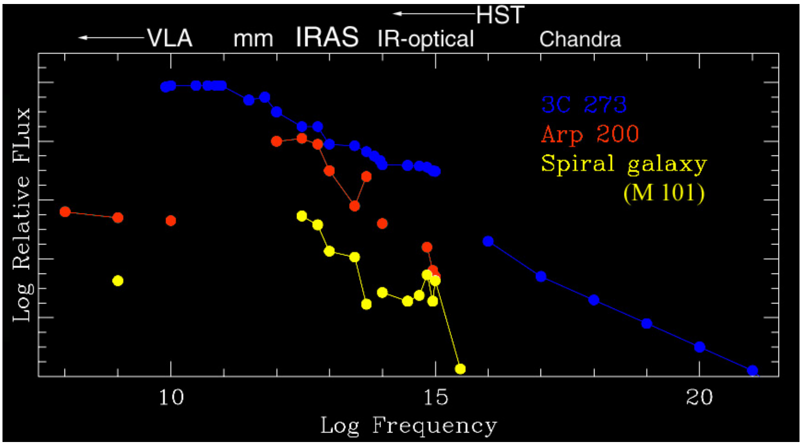
The Lives of Quasars

Quasars are the lighthouses of the Cosmos. Their beacons reach us from baryon islands in a vast dark-matter ocean, and whisper of how things were as galaxies formed in a hotter, more compact Universe. Their tremendous luminosity across the electro-magnetic spectrum makes them prime targets for study by ground and space-based observatories. When we look back to the far reaches of the Universe, we find an era like the Golden Age of Ancient Greece, a brief episode when quasars produced a tremendous burst of activity. How did this come about and why did it stop? Almost 40 years after the discovery of quasars, astrophysicists have developed theories of how they formed, generate their tremendous energy, and evolve. A consistent picture is now emerging that makes key predictions about the high-redshift universe. Remarkably, many quasars seem to have been overlooked because of heavy dust shrouds.

Quasar light appears to have had a profound influence on the formation of galaxies, and the thermal history of the Universe. In this chapter we review recent developments in our understanding of quasars.

Quasars Today

The distinguishing characteristic of quasars is that they emit photons over a much greater energy range than generated by a galaxy of stars of different temperatures. Their spectrum is characteristic of gas that has disintegrated into electrons, protons, and neutrons, and of emission from hot dust.



THE OBSERVED LIGHT SPECTRA from the nearby dust-clear quasar 3C 273 and ultra-luminous infrared galaxy Arp 220 are compared to that from the nearby, star-forming spiral galaxy Messier 101. The sensitivity ranges of various telescopes are shown at top. The relative intensities of Arp 220 and M101 have been adjusted to place them at the same distance to us.

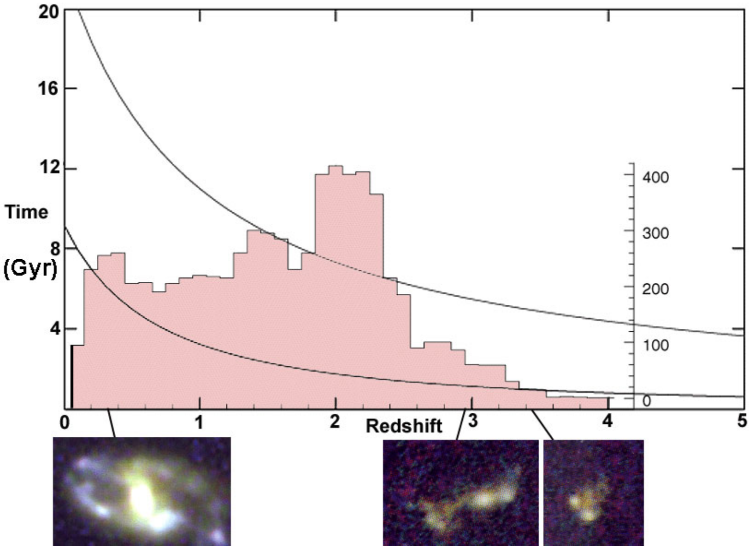
Abrupt X-ray brightening show that the core traced by the highest-energy particles is comparable to the size of our solar system. Yet this tiny volume outshines the light of the rest of the galaxy. Based on this enormous luminosity yet compact volume, what compresses and accelerates gas is likely the gravitational field near a heavy black hole. Computer models show that gas near a black hole will first settle into an accretion disk then is dragged inward by viscosity. Near the inner edge, gas shocks to high temperature, and cools by emitting gamma-ray photons and by forming particle/anti-particle pairs. Some of these are absorbed by the black hole, adding to its mass and spin. The quasar core shines brightly by converting several solar masses of material into energy each year. At this rate, it would consume much of its host galaxy if it operated over much of the age of the Universe. But quasars are rare today, so the energy consumption has somehow slowed.

