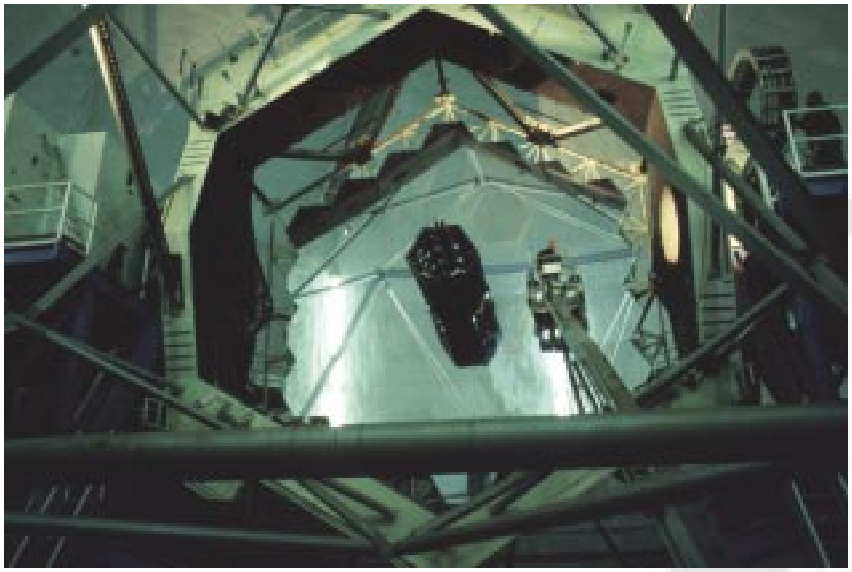
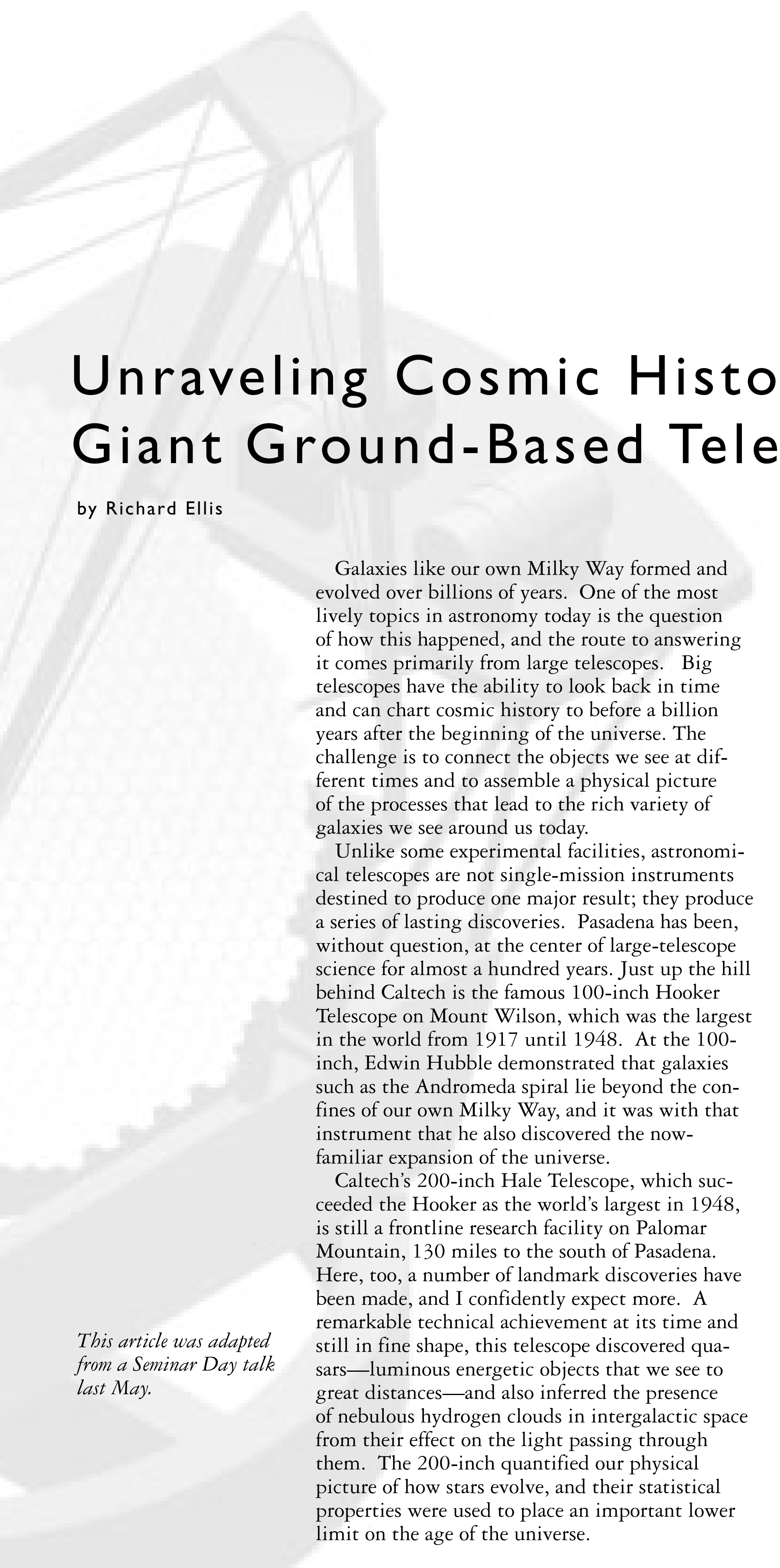


Since 1917, Caltech has been a partner in each of the world's largest telescopes (whose primary mirrors are shown here very roughly to scale): the 100-inch Hooker Telescope on Mount Wilson (top left), the 200-inch Hale Telescope on Palomar Mountain (top right), and one of the twin 10-meter Keck Telescopes on Mauna Kea, Hawaii (above). Joining this eminent group in the future may be the 30-meter CELT (California Extremely Large Telescope), now on the drawing boards.



Unraveling Cosmic History with Giant Ground-Based Telescopes

by Richard Ellis

This article was adapted from a Seminar Day talk last May.

