Quasars and Active Galactic Nuclei

This is the WWW version of a slide set produced for the Astronomical Society of the Pacific, covering QSOs and other kinds of active galaxies. The 35mm slides should be listed in the next edition of the ASP catalog. Each listing points to a reduced image and caption - the graphics on reduction sometimes look questionable, but the full-sized image is linked to the shrunk version. I don't get royalties from the ASP, so this isn't an ad - Bob Havlen kindly allowed me to put the set out in this form for occasional use and previewing. They are sorted by topic here - and you can also see text versions of the introduction, acknowledgements, glossary, and other supporting material.

General aspects:

- Comparing optical spectra of various classes of AGN,
- The broadband spectrum of Markarian 421 from 20 cm to 1 TeV
- Variability of active nuclei in the radio, ultraviolet, and X-ray domains

Seyfert galaxies:

- A gallery of Seyfert galaxies
- HST closeups of Seyfert nuclei
- The broad-band emission spectrum of NGC 4151
- A wide view of NGC 1275 and its gaseous filaments
- An HST view of the enigmatic nucleus of NGC 1275
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Introduction - Discovery of Active Galactic Nuclei

Five and a half decades after the recognition of the class of Seyfert galaxies, active galactic nuclei of all kinds still present major puzzles to astrophysicists. They clearly embody some of the most extreme conditions to be found anywhere, and include the most powerful individual objects that we've found throughout the Universe.

The recognition of active galactic nuclei may be conveniently traced to three discoveries, which taught us distinct aspects of the phenomenon as well as how they might be linked.

The class of Seyfert galaxies was first recognized by Carl Seyfert in a 1943 paper, which discussed the set of (mostly spiral) galaxies whose spectra showed unusually broadened emission lines from bright, starlike nuclei. In retrospect, these were hints that large masses might be involved, to produce such high gas velocities without spraying the material right out of the galaxy, and that the phenomenon was concentrated in a small volume (giving the starlike appearance of the nuclei). While Seyfert nuclei had been occasionally observed earlier - in fact, NGC 1068 was among the first few galaxies whose redshift was measured - this was the first definition of a class of similar objects. Seyfert nuclei were divided into two classes (1 and 2, with the panache for which astronomers are so famous) by Ed Khachikian and Daniel Weedman, based on whether all their emission lines had similar amounts of broadening. In the type 1 nuclei, certain emission lines were much broader - the ones that could originate at the highest gas density. In type 2 objects, all lines have broadly similar widths. Both kinds have very similar sets of emission lines seen, implying the simultaneous existence of atoms in states normally associated with a huge range of density, temperature, and incident radiation.

Meanwhile, the opening of new spectral windows beyond visible light showed us other kinds of active nuclei. New developments in radio astronomy started to allow accurate measurements of just where radio sources are in the sky, so that in the 1950s optical astronomers could start asking what visible-light objects (if any) were producing the mysterious radio emission. A common pattern for radio sources away from the Milky Way was to see a pair of radio sources with a galaxy in between - what came to be called radio galaxies. Many of these were normal-looking elliptical galaxies, but a few showed interested, or just plain odd, features. M87 showed a jet of emitting matter shooting thousands of light-years from its core, one which had been discovered in the optical range as early as 1918 by astronomers at Lick Observatory. Centaurus A looked like an elliptical galaxy cut in two by a thick, irregular absorption lane of dust and gas. And Cygnus A, at the then-remarkable redshift of $z=0.056$, was a small fuzzy image with two main lumps. Colliding galaxy, splitting galaxy, Centaurus A clone seen far away? Speculation ran wild. As radio-astronomical techniques improved, not only could vast numbers of radio galaxies be found, but their structures could be mapped in exquisite detail. Interferometer arrays such as the Westerbork Synthesis Telescope (WSRT) and Very Large Array (VLA) revealed that many showed jets of radio-emitting material tracing from the twin lobes of emission back to a tiny nuclear source; M87 was only the tip of the iceberg. Whatever produced the radio emission had to have a long memory, preserving its direction over millions of years. Optical telescopes showed a variety of spectra for radio galaxies - some looked much like type 1 Seyferts, some type 2's, some showed only a few weak emission lines, and
many showed no spectroscopic peculiarities at all - only the combined spectra of normal old stars.