There are many assumptions. First, what evidence exists for these accretion disks? In early 1999 Japanese astronomers using an X-ray satellite saw for the first time gas entering a supermassive black hole. The observations confirmed a prediction of general relativity that the disappearing gas would emit X-ray spectral lines that are highly Doppler shifted to red wavelengths.

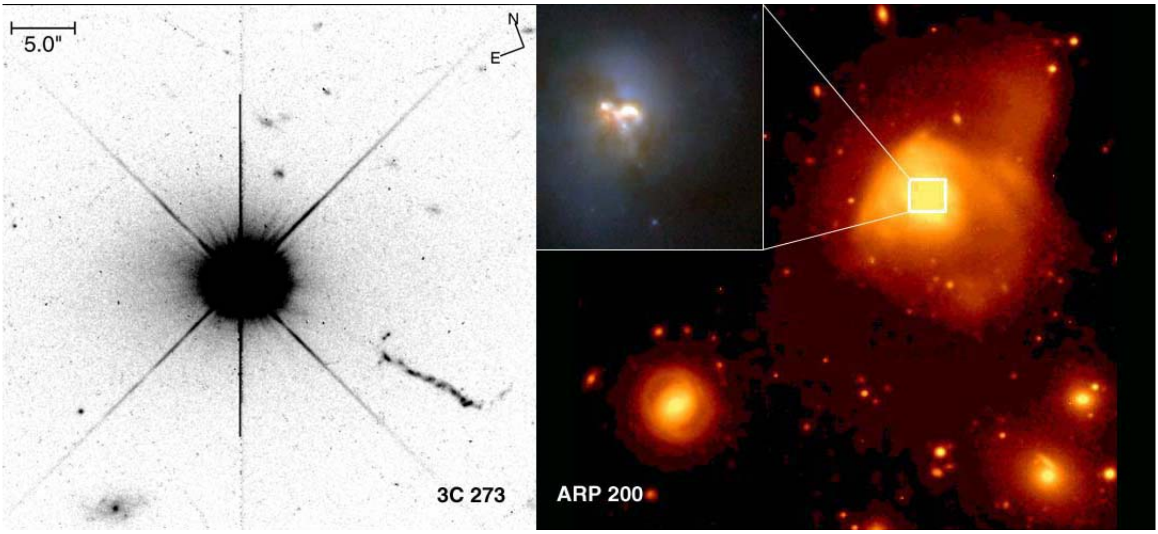
That we see molecules in the cores of certain active galaxies shows that accretion disks can be dense enough to shield gas from the tremendous heat of the black hole. Remarkably, water absorbs radiation from near the black hole and can beam this towards us in natural microwave lasers, masers [see “Masers in the Sky”, Moshe Elitzur; *Scientific American*, February 1995]. Enough masers beam light to us to delineate accretion disks in two active galaxies, Messier 106 and NGC 1068. Although these nuclei are far less luminous than that of a typical quasar, gas motions are consistent with those expected in an accretion disk in orbit around a black hole several tens of millions of times as massive as the sun.

Another characteristic of quasar spectra is broad emission lines. Broadening seems to arise as gas particles whirl around the black hole. Indeed the Hubble Space Telescope (HST) and ground-based telescopes have found strong evidence for a dark, billion solar-mass concentration at the center of several galaxies. Theorists have been hard pressed to come up with alternatives to a black hole.