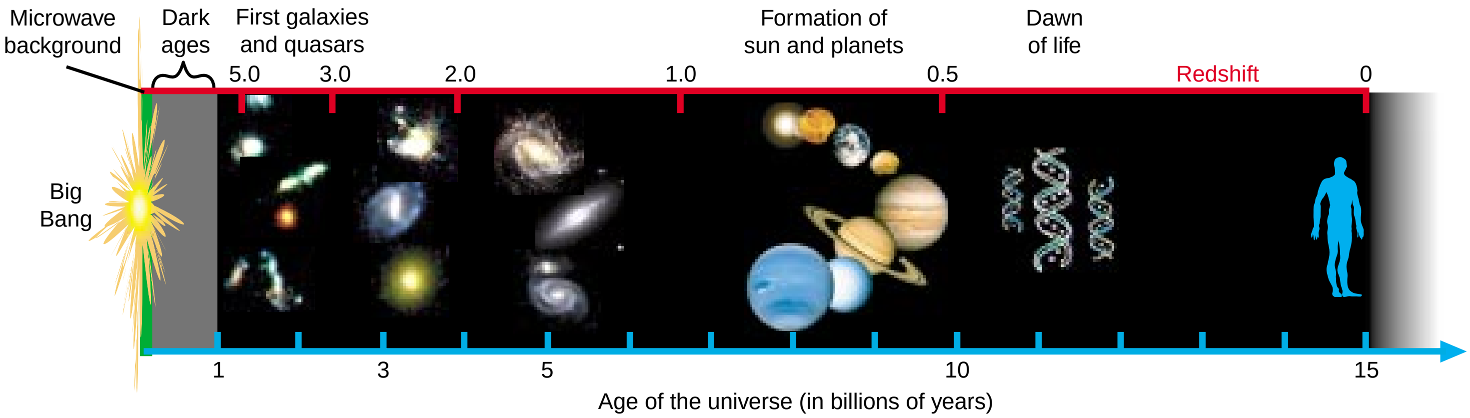
Galaxies like our own Milky Way formed and evolved over billions of years. One of the most lively topics in astronomy today is the question of how this happened, and the route to answering it comes primarily from large telescopes. Big telescopes have the ability to look back in time and can chart cosmic history to before a billion years after the beginning of the universe. The challenge is to connect the objects we see at different times and to assemble a physical picture of the processes that lead to the rich variety of galaxies we see around us today.

Unlike some experimental facilities, astronomical telescopes are not single-mission instruments destined to produce one major result; they produce a series of lasting discoveries. Pasadena has been, without question, at the center of large-telescope science for almost a hundred years. Just up the hill behind Caltech is the famous 100-inch Hooker Telescope on Mount Wilson, which was the largest in the world from 1917 until 1948. At the 100-inch, Edwin Hubble demonstrated that galaxies such as the Andromeda spiral lie beyond the confines of our own Milky Way, and it was with that instrument that he also discovered the now-familiar expansion of the universe.

Caltech's 200-inch Hale Telescope, which succeeded the Hooker as the world's largest in 1948, is still a frontline research facility on Palomar Mountain, 130 miles to the south of Pasadena. Here, too, a number of landmark discoveries have been made, and I confidently expect more. A remarkable technical achievement at its time and still in fine shape, this telescope discovered quasars—luminous energetic objects that we see to great distances—and also inferred the presence of nebulous hydrogen clouds in intergalactic space from their effect on the light passing through them. The 200-inch quantified our physical picture of how stars evolve, and their statistical properties were used to place an important lower limit on the age of the universe.

Now Caltech's largest telescopes are the twin 10-meter Keck Telescopes on the summit of Mauna Kea on the big island of Hawaii. The Kecks are used for a wide variety of research (including many projects unforeseen at the time their construction was proposed): locating the enigmatic gamma-ray bursts and proving these are at great distances; using supernovae to determine that the universe is probably not just expanding but accelerating (an exciting project with profound consequences that I'm involved in myself but won't have room to discuss here); and weighing the black hole at the center of the Milky Way. But I want to concentrate on the role of large telescopes in understanding how galaxies evolved to their present forms.

Ground-based telescopes suffer to differing extents from the fact that they are forced to view celestial objects through the earth's atmosphere. Even from Mauna Kea, where we are about half way to space in terms of the column of air above sea level, light rays are distorted by turbulent layers high in the atmosphere. Light pollution from San Diego and Los Angeles significantly affects many kinds of observations from Palomar and Mount Wilson, respectively. At infrared wavelengths, from even the darkest sites, the night sky and telescope structure generate a strong thermal background that plagues us. For these reasons, telescopes placed above the earth's atmosphere, such as the Hubble Space Telescope (HST), can produce stunning images at high resolution and, if kept cold and equipped with infrared sensors such as the upcoming Space Infrared Telescope Facility (SIRTF), can be particularly effective for certain studies. Because of the high cost of launching telescopes into space, however, HST and SIRTF are not large-aperture telescopes; both have primary mirrors smaller than the 200-inch constructed in 1948. The modest aperture of space telescopes does therefore restrict their applications. But large ground-based



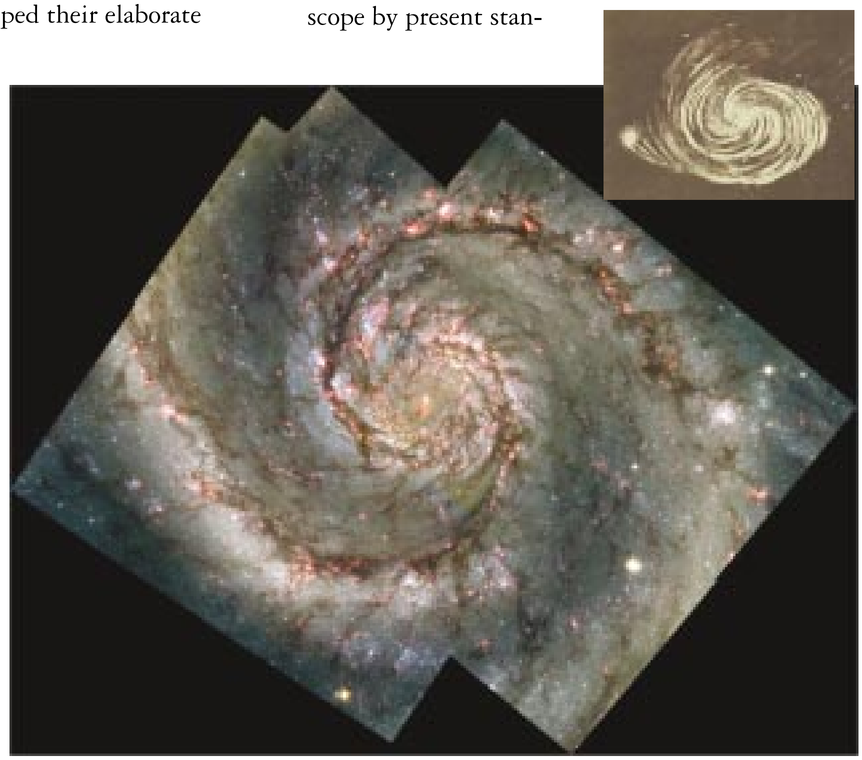
Above: The history of the universe. The Big Bang 15 billion years ago and the resulting microwave background are mere fractions of cosmic history at one end, with the age of man an insignificant segment at the other. The first galaxies began to form when the universe was about a billion years old, evolving over the next 10–12 billion years into the mix of spiral and elliptical galaxies we see today.

telescopes such as the twin Kecks are working together with the Hubble Space Telescope in a complementary partnership, as I shall explain.