The discovery of quasars has been recounted often. A few strong radio sources stubbornly resisted identification with any obvious visible-light counterpart until positional accuracies from radio observations reached only a few seconds of arc. Some radio sources appeared to be nothing more than galactic stars, but their spectra were very peculiar, with strong, broad emission features at wavelengths that didn't match any plausible features expected from stars - young, old, or exploding. It took some time for Maarten Schmidt at Palomar Observatory to show that these were indeed familiar spectral features, but redshifted to an unprecedented degree. The name quasi-stellar radio source (soon shortened to quasar) was coined for these enigmatic objects. As it turned out, many similar objects are not strong radio sources, and these are distinguished as quasi-stellar objects (QSOs), though both are often lumped together as quasars. Quasars taught us more new aspects of the phenomenon of active nuclei. To be so bright at the large distances implied by their redshifts, they had to be much more luminous than any ordinary galaxies - hundreds of times brighter. Yet they must be tiny, with most of the light coming from a region no larger than our own solar system. This was found from the fact that quasars vary (in both visible light and radio core output) in timescales so short that the object responsible (which cannot be any larger than the distance light travels in this timescale) must by only a light-day or so in size.

A new wrinkle in the AGN picture was added in the late 1970s, with the identification of a few enigmatic objects from variable-star catalogs as highly variable nuclei of distant galaxies. Named after their prototype, such BL Lacertae objects are frustrating for the optical astronomer because their spectra are almost perfectly featureless - the nucleus produces a smooth rainbow of radiation, which can be bright enough to swamp the surrounding galaxies and has no telltale emission or absorption lines to measure its redshift. Redshifts have been measured, either from the surrounding galaxy or by waiting for the object to appear unusually dim so it doesn't drown out the emission lines from surrounding gas. BL Lac objects are most notable for being strongly and rapidly variable at all wavelengths, in both intensity and polarization. Their properties are usually thought to reflect our viewing the jet of a radio galaxy almost along its own axis, so our view is dominated by Doppler-boosted radiation from the jet rather than the more usual view of the nucleus and its surroundings. Some quasars with unusually weak emission lines share some of these variability properties as well, so they and BL Lac objects may be lumped together as blazars.

In the 1980s, it became clear that nuclear activity can extend to lower levels, and appear in more galaxies, than a census of Seyfert nuclei would show. Many galaxies were found to show gaseous emission from their nuclei which could not be explained in detail by young stars, and this was dubbed the class of Low-Ionization Nuclear Emission-line Regions (LINERs) by Tim Heckman and Bruce Balick. There remains debate as to how many kinds of objects fall in this category, but spectroscopy, X-ray and ultraviolet observations show that some of these are indeed lower-power versions of Seyfert nuclei, complete with X-ray source, blue continuum, and variability. The phenomenon of nuclear activity now appears to range over 6 orders of magnitude in luminosity, and to show up in a significant fraction of bright galaxies.
Some words of thanks!

A casual glance at the slide captions will show that many astronomers have contributed data for this project. In more or less chronological order, I am grateful to Meg Urry, Riccardo Scarpa, Bob Fosbury, Gerry Kriss, Trevor Weekes, Mike Fanelli, J. Buckley, Rick Perley, Dayton Jones, Rodger Thompson, Peter Shaver, Dayton Jones, Ed Turner, Mike Blanton, John Hutchings, Varsha Kulkarni, Karl-Heinz Mack, Thomas Boller, Matt Malkan, Herman-Josef Roeser, Alex Filippenko, John Bahcall, Sofia Kirhakos, Malcolm Longair, Philip Best, Don Osterbrock, Andre' Martel, Stefi Baum, Limin Lu, Michael Rauch, Peter Boyce, Mike Disney, Alessandro Marconi, Alessandro Capetti, Jack Gallimore, Bob Goodrich, Ann Wehrle, John Biretta, and Frazer Owen. Many of these data sets were collected with the Hubble Space Telescope at the Space Telescope Science Institute, operated by AURA, Inc. under contract with NASA. AURA also operates Kitt Peak National Observatory under a cooperative agreement with the National Science Foundation, which funds the National Radio Astronomy Observatory as well through AUI. The Digitized Sky Survey, used in a few of these images, is based on photographic data obtained using the Oschin Schmidt Telescope on Palomar Mountain. The Palomar Observatory Sky Survey was funded by the National Geographic Society. The Oschin Schmidt Telescope is operated by the California Institute of Technology and Palomar Observatory. The plates were processed into the present compressed digital format with their permission. The Digitized Sky Survey was produced at the Space Telescope Science Institute (ST ScI) under U. S. Government grant NAG W-2166. The Infrared Space Observatory (ISO) is an ESA project with instruments funded by ESA Member States (especially the PI countries: France, Germany, the Netherlands and the United Kingdom) with the participation of ISAS and NASA.

Glossary

**ASCA** - Advanced Satellite for Astrophysics and Cosmology, a Japanese X-ray astronomy satellite optimized for X-ray spectroscopy. It was launched on February 20, 1993.