The great luminosity of quasars allows us to study their evolution. All we need do is study progressively fainter examples to see them on average farther back into the past. Of course our expanding Universe was more compact then, the dilation factor being (1+z) since redshift z. A galaxy at z=5 emitted its light when the Universe was less than 1/6 of its age today [see "Galaxies in the Young Universe", by F. Duccio Machetto & Mark Dickinson; *Scientific American*, May 1997].



This figure shows how age is related to redshift, and how over 7300 quasars that were selected by their optical emission are distributed in z (quasars beyond z = 5 have recently been found.) The two curves bracket the range of cosmologies allowed by current data. The galaxy images, from the 10-day long Hubble Deep Field-North exposure, show how difficult it is to study the structure of objects at the redshifts shown even with HST. These objects appear disturbed. The galaxies that host quasars are even harder to study because the bright quasar core overwhelms the starlight. Credits for galaxy images: STScI.



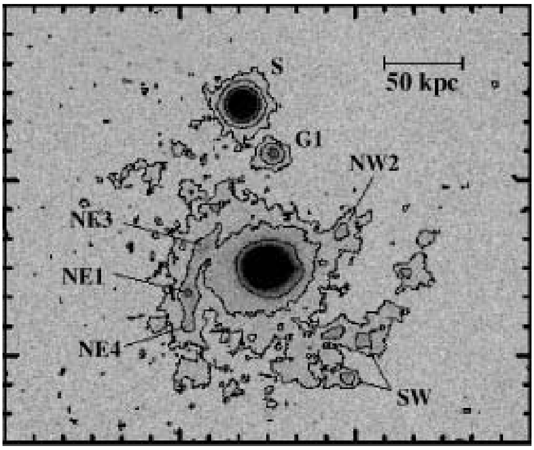
(Left) the dust-clear quasar 3C 273 with its radio jet at right (the spikes are diffraction from the HST mirror supports), and (right) Arp 220 from the ground and (insert) with an infrared camera on HST showing starlight in blue and dust in brown. Credits: left, John Bahcall, Institute for Advanced Study; right, JPL & Nicholas Scoville, CalTech.

It is therefore fortuitous that two luminous examples are comparatively close to us. These two galaxies — with catalog names 3C 273 and Arp 220 — represent dust-clear and -enshrouded quasars, respectively. Clearly both are not starlike. In fact "fuzz" surrounds the bright core of many quasars, and contributes on average about 20% of the total light from the quasar. Pioneering spectra taken by astronomers Todd Boroson and Bev Oke nearly 20 years ago showed that this is starlight from the galaxy that hosts the quasar core. Boroson and Oke could make these measurements because their CCD allowed accurate subtraction of scattered core light from the much fainter galaxy starlight.

Such measurements fight two fundamental limits: first, astrophysicists have no clear expectation of how the mass of the quasar galaxy is distributed in space. The greatest uncertainty relates to the distribution of “dark matter”. Was it clumped on the scale of the galaxy, as it seems to be today, or was it still distributed diffusely? Only by measuring the motions of stars in the quasar host galaxy can we see if mass was distributed into patterns that resemble those seen in nearby galaxies today. But the second problem is that starlight fades as $(1+z)^{-4}$, so rapidly that by $z = 2$ quasars show only the brightest clumps outside the nucleus. These features are unlikely to track the distribution of mass in the host galaxy.

Instead we would like to see how the older stars — which carry most of the galaxy mass — move. The quasar redshift displaces this starlight into the infrared. At these wavelengths HST produces fuzzier images than large, ground-based telescopes because of its larger diffraction. Optical systems on 8-10m aperture telescopes will be activated in a year or two to deblur the effects of our atmosphere [see “Adaptive Optics”, by John W. Hardy; *Scientific American*, June 1994]. Such so-called adaptive optics will also improve the contrast of faint material against the bright infrared sky, enabling study of distortions at higher redshifts. These studies will accurately assess the effects of distortions at different places and times in the past.