We think the universe is about 15 billion years old. We can deduce this from the age of the oldest stars in our locality as well as from the rate at which the universe is expanding—extrapolating backward to that moment when the cosmic density would reach an infinite value. (Actually, it's something of a relief that these two estimates now agree; this wasn't always the case.) The drawing above shows roughly where we are today in cosmic history. From the Big Bang to the first directly observable era, when the microwave background was produced, was just a sliver of time compared to the long subsequent period during which galaxies formed and developed their elaborate structures. Similarly, life in the solar system began only 4 billion years ago, and modern civilization is only a minuscule chapter at the end of the cosmic tale.

My own research covers the very large time interval between the production of the microwave background and the modern day (so naturally I tend to think it's pretty important!). But astronomers don't generally deal in units of time; rather we prefer to think in terms of the *redshift,* denoted conventionally by the letter z. This is inferred by the displacement of a distant object's spectral lines toward longer wavelengths. Redshift is related to the distance (via the cosmic expansion which "stretches" light) and the "look-back" time to a source, but more fundamentally it indicates the scale of the universe at the time the light from that redshifted source left on its long journey to our telescope.

It takes some mental agility to deal with this concept, but, just as an archaeologist can slice below the streets of Rome or London and probe different eras, so astronomers can slice the observable universe into different time shells. The finite speed of light means that we're looking back in time as we look deep into space and, remarkably, even a modest telescope by present stan-



Right: The "grand design" spiral galaxy, Messier 51, was the first in which the spiral structure was observed visually (by Lord Rosse, who also sketched it, inset). The recent Hubble Space Telescope image (observed by Scoville and Polletta) of the central regions of Messier 51 shows the blue light that arises from the continued production of young stars in this class of galaxy.

Messier 87 is a giant elliptical galaxy in the constellation of Virgo. This color image demonstrates the remarkably homogeneous color of the constituent stars. Orange stars generally indicate an older population, and the uniformity suggests that such galaxies are devoid of young stars, having exhausted their hydrogen supply many billions of years ago. (Courtesy Anglo-Australian Observatory)

dards, such as the 100-inch Hooker Telescope, is capable of looking back to galaxies 5 billion years ago, corresponding to $z = 0.5$. The physical significance is that $1+z$ (i.e. 1.5) is the factor by which the universe was smaller in linear terms at the time such a source is being observed. Redshift is thus an important yardstick and has the distinct benefit, unlike distance, of being directly observable once a spectrum of a distant source is obtained.

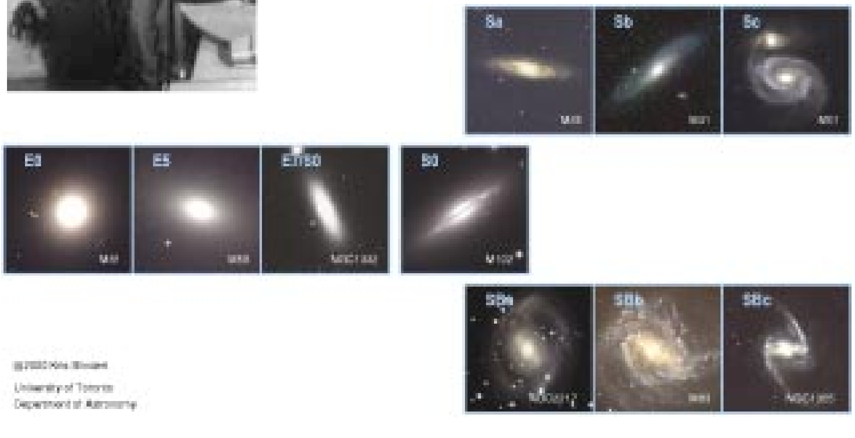
Seeing a particularly distant object is obviously exciting, since we are directly witnessing the past. This excitement has driven the construction of larger and larger telescopes over the past century, but to understand the significance of what we are seeing, it is first helpful to conduct an inventory of what's around us today. Anyone who has casually examined a picture book of galaxies will be aware that there is quite a variety of types. The stunning Hubble Space Telescope image on the opposite page, observed by Moseley Professor of Astronomy Nick Scoville and Maria Polletta at JPL, is the Whirlpool Galaxy, Messier 51—a famous spiral. Inset is a wide-field view of the same galaxy, as sketched by the third Earl of Rosse in the middle of the 19th century using his 72-inch Leviathan telescope, which was the world's largest at the time. If you think it's tough to observe galaxies nowadays in Los Angeles, I suggest you go to the peat bogs of Ireland, as my wife and I did a couple of years ago, to visit Lord Rosse's telescope, which rarely sees a clear night. That amazing telescope has, through great efforts, been recently refurbished. The telescope is unusual in being on a fixed azimuthal mount so an object of interest can be observed only for a short period, which oftentimes would coincide with cloud or rain. One has to admire Rosse's perseverance; he discovered spiral structure—by eye of course, without any recording medium. He was, by all accounts, somewhat eccentric. (Indeed, most astronomers are eccentric, Caltech having its fair share!)

Besides spirals, we also see elliptical galaxies, such as Messier 87, which are simply balls of stars. You'll notice that most of the stars in this galaxy (left) have a uniform orange-red color, and this is quite an important distinction between these systems and the spirals discussed above (which have many blue stars). The color of a star is a fairly reliable guide to its age—the redder stars are older. Uniformity of color is thus an indication that the galaxy had a simple history, with all its stars being the same age. Bluer stars such as those seen in the beautiful spiral arms of Messier 51 formed *after* the bulk of the galaxy assembled.

In 1926, Edwin Hubble classified the galaxies he photographed by their visual color. His famous diagram resembles a tuning fork. He ordered spirals in terms of the degree to which their arms are tightly wound. He further divided spirals into normal examples and those with nuclear "bars." Hubble's student, Allan Sandage, PhD '53, who is still working actively at the Carnegie Observatories, summed up Hubble's achievement when he said that this diagram, which was a purely visual classification system, describes a true order among the galaxies. In other words, it's a lasting classification that has a good physical basis. It is a tribute to Hubble's intuition that this classification system is still the one in use today.

In Hubble's tuning-fork diagram, two key physical facts should be noted. First: as we go

Edwin Hubble at Palomar.