**Blazar** - broader term including BL Lacertae objects and those quasars which share their characteristics of unusually weak spectral features, plus strong and rapid variability.

**BL Lacertae object** - a variety of active galactic nucleus with a nearly featureless spectrum and rapid strong variability. These may be other kinds of radio-loud AGN seen nearly along their jets, so that the Doppler-boosted radiation from the jet overwhelms everything else.

**Cerenkov radiation** - radiation produced when a particle enters a medium travelling faster than the speed of light in that material. It appears as very short pulses in a cone around the particle's direction of travel. This radiation is used to detect very-high-energy gamma rays, which produce pairs of subatomic particles when they interact with material in the Earth's atmosphere. These particles then produce Cerenkov radiation as they dive deeper into the atmosphere, and it is these flashes that can be detected by large mirror arrays on the ground.

**CGRO** - Compton Gamma-Ray Observatory, the second of NASA's "Great Observatories". It carries the Energetic Gamma-Ray Experiment Telescope (EGRET), Oriented Scintillation Spectrometer Experiment...
Doppler boosting - an effect of relativity which enhances the radiation from material that is moving toward us at nearly the speed of light, and hides material moving away from us at such speeds. For example, if there are many quasars with radio jets moving at relativistic speeds, the strongest radio sources will be those that are most nearly pointed in our direction. This is important in understanding BL Lacertae objects and superluminal radio sources.

EGRET - Energetic Gamma-Ray Experiment Telescope on the Compton Gamma-Ray Observatory (CGRO). This instrument has carried out an all-sky survey in many energy bands, along with dedicated pointed observations of particularly interesting or variable objects.

electron volt (eV) - the amount of energy an electron gains when accelerated across a difference in electric potential of one volt. This is a convenient and customary energy unit in high-energy astrophysics. A hydrogen atom can be ionized by absorbing a photon of energy 13.6 eV, or wavelength 912 Angstroms. X-rays are generally taken to have energies from about 0.5-10 thousand eV (kilo-eV or keV), while gamma rays have energies in the million-eV (MeV), billion-eV (giga- or GeV) range or even higher.

EUVE - Extreme Ultraviolet Explorer. This mission conducted the first deep all-sky survey in the extreme ultraviolet region, below the Lyman limit and into the soft X-ray region. This survey detected many active nuclei in directions where foreground absorption from neutral hydrogen in the Milky Way is unusually low. The mission, operated by the Center for EUV Astrophysics in Berkeley, California, has also carried out spectroscopic measurements of the brighter sources.

HST - Hubble Space Telescope. Deployed into low Earth orbit by the space shuttle Atlantis during STS-31 (1990), since refurbished and given instrument upgrades during STS-61 (December 1993) and STS-82 (February 1997). The current complement of science instruments includes the Wide Field Planetary Camera 2 (WFPC2), Faint-Object Camera (FOC), Near-Infrared Camera and Multi-Object Spectrometer (NICMOS) and Space Telescope Imaging Spectrograph (STIS); the Faint-Object Spectrograph (FOS) and Goddard High-Resolution Spectrograph (GHRS) were replaced by these latter two instruments during the 1997 refurbishment mission. Built in cooperation with the European Space Agency (ESA), this is the first of NASA's planned four "Great Observatories".

HUT - Hopkins Ultraviolet Telescope, flown on the Astro-1 and Astro-2 missions of the space shuttle. Designed to measure the spectra of celestial objects in the deep ultraviolet range from 912-1800 Angstroms, especially in the rich spectral region just shortward of 1150 Angstroms where the Hubble Space Telescope's mirror coatings and detectors become ineffective.

ISO - Infrared Space Observatory, a mission of the European Space Agency carrying a cryogenically cooled 60 cm telescope and suite of deep-infrared cameras and spectrometer. It operated from November 1996 to April 1998, when the liquid-helium coolant was exhausted (almost a year after the primary mission specification).

IUE - International Ultraviolet Explorer, a satellite observatory sponsored jointly by NASA, the UK Science Research Council, and the European Space Agency, and launched into geosynchronous orbit in 1978. Designed strictly to measure the ultraviolet spectra of celestial objects, it operated until 1996. One
of the most successful of space astronomy, its interactive operation introduced a generation of astronomy to space-based measurements.

**LINER** - Low-Ionization Nuclear Emission-line Region, gaseous regions common in the centers of many kinds of galaxies. Some of these have been shown to be low-luminosity active galactic nuclei, perhaps an extension of Seyfert activity to the lowest levels and implying that the whole phenomenon of nuclear activity occurs in a significant fraction of bright galaxies.