In fact, one of us (JBH) has developed a technique to improve contrast that works on even a small 4m telescope without adaptive optics. The Taurus Tunable Filter uses extremely narrow wavelength intervals tuned to study gas around quasars, among other targets. The narrow band greatly reduces natural light pollution in the Earth’s sky. While not the dominant mass component, gas can be an excellent tracer of agitated motions. Such techniques, used on larger telescopes with adaptive optics, will clarify our views of distant quasars.



A NEARBY ($z = 0.06$) QUASAR, imaged by us with the Taurus Tunable Filter at the 3.9m Anglo-Australian Telescope. A gas envelope 600,000 light years across, companion galaxy, and spiral arms are shown with unusual clarity in the light of ionized hydrogen gas. Credit: Patrick Shopbell

Back Into the Past

Even these techniques simply delay the time into the past when gas streams or starlight become too redshifted hence dim to see. Fortunately, quasars reveal their influence on nearby material in ways that do not depend on distance. As light from the quasar travels to us, it encounters tenuous gas clouds. The gas may absorb or scatter the quasar light anywhere along the vast distance to the quasar, attenuating it in narrow spectral lines. However, if the lines have redshifts close to the quasar, we can be confident that they are also close in space. When spectral absorption lines close to quasars are compared to those formed by more distant gas, astronomers infer that the quasar’s strong radiation field has ionized the gas, disintegrating low-mass structures within a sphere millions of light-years across. Beyond, the reduced intensity of ionizing radiation from the quasar allows light-absorbing gas clumps to remain. This “proximity effect” allows us to measure the influence of the population of quasars near a certain redshift on the ionization of intergalactic gas. The degree to which these ionized bubbles overlap is very hard to pin down. Nonetheless, astronomers estimate that the number of dust-cleared quasars is insufficient to explain the inferred average ionization in intergalactic space.

Dust shrouds do not impede X-ray or sub-millimeter photons, and X-rays ionize gas. Could dusty objects also have contributed to the ionization? Space observatories have separated the X-ray sky into numerous point sources, which are generally invisible to optical or infrared telescopes. Curiously, the sky we see today has proportionally more X-ray photons than seen in quasars. A natural explanation is that before the apparent peak in quasar activity near $z = 2$, most massive black holes were enshrouded in dust and gas. Only the most energetic X-rays leaked out.

The redshifts of some of the X-ray-background objects can be inferred from their overall spectrum when measurements from sub-millimeter telescopes are included. This combined technique suggests that 80-90% of the activity in galaxies at $z < 4$ is hidden by dust. When this recently discovered population is included, the X-ray background can be accounted for. Depending on how efficiently ionizing ultraviolet photons escape as the dust shroud clears, the ionization of the intergalactic medium may also be explained.

How Was the Dust Veil Lifted?

Gas on orbits like those found in galaxies today does not fall into a central accretion disk, thence black hole. But, if agitated, the gas would shock and dissipate energy to flow inward. Exploding a gas clump certainly agitates it, and also makes it bright enough to see at great distances. Massive stars explode as supernovae within tens to hundreds of millions of years after their birth. It turns out that in such “star bursting” galaxies much gas is shock heated to such high temperatures that is boils off the galaxy as a wind (see Veilleux, Cecil, & Bland-Hawthorn, Chapter X), so cannot fuel the black hole. In dust-enshrouded quasars, the wind will be channeled by dense gas to break out perpendicular to the galaxy disk.