Hubble's "tuning fork" classification system for normal galaxies is arranged here with photographs of typical examples. He classified galaxies according to the dominance of their central bulge, which is largest for ellipticals (E) and minimal for spirals of type Sc. Note also how the integrated color becomes redder as the bulge becomes more dominant. The intermediate lenticular galaxies (SO) appear as spirals with red colors similar to ellipticals. Hubble also separated spirals into barred (SB) and non-barred versions. (Courtesy Kris Blindert, U. of Toronto)

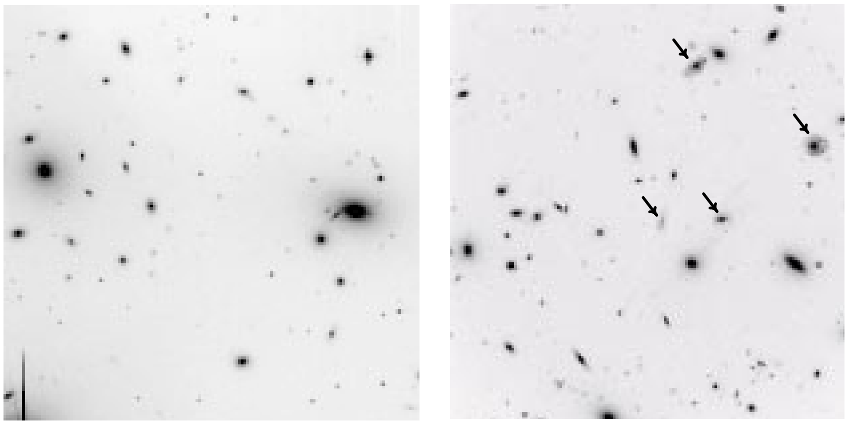
Ellipticals are particularly numerous in dense clusters. The left panel (courtesy Anglo-Australian Observatory) shows that such systems in the nearby Virgo cluster have remarkably similar colors, powerful evidence that they completed their star formation billions of years earlier. Similar analysis of the HST image (right) at a redshift of 0.54 (6 billion years ago) implies that earlier examples share similar properties, strengthening further the conclusion that these galaxies contain very old stars.

from spirals toward elliptical galaxies, the central region, which we call the *bulge* of the galaxy, becomes more prominent. When we reach the ellipticals, the bulge effectively becomes the whole galaxy. So one way to characterize the sequence physically is in terms of the fraction of the galaxy's total light contained in this bulge. This gives a structural explanation of Hubble's sequence.

Second: as we go along the sequence in the opposite direction, the galaxies become bluer in color. As we discussed, the ellipticals are uniformly orange-red, but by the end of the sequence on the right, the spiral galaxies are much bluer except in their bulge regions. Elliptical galaxies are thought by many to be very old, perhaps the first systems that formed, whereas the spiral galaxies appear to have continued to form stars, as is evidenced by their blue, younger stars. Note that spirals need not be actually younger than ellipticals; it could be that they are just as old but simply continued to form stars to more recent times. In this respect, Hubble's sequence is thus telling us about the *rate at which stars form to make a galaxy*. A simple explanation would be that ellipticals are those galaxies that formed their stars fairly quickly at some point in the past, whereas spirals continue to form stars over their entire lifetimes. Now as stars form from cold clouds of hydrogen gas, this distinction would be telling us about how quickly the reservoir of gas was exhausted—fairly quickly in the case of the ellipticals but very slowly for the spirals.

This speculation, from the "fossil record," about how the local population of galaxies came to be is all well and good, but the great advantage of looking at great depths into the universe is that we can trace the evolution of these objects directly—we can look for elliptical galaxies and spirals at earlier times. Because objects appear smaller when viewed at a great distance, it was not until the Hubble Space Telescope was launched that it was possible to accurately distinguish between, for example, spirals and ellipticals at significantly earlier cosmic epochs.

If we look at distant clusters of galaxies, where galaxies congregate together under a common gravitational field, even 6 billion years ago we find that elliptical galaxies are still present with approximately their present properties (above). Importantly, there's still a striking uniformity in their colors, both internally and when we compare one galaxy with another at the same redshift in a different cluster. Either these galaxies all had star-formation histories that were somehow synchronized across the population (which seems a bit far-fetched), or whatever differences occurred in their histories happened so long ago that by the time we are now viewing them, those differences are inconsequential. This result, which we



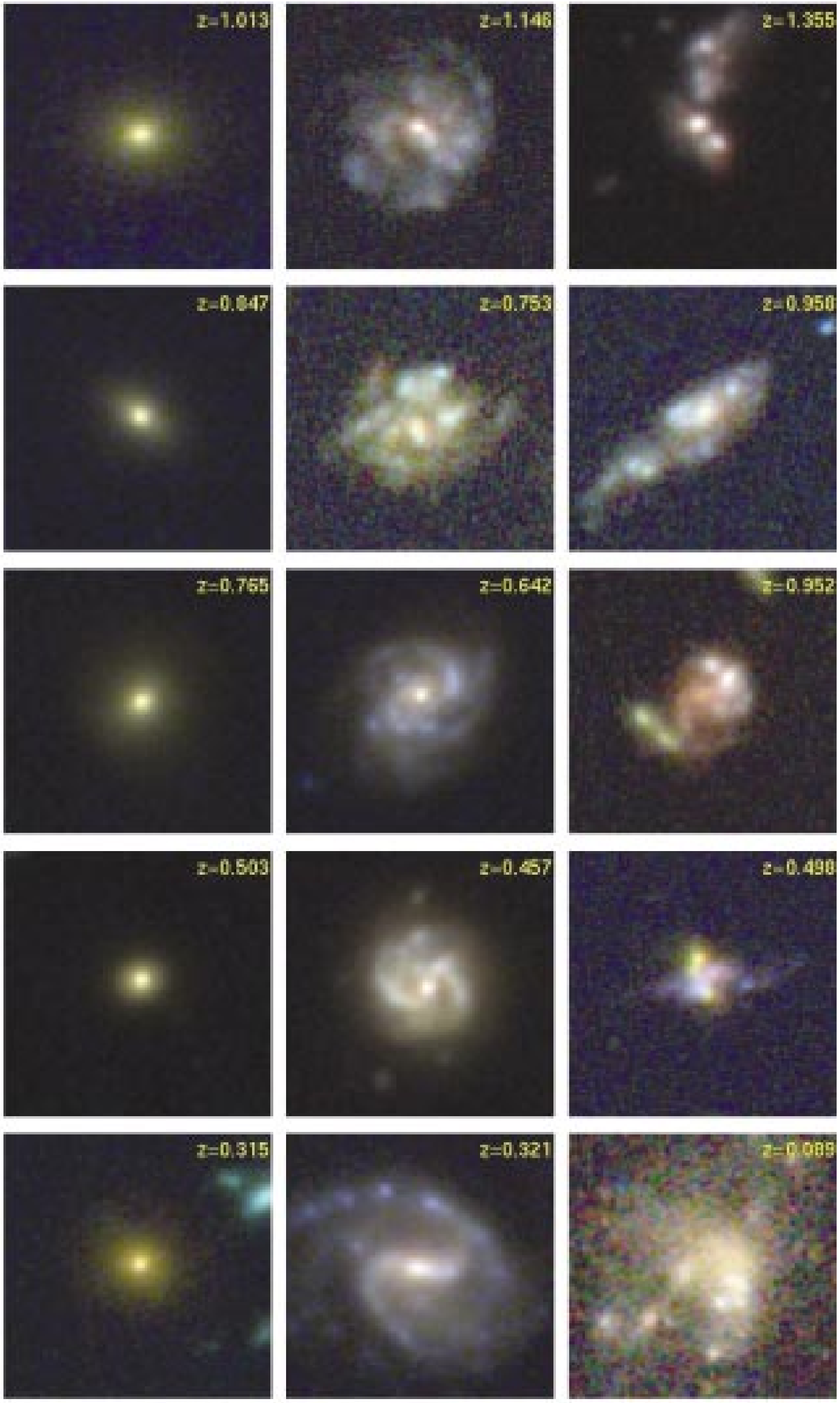
A comparison of galaxy populations in their dense cores shows mostly old ellipticals and lenticulars in the nearby cluster (left). But in the distant cluster (right), at a redshift of 0.4 or 4.5 billion years ago, the HST reveals, along with the ellipticals, a different population: spirals (see arrows). These spirals must have suffered some fate in the intervening time that transformed them into the later abundant lenticulars.

