful discoveries still await us? □

Associate Professor of Astronomy S. George Djorgovski got his BA in astrophysics from the University of Belgrade in 1979, and his PhD in astronomy in 1985 from UC Berkeley. He then spent two years as a junior fellow at Harvard, and joined the Caltech faculty in 1987. His interests span many fields of astronomy, but in particular include questions about the structure, formation, and evolution of galaxies, quasars, and globular star clusters. He was an independent co-discoverer of what has come to be called the "fundamental plane," which describes the global properties of elliptical galaxies—that three measurable variables (radius, luminosity density, and the average kinetic energy of the galaxy's stars) satisfy a simple mathematical relationship. This insight has provided a benchmark against which theories of galaxy formation can be tested. (The question of where galaxies come from is one of the most exciting problems in astronomy today.) He was awarded a Presidential Young Investigator grant by the NSF in 1991, and was an Alfred P. Sloan Fellow from 1988 to 1991.