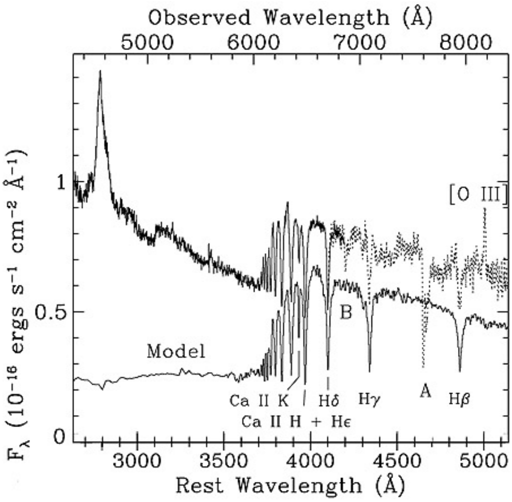
While supernovae from young stars agitate the gas to keep the black hole obscured, the black hole continues to feed and grow on this gas. Heating and magnetic fields cause electrons to scatter against one another and high-energy photons in a rarefied plasma shell above the inner accretion disk similar to the corona of our Sun. Like the solar wind, the corona is hot enough to expand. This superwind is impeded in some directions by dense gas/dust and the equatorial accretion disk, but can emerge near either pole. The outflowing particles sweep up gas and dust, and expel them from the galaxy. The Golden Age of quasars may be the epoch in which quasar winds blow away intervening dust to reveal the quasar nucleus. The bright clumps seen in quasar galaxies may be regions of intense star formation in leftover gas.

Why are black holes today so quiescent and have not grown larger? Few stars that form in a burst are massive enough to explode as supernovas. The rest form a stellar sphere, and dribble gas from stellar winds into the accretion disk [see “Unmasking Black Holes”, by Jean-Pierre Lasota; *Scientific American*, May 1999]. Once most gas converts into stars, the black hole and stellar sphere cease growing and quasar activity fades.

What evidence supports this view? Pioneering work by Frank Low and George Rieke at the University of Arizona in the early 1970’s unveiled a new class of galaxies whose “ultrahigh” far-infrared luminosities rivaled the total energy output by quasars. Their work paved the way for the Infrared Astronomy Satellite, which in 1983 discovered across the sky more “ultraluminous infrared galaxies” (ULIGs) than optical quasars, the only objects with comparable luminosities. Studies since have shown that most ULIGs are undergoing spectacular collisions and show signs of activity in their nuclei, including narrow emission lines from very young stars and broad lines that suggest an accretion disk. From these results, David Sanders and his collaborators at the California Institute of Technology suggested in the late 1980's that ULIGs were young quasars in formation, still surrounded by their dusty cocoons.

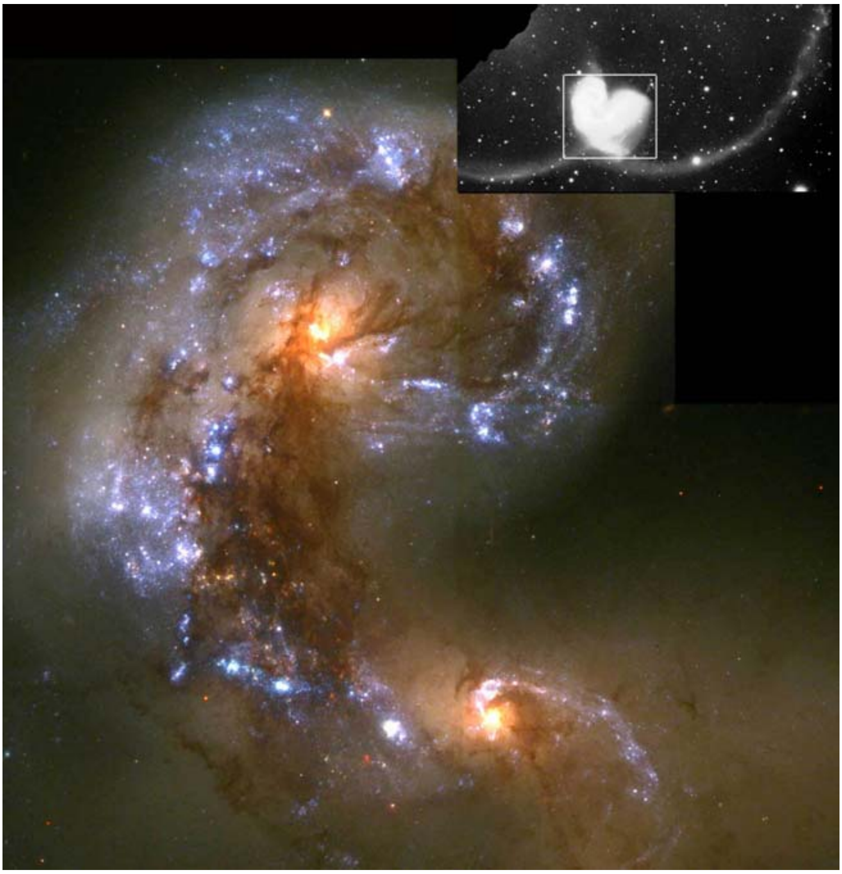
These astronomers were motivated in part by computer simulations of colliding galaxies. In slow collisions, two galaxies coalesce to form what resembles a normal elliptical galaxy [see “Colliding Galaxies”, by Joshua Barnes, Lars Hernquist and François Schweizer; *Scientific American*, August 1991]. Much of the gas in the model galaxy flows to the center of the merger, possibly to form stars. What happens next is speculative because it happens behind an opaque dust veil. Perhaps leftover gas is fed to a pre-existing supermassive black hole. In its early evolution, the starburst coexists with the active nucleus. Much of the energy produced by starburst and active nucleus heats surrounding dust that then cools by emitting infrared radiation. The dust shroud is gradually swept by the combined wind action of starburst and active nucleus. This housecleaning leaves little gas, so the starburst fades rapidly until only the more efficient black-hole engine shines as an optical quasar. Once two spiral galaxies have merged, the result is a normal-looking elliptical galaxy that hosts a quasar in its core.