deduced fairly soon after the Hubble Space Telescope was launched, is consistent with the view that the stars that make up elliptical galaxies in clusters formed a very long time ago, perhaps 12 billion years, corresponding to a redshift greater than 3. So, for these galaxies at least, we are confident that their stars formed fairly soon after the Big Bang.

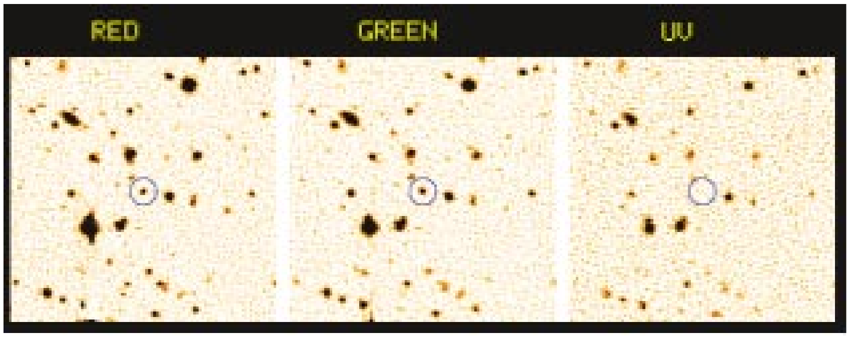
Unfortunately, as so often happens, as we learn more we find that things may not be so simple. Galaxies don't evolve in isolation. We have already seen that they cluster together, and, as we wind the clock back, the universe gets smaller, so galaxies get closer to one another. It seems reasonable to suppose one galaxy can be influenced by its neighbor. Take the nearby cluster (the left panel) at the bottom of the opposite page: the galaxies in the dense central regions look fairly uniform and featureless; many of them are indeed ellipticals. But if we look back to only 4.5 billion years ago (a redshift z=0.4) in the same kind of environment, we see spiral galaxies (right-hand panel).

Let me now introduce a classic problem of evolutionary deduction; we cannot be absolutely sure that a particular cluster seen 5 billion years ago evolves into a particular one we see today. The only way around this is to appeal to a statistical comparison of many such systems. When we do this, we get the revelation that some galaxies must be transforming from one class to the other. It seems there are environmental processes that change a spiral galaxy, removing its gas supply, curtailing the production of young stars so as to make them end up as a galaxy of a different Hubble type. Clearly, if galaxies can change from one class to the other, we are going to have to be cleverer in figuring out how to trace their evolution.

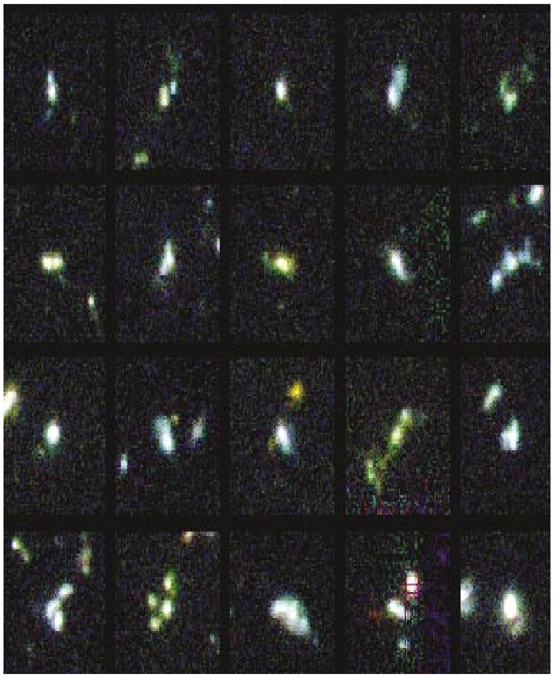
So, how far back can we see regular spirals and ellipticals? The Hubble Space Telescope can just about identify recognizable spirals and ellipticals at a redshift of 1, corresponding to about 8 billion years ago. Beyond that, more examples may exist,



The redshifts of these HST images of faint galaxies are drawn from a comprehensive survey undertaken by Ellis and his colleagues, using ground-based telescopes. Galaxies of various types have been studied to a redshift of 1, corresponding to about 8 billion years ago. Such systematic surveys of random patches of sky are essential to understanding how normal "field" galaxies (those outside dense clusters) evolve. The left-hand column shows ellipticals, spirals are in the center column, with irregulars on the right. A much higher fraction of irregulars is seen in the past, and Ellis's group is trying to understand what happened to them.