**MERLIN** - Multi-Element Radio-Linked Interferometer, a dedicated network of radio telescopes in the United Kingdom for long-baseline interferometry. While there are fewer elements than the VLA so the level of detail is typically smaller, its resolution is substantially greater than that of the VLA because of the long baselines; it has been used to bridge the gap between Westerbork or VLA measurements and maps using intercontinental baselines.

**Quasar** - from QUAsiStellar Radio Source, an object at large redshift (z>0.1) showing strong broad emission lines. Variability shows that the energy must arise in a tiny region, although some quasars have hundreds of time the energy output of normal galaxies. Their radio structures often include jets and lobes similar to what we see from radio galaxies.

**Quasistellar object (QSO)** - an object with optical properties as described for quasars, but not necessarily a strong radio source. Only about 10% of QSOs are radio-loud. "Quasar" is often used more loosely to include QSOs.

**radio galaxy** - a galaxy showing unusually strong radio emission, too intense to be produced by the normal processes of starbirth and stardeath. This may come only from the nucleus, or from a pair of more or less symmetric lobes stretching as far as a million light-years. Many show emission from jets connecting the nucleus to these lobes. Optical spectra of radio galaxies may show nothing unusual, but in many instances show strong emission lines, either narrow (NLRG, like type 2 Seyferts) or including broad lines of certain species (BLRG, like quasars and type 1 Seyferts).

**ROSAT** - ROentgen SATellit, a Germany/UK/USA satellite dedicated to X-ray astronomy. It as launched June 1, 1990 on Delta II booster and remains in service as of 1998. It carries three instruments, one of which was used in a dedicated two-year survey of the entire celestial sphere. A second, the HRI (High-Resolution Imager), delivered the most detailed X-ray images of deep-sky sources to date.

**Seyfert galaxy** - galaxy, usually a spiral or disturbed system, whose nucleus shows strong emission lines which are too broad and of ionization too high to be produced by the galaxy's stellar population. Often, we see a bright starlike nucleus associated with this. In type 1 Seyferts, some of the emission lines, those that an be produced at high densities, are still broader, while in type 2 nuclei, all the linewidths are comparable. Seyfert nuclei are strong X-ray sources, and many show significant radio emission.

**superluminal sources** - radio sources which show internal motions (for example, increasing separation between the core and a knot in the jet) which appears faster than the speed of light in our frame of reference. The data are consistent with this being a transformation effect from seeing jets moving almost directly toward us, so that the emitting material almost catches up with its own radiation. This has the effect of compressing the scale of time that we measure for it, and so increasing the observed speed.

**UIT** - Ultraviolet Imaging Telescope, flown on the Astro-1 and Astro-2 missions of the space shuttle. Used an image intensifier to photograph numerous celestial objects at wavelengths 1200-2800
Angstroms, all of which are absorbed by the Earth's atmosphere.

**unified scheme** - one of two pictures in which different kinds of active galactic nuclei have been suspected to be the same, only viewed from different directions relative to their axis. For Seyfert galaxies, the notion is that some Seyfert 2 nuclei are actually Seyfert 1 objects with our view of the innermost region blocked by a thick disk or torus of dust and gas. For BL Lacertae objects, quasars, and radio galaxies, the scheme is that all are quite similar - some radio galaxies are quasars with our view of the central engine blocked, and BL Lacertae objects are the ones in which we happen to be looking right down the jet. These schemes have broad support from several kinds of evidence, but some nagging details mean that at least some parts need to be added to the theories.

**VLA** - Very Large Array, a radio telescope consisting of 27 linked antennas. Operated by the U.S. National Radio Astronomy Observatory, and located about 100 km west of Socorro, New Mexico.

**VLBA** - Very Long Baseline Array, a dedicated array of radio telescopes for very-long-baseline interferometry (VLBI) operated by NRAO. It stretches from the island of Hawaii to the U.S. Virgin Islands, and provides much more extensive opportunities for VLBI measurements than ad hoc collections of miscellaneous antennas.

**VLBI** - Very Long Baseline Interferometry. A technique for combining signals received by physically separated radio telescopes to yield some of the results of observations with a single dish as large as the separation between dishes. This can yield resolutions of order one thousandth of an arcsecond (milliarcsecond), and even better when one of the antennas involved is in space and thus yields baselines larger than the Earth's diameter.