Astronomers have invested much effort to test this evolutionary picture. The powerhouse of a ULIG is expected to switch from starburst to quasar as the merger progresses. Recently, M. Brotherton and colleagues obtained the spectrum of a quasar that shows the clear signature of a starburst. Optical and infrared studies by several groups — including one led by one of us (SV) — reveal quasars among the more luminous galaxies with “warm” quasar-like infrared spectra, as expected in this model. The host galaxies of quasars and quasar-like infrared galaxies also appear to be farther along the merger sequence.



QUASAR WITH A STARBURST 1-hour exposure with the Keck 10-m telescope of a quasar at z=0.63. A model starburst that occurred 400 million years earlier is shown, and fits the non-quasar light. Credit: M. Brotherton, Lawrence Livermore National Lab.

HST images reveal that nearly all quasars are in elliptical galaxies, as expected in the merger model. The abundant molecular gas in ULIGs and many quasars — more than ten times that in our Milky Way Galaxy — also supports the idea that these two types of object are related. Tides can also warp the accretion disk, opening a more direct route for gas to flow to the black hole. Indeed, pictures of nearby active galaxies from the ground and HST often show clear distortions by gravitational tides, and the maser measurements discussed before show that both of those accretion disks are warped.



THE ANTENNAE imaged by HST is an example of a nearby pair of galaxies whose merger is triggering star formation (blue.) The insert is a ground-based view on larger scale to show the tidal arms of stars and gas. Credit: STScI

If ULIGs give birth to quasars, their density in space should evolve like that of quasars. Only recently have sensitive detectors been developed to seek dusty objects at high redshifts to test this idea. Over the last two years, the Submillimeter Common User Bolometer Array (SCUBA) camera on the James Clerk Maxwell Telescope at Mauna Kea Observatories in Hawaii has carried out deep surveys of the distant infrared universe. Several groups recently announced the detection of ULIGs at redshifts inferred to be in the range 1 to 3. These results imply that ULIGs evolve strongly, like quasars. The importance of these findings may extend beyond that of the origin of quasars. The SCUBA sources may emit most of the luminosity of galaxies over cosmic time. They may therefore account for most of the far-infrared background light outside our Galaxy, and even possibly the X-ray background if many of these distant objects prove to have buried quasars.