Left: The most distant galaxies can be picked out from the myriad of other systems in the foreground by using a technique based on the ultraviolet-absorbing effects of hydrogen gas. This absorption produces a characteristic drop in the light received from the most distant galaxies. In these images of the same field with different color filters, the central source disappears in the ultraviolet, indicating that it's sufficiently redshifted for hydrogen absorption to have occurred. (Courtesy Chuck Steidel)



Right: HST images for an array of distant galaxies found via the above technique. At these redshifts (z=2–3, corresponding to 10–12 billion years ago), few look like familiar spirals and ellipticals. Many have irregular forms and multiple components, and these are young systems in the process of assembling.

but we start losing resolution with the HST's current camera, and we also find it hard to measure accurate redshifts from which to deduce distances, except in restricted cases. My recent work has involved taking a census of galaxies of different types looking back 4 to 8 billion years. Using large ground-based telescopes, in partnership with the HST, I've been categorizing galaxies according to their morphologies. Lest I overemphasize the Hubble Space Telescope, let me point out that a crucial ingredient in this project is the galaxy redshift, available only from ground-based telescopes; this tells me how far back I'm looking. I have also measured their infrared brightnesses with the Keck, which determines how many stars are in each one. Infrared light is a better guide to the underlying stellar composition of a galaxy than blue light, which highlights only the transient young stars.

One of the most interesting results from this census of galaxies back to redshifts of 1 is the preponderance of faint galaxies that are neither ellipticals nor spirals; these are irregular in form and frequently seen to be blue and to be interacting with other systems. Although we can find local irregulars, they appear to have been much more common in the past. What led to their demise?

The infrared brightness provides us with an important accounting tool of how many stars there are in each category (spiral, elliptical, and irregular) at each epoch. By tracking the fraction of the total stellar mass in each type at each redshift we can determine whether galaxies are changing from one type to another. We find that the stellar mass in ellipticals and spirals is slowly growing as the universe expands, at the expense of a substantial decline in the stellar mass in irregulars. We deduce that there must be some process for "converting" irregulars into these more regular forms.

The most likely explanation for these transforms is that the merger of galaxies plays a key role in their evolution. We can find examples of galaxies interacting with one another today, and computer simulations suggest that if we throw two self-respecting spirals at each other, they produce, perhaps surprisingly, not a mess, but a galaxy that is further to the left in Hubble's tuning-fork diagram. Because the universe was denser in the past and galaxies were closer together, merging was surely more prevalent then.

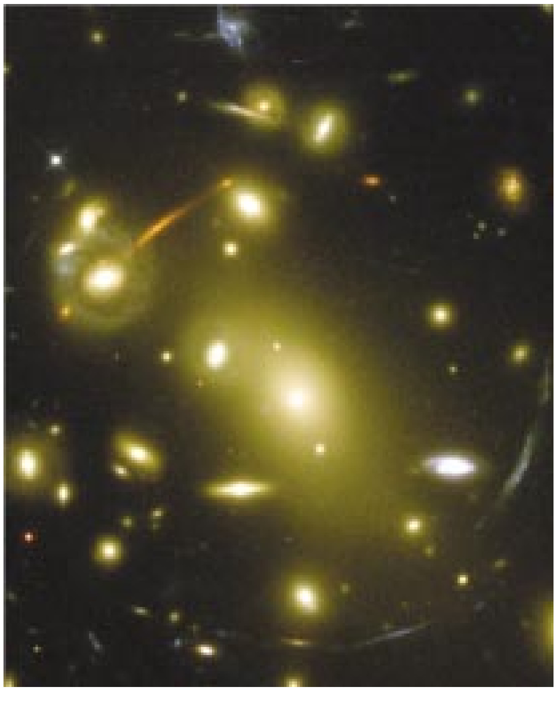
Let us now consider what galaxies look like even before 7 billion years ago. Professor of Astronomy Chuck Steidel and his colleagues have been locating and studying such early examples. One of the key techniques that Steidel has pioneered is based on the energy spectrum of a galaxy, utilizing the expected drop in ultraviolet light caused by the absorbing effects of hydrogen gas, both in the galaxy and along the line of sight to it. This absorption edge occurs in the far ultraviolet but, for a source beyond redshift 3, the wavelength at which it occurs is shifted into the optical, where it can be detected with sensitive cameras at Palomar. A galaxy at redshift 3 or more is visible in red and green filters but is extinguished in the ultraviolet

(UV) filter. This "drop" is the telltale sign that it is an extraordinarily distant object. The project is an excellent example of the partnership between Palomar and Keck. Palomar searches for these signatures with its panoramic cameras, and Keck, with its superior light grasp, verifies via the spectrum that this is indeed a very distant object.

What do the earliest galaxies look like? Interestingly, they don't look anything like Edwin Hubble's galaxy sequence. Many of them are lumpy with multiple components; they're physically very small, and the spectra tell us they are forming stars at a prodigious rate. So it seems that these may well be primeval galaxies, the ancestors of the bigger systems that we see at later times.

So, now we've used a succession of telescopes to explore the depths of the universe, and we have some kind of census at each epoch. We have Steidel's early star-forming galaxies at redshifts of 3 to 4; we have my inventory of all massive galaxies at redshifts up to 1; and we have the present-day Hubble sequence. How do we join these data together into a single coherent story?

Many astronomers believe the answer to this question lies in understanding the role of dark matter. It has been clear for more than 10 years that the universe contains a large amount of dark matter. We think it is present at the earliest stages in the expansion of the universe and that it acts as a seed for the infall of hydrogen gas, which leads to the formation of stars and subsequently galaxies. In the same way that a dust particle can accelerate the growth of a raindrop, so a dark-matter particle can act as the gravitational focus to lure hydrogen gas into that region. Without dark matter, it seems impossible to explain the structures we see around us today.



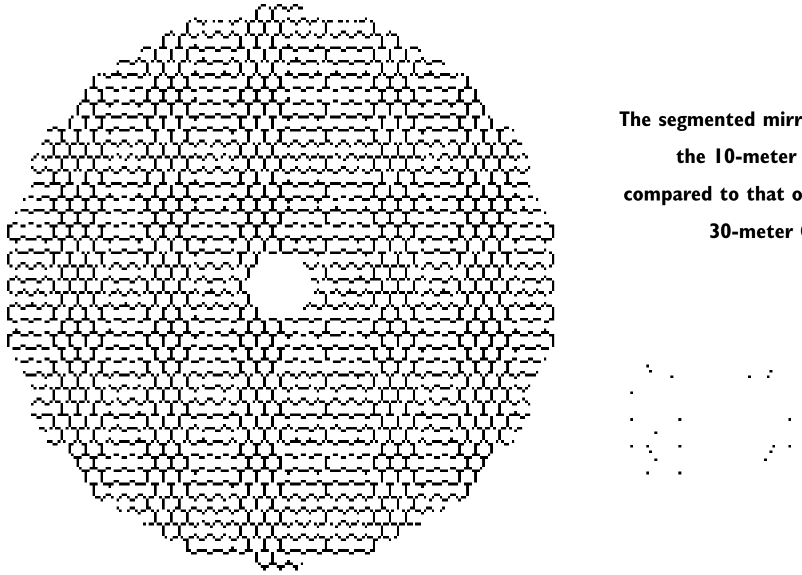
Einstein at work: Light signals from distant galaxies are distorted by foreground masses, as can be seen in this HST image of the rich cluster Abell 2218 (z=0.18). The orange/red objects are cluster ellipticals, but the blue and red distorted arcs represent faint background galaxies stretched and magnified by the gravity of Abell 2218—a phenomenon called gravitational lensing predicted by general relativity. The degree of distortion can be used to determine the mass of the cluster, which exceeds by 50 times the mass of the visible orange galaxies. This is a simple but powerful proof that dark matter exists.

Without dark matter, it seems impossible to explain the structures we see around us today.

You might ask how we are so sure dark matter is there if we can't see it. Well, we can detect its effect in a number of ways. The most elegant in my opinion follows from Einstein's prediction that light rays can be deflected by massive objects. And just as objects seen through an optical lens can be distorted, so a sheet of distant galaxies appears distorted by lumps of matter in the foreground *even if that matter is not shining*. In the illustration at left of a cluster of galaxies, the arc-like objects are much more distant galaxies whose light is being gravitationally deflected and stretched by matter in the foreground cluster. The amount of distortion seen reveals there is 50 times as much mass in this cluster as that estimated from the stars that make up the cluster galaxies. Very recently my collaborators and I detected the same distortions statistically in random fields on the sky, providing valuable confirmation that dark matter is not just sitting in special locations like the cluster shown.

It really would be helpful to know what this dark matter *is*, but that's another story. (Let me confess, at least, that nobody is really sure!) For our purposes, it's enough to know that it obeys the laws of gravity, and because it does, we can predict quite easily how it congregates and assists in forming the structures that seed galaxy formation. This theory of hierarchical assembly is remarkably simple and powerful. It can explain the fluctuations in the microwave background seen shortly after the Big Bang, and also the large-scale distribution of galaxies that we see today. It is ultimately capable of predicting the origin of Hubble's sequence, and indeed several theorists are already very confident they are on the right track. Our job as observers is to keep them under control and make sure they don't become overconfident in their assertions.

The challenge we now face is how this assembly history, which we can sketch in outline, leads to the detailed structures that we see inside galax-



The segmented mirror of the 10-meter Keck compared to that of the 30-meter CELT.

Below: How do we establish the "big picture"? Astronomers have now developed various techniques to select sources at different epochs in the history of cosmic expansion. What are the processes that transform the ancient galaxies on the left (seen in HST images) into the mature regular systems on the right that we see today?

ies—for example, the bulges and bars in spirals and the physical processes that occur when irregulars merge with larger systems and lose their identity. Bars and bulges are just examples of the kind of internal details we would like to study at high redshift; they are important diagnostics for the dynamical state and evolution of spiral galaxies.

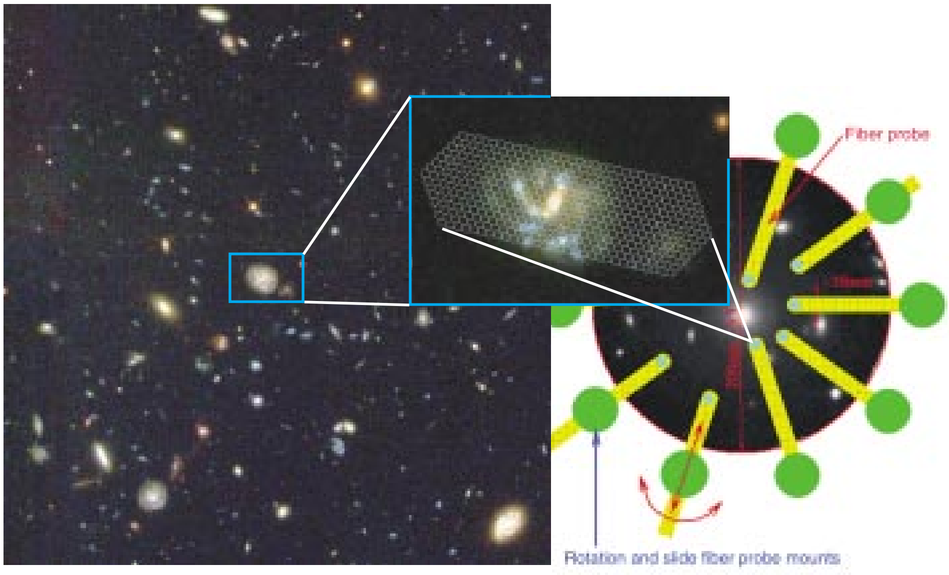
The Keck Telescopes have truly revolutionized our view of the distant universe, but, to be frank, even those giants will be unable to study precisely the *internal properties of distant galaxies*. To analyze the spectroscopic signal from individual subcomponents of a faint galaxy demands the exquisite angular resolution of the Hubble Space Telescope *and* about 10 times the light grasp of the Keck Telescope. A larger aperture is essential to dissect galaxies into their subcomponents because each subunit will be correspondingly fainter and more challenging to observe.

The Keck's 10-meter-diameter primary mirror, the world's largest, is composed of 36 hexagonal segments, each with an edge length of 0.9 meters. Keck was a very ambitious experiment at the time it was conceived, because it was the first telescope to be made of many individual segments. Can one contemplate making a larger primary mirror from more segments and hence a more powerful telescope?

This brings me to the proposed CELT project, the California Extremely Large Telescope (a name I'm particularly fond of since I *am* a Celt). Modeled on the segmented-mirror technology of Keck, the 30-meter CELT mirror requires a thousand segments, each with an edge length of 0.5 meters. It may sound like a formidable task, but the transition from the 200-inch telescope at Palomar to the Keck could, in some sense, be viewed as a more imaginative leap and a bigger technical challenge than replicating the Keck's technology on a larger scale.

With triple the diameter, CELT will have 3^2, or 9 times, the light-gathering power of the Keck. The current design has a fast focal ratio (or f/number), which means that the dome that contains it will be as small as possible. A unique feature is its wide field of view, bringing many objects at once within the range of observation. And my colleagues are confident they can achieve the resolution of the Hubble Space Telescope, if not better, over a limited field—which is very exciting. In the last decade, there's been a revolution in our ability to correct the blurring that's caused by the earth's atmosphere, a technique we call adaptive optics.

So where are we with this undertaking? As with the Keck Observatory, this is a 50–50 partnership with the University of California, led by Jerry Nelson, BS '65, the former project scientist for Keck. We've been working on the



Catching faint, early galaxies in the act of assembling themselves is a major motivation for building CELT. An array of fiber probes trained on a sample of irregular galaxies (above, center) can analyze the spectroscopic data of the galaxy's subcomponents and answer questions about their physical state. Keith Taylor, member of the professional staff, is designing robotic fiber probes (one example is shown above, right) that will dissect the images of many faint galaxies simultaneously.

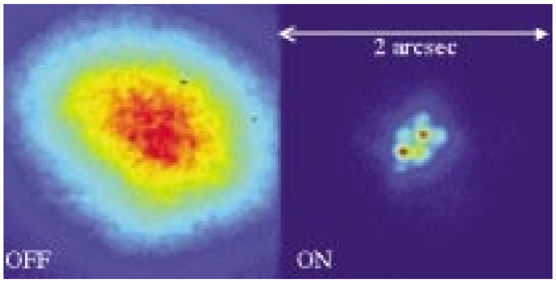
design of the telescope for over a year, and working groups composed of astronomers and instrumental scientists have been looking into various concepts. We have developed a scientific case that acts as a target of what we want to achieve. We've also been studying the instruments. And we've been looking at where to put the telescope.

The biggest challenge is not necessarily the size of the mirror and the manufacture of the segments. Nelson believes the mirror segments can be made much more efficiently than they were for the Keck, and he has been investigating novel techniques for polishing many simultaneously. Segmented-mirror technology is a relatively new development in world astronomy, and Caltech and UC are well ahead of the competition in the only practical way to make larger primary mirrors.

Adaptive optics will help enormously. This technique allows us to correct for the distortion of Earth's turbulent atmosphere, thereby gaining the same resolution in a large, ground-based telescope that we get from spaced-based ones, like the HST, above the atmosphere. We have already demonstrated this technique at an elementary level at both Palomar and Keck Observatories. Here's how it works: A light wave coming through the atmosphere gets distorted. When the signal from that wavefront hits a mirror with several hundred deformable components, the mirror adjusts the position of each of the components to create an opposite deformation that cancels out that of the incoming wavefront. In the demonstration at Palomar, in fairly typical conditions, my colleagues were able to correct the blurred image of a binary star and see it at considerably improved resolution. It's exciting for me personally that Palomar can play a key role in developing this technology, further integrating our various observatories.

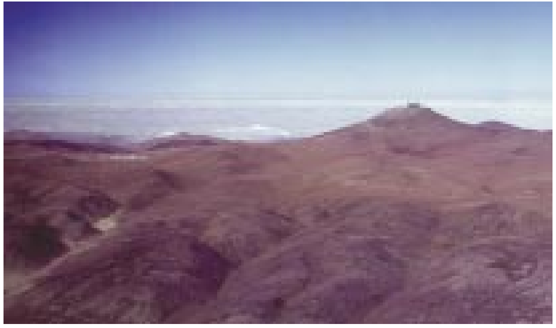
A telescope is, of course, just the light-gathering collector; we need big instruments—detectors, spectrographs, cameras—to analyze the light collected with our big mirror. Typical Keck instruments weigh four tons. Scaling this up to a 30-meter telescope, we could be talking about instruments the size of a tennis court—unless we're very clever. Innovation will be vital in keeping the cost down. The largest detector at Palomar, the panoramic imager that's used for finding Steidel's remote galaxies that I mentioned earlier, contains six charge-coupled devices (CCDs), each 4,000 by 2,000 pixels. CELT will need much larger detectors, including huge ones operating at near-infrared wavelengths, where the technology is not yet so far advanced. And, in order to dissect a distant galaxy and measure the signal from each subcomponent, we're going to need robots that position little units on top of the galaxies we want to study.

Where can we put this giant telescope? We have two basic options, one in the northern and one in the southern hemisphere (believe me, there are no other hemispheres, we've looked). The first is located on the summit of Mauna Kea. That's where the two Keck Telescopes are, as well as



An adaptive optics technique developed at Palomar by Rich Dekany, BS '89, member of the professional staff, and colleagues at JPL uses a sensor tuned to real-time measurement of the distorted incoming wavefront to restore the smeared image of a binary star (left) to the resolution typical of an HST image (right).

Two possible sites for CELT are Mauna Kea (right) in Hawaii and the Atacama Desert (below) in Chile. Professor of Astronomy George Djorgovsky leads the site review team.



several others. As you can see (above) it's getting kind of crowded up there. Fortunately a plan has been developed for replacing the smaller telescopes with larger ones over the years; we are hopeful that CELT will be a high-priority replacement in the next decade.

The other alternative is in the southern hemisphere, in Chile's Atacama Desert. This is where the Europeans have their VLT (Very Large Telescope), which consists of four 8-meter telescopes that, when linked as an interferometer, will effectively operate as a 16-meter mirror. There are a number of excellent sites in the Atacama Desert, but their characteristics are not as well known as those of Mauna Kea. We have drawn up a list of criteria, including how stable the atmosphere is, how the weather varies with seasons, and whether the nights are uniform in temperature. An international program, involving ourselves as well as other U.S. and international teams, is currently gathering site information for many of the Chilean locations. In view of economic and political considerations, it's most important to have at least two viable sites.

To sum up: With our existing telescopes we have already explored the universe over a wide range in its cosmic history, back to barely a billion years after the Big Bang. But the exploring is over. The challenge we now face is to understand how gravity built up the structures we see. We have a theory based on the presence of dark matter, but we need to understand the detailed physics of how it led to galaxies assembling. We are confident that we can develop the technology to examine the internal workings of distant galaxies, but for this we need a much larger telescope and investment in detectors, adaptive optics, and, of course, the manufacture of hundreds of mirror segments. Even though the 30-meter telescope is a very ambitious experiment, I consider it no more ambitious than the 200-inch Hale was in the 1930s and the 10-meter Keck in the 1980s. In the case of adaptive optics we have the great advantage that we can experiment with our existing telescopes, such as the venerable Palomar Observatory, which will be given a new lease on life as a valuable base from which to make these key innovations for the future. □

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Professor of Astronomy Richard Ellis claims no responsibility for naming the California Extremely Large Telescope, although he is a genuine Welsh-born Celt himself. He earned his B.Sc. from University College London in 1971 and his D.Phil. in astrophysics (1974) from Oxford University. From 1974 to 1993 he was a member of the faculty at the University of Durham, and in 1993 was appointed the Plumian Professor of Astronomy and Experimental Philosophy (a chair formerly held by the late Sir Fred Hoyle) and director of the Institute of Astronomy at the University of Cambridge. Although he had been a visiting professor at Caltech in 1991 and 1997, the lure of large telescopes finally brought him here on a more permanent basis in 1999 to continue to pursue a number of aspects of observational cosmology—and even larger telescopes. He is also director of Palomar Observatory and retains a joint appointment as professor of observational astrophysics at Cambridge.

Celtic influence? The 30-meter California Extremely Large Telescope happens to be about the same diameter as a somewhat older astronomical observatory.