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**The Electromagnetic Spectrum**

Perhaps more than any other kind of objects in the Universe, active galactic nuclei have required observations at many wavelengths to piece together our present understanding. While divisions of the continuous electromagnetic spectrum are rather arbitrary, and driven as much by our particular means of detection as by more basic distinctions such as how they are produced, the following slices are generally recognized:

- **Radio** - the lowest-frequency domain that we've needed to name. It extends from wavelengths of a kilometer or so, the longest that will propagate through the interstellar medium, down to about a millimeter (where we generally start speaking of the millimeter, microwave, or even far-infrared). Detection of radio radiation is often done using wave techniques rather than photon-counting, because of the low photon energies, and this offers distinct advantages for such applications as interferometry which astronomers working in the infrared and optical regimes view with some envy. From active nuclei, we often detect synchrotron radiation in this range - radiation produced as energetic charged particles (mostly electrons) produce when they are deflected by magnetic fields.

- **Infrared** - A very broad slice of the spectrum, reaching from about 1 micron on the short side to hundreds of microns (depending on whether one wants to separate a distinct microwave portion of the spectrum). Starlight, line emission, and especially the thermal emission from dust grains warmed by various processes can be detected in the infrared. An important feature is that infrared radiation is much
less subject to dimming by dust grains than optical or ultraviolet radiation, so we can see deeper into dusty regions at these wavelengths.

- **Optical** - The original domain of astronomy (and all the sciences), defined at first by the wavelengths that the human eye responds to. This extends from about 4000-6800 Angstroms, often extended in astronomy to include the entire window around this band which the atmosphere passes with little attenuation (3000 Angstroms to about 10,000 Angstroms = 1 micron). Familiar technologies (lenses, aluminized mirrors, photographic emulsions, charge-coupled devices) are at their best here. Stars are obviously important sources of optical radiation, as are ionized gas and, in some nuclei and jets, synchrotron radiation from particles carrying very large energies.

- **Ultraviolet** - There is a naturally imposed bound for distant objects at 912 Angstroms (13.6 eV), the energy needed for a photon to be absorbed by a hydrogen atom and liberate its lone electron in the process. There is so much neutral hydrogen in our galaxy that we cannot see very far away at wavelengths shortward of this until about 100 Angstroms, when the absorption by hydrogen (now assisted by other, trace elements) has dropped enough for the interstellar gas to become transparent once again. Aside from starlight and synchrotron radiation, the UV contains several very important strong spectral lines from abundant atoms.

- **Extreme ultraviolet** - loosely, the range between the trough produced by hydrogen absorption starting at 912 Å and the X-ray regime. By rough convention, taken to be 10-500 Angstroms wavelength. Observations in this range require some of the same techniques of grazing-incidence mirrors and photon detection as do X-ray measurements.

- **X-rays** - In ordinary use in physics, loosely associated with processes in atomic nuclei rather than the surrounding electrons. However, some of the innermost electrons in elements such as oxygen and especially iron can produce features in the soft X-ray region (say at energies below a few keV). The very property which makes X-rays so useful in ordinary life - their penetrating ability through many kinds of matter - creates difficulty in trying to collect them for analysis. X-rays will travel right through ordinary mirrors, even metal ones. Except for devices working in a single, very narrow band of energy, X-rays can be focussed into images only by mirrors which make a very shallow angle with the X-rays' direction of travel - so-called grazing incidence mirrors.

- **Gamma rays** - more or less, any radiation more energetic than X-rays. Energies as high as 1 TeV (tera-electron volt, trillion eV) have been recorded from cosmic sources. Gamma-ray detection generally has very poor directional sensitivity, so detail discrimination is poor compared to other wavelength regimes. These photons trace the most energetic processes in the Universe.

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Optical spectra of various kinds of active galactic nuclei

Many of the distinctions among the various flavors of AGN rely on spectroscopic clues, shown here in a montage of optical spectra of some examples. They have all been shifted to their emitted wavelength scales for ease of comparison. Seyfert and radio galaxies come in flavors with all emission lines about the same width (Seyfert 2, narrow-line radio galaxy or NLRG) and with certain emission lines much broader (Seyfert 1, broad-line radio galaxy or BLRG). These pairs are similar in optical spectrum, except that BLRGs may have emission lines that are broader and contain more profile structure than found in Seyfert 1 nuclei. Quasars, represented here by a composite produced from many individual objects, have a family resemblance to Seyfert 1 nuclei, and in most cases, the bumps of Fe II emission are even more prominent in quasars, rippling the spectrum between the string individual lines. BL Lacertae objects have virtually featureless spectra, making even their redshifts difficult to measure unless the surrounding galaxy can be detected, or emission lines show up when the nucleus is temporarily much fainter than usual. At lower activity levels, many galaxies contain nuclear emission regions known as