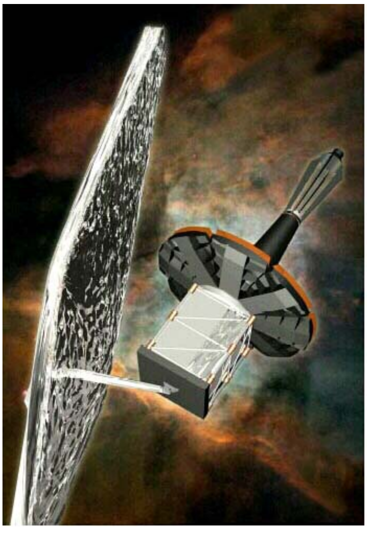
The evidence indicates that most quasars have faded to invisibility, but that their number in the past equals that of galaxies somewhat more massive than our own Milky Way. In other words, many larger galaxies may have a dead quasar in the core.

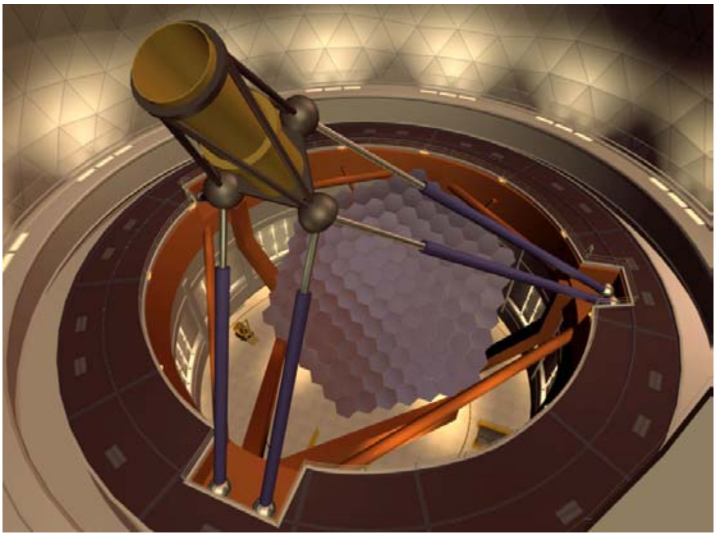
Anticipating the Future

Technological advances like SCUBA stretch our knowledge of quasars. The Cosmic Origins Spectrograph to be installed by astronauts in 2003 will increase the efficiency of HST to obtain UV spectra of nearby quasars more than tenfold, and allow astronomers to determine the present-day proximity effect hence ionizing influence of nearby quasars. To study the high-redshift universe, astronomers in Europe, the USA, and Japan are preparing to construct a large array of submillimeter radio telescopes that will be sited in Chile nearly 2 kilometers higher than the summit of Mauna Kea.

Tremendous gains in information will come from 30-100m aperture optical telescopes currently on drawing boards. Costing $0.4 to 2.5 billion each, this possibly final generation of ground-based facilities will work at 3.5-10 micron wavelengths to obtain spectra of objects at redshifts up to z = 10 when most dust-enshrouded quasars are thought to have formed. One goal will be to learn how heavy elements were produced in the first generation of stars. Some can be used as cosmological clocks, to accurately time the formation of the quasar. Perhaps we will even learn what seeded the first black holes. Did they arise from the fabric of space itself?

A TOOLKIT WITH WHICH TO STUDY QUASARS Concepts for (left) the ALMA sub-millimeter array. Up to 96 antennas will be deployed at 18,000’ altitude in the Chilean altiplano, (bottom left) the 8m Next-Generation Space Telescope and its large sunshade, (bottom right) a 25m-aperture extremely large telescope (ELT) optimized for IR. Credits: ALMA, ESO; NGST, NASA Goddard Space Flight Center; ELT, Tom Sebring.





Within 15 years, the L2 point between Earth and Moon may seem as crowded as the summit of Mauna Kea is today. The 8m Next Generation Space Telescope (NGST) may hover there, along with an array of X-ray telescopes called Constellation-X to replace the recently launched Chandra X-Ray Observatory. With the Earth and its natural satellite distant disks in the sky, the low background light will allow deep surveys. NGST will be optimized for imaging and mid- and near-IR spectroscopy of bright regions within the host galaxies of quasars, to study their masses. These missions will firm up our understanding of quasar birth, and no doubt uncover new puzzles in their lives. Their enormous luminosities ensure that quasars will remain our best time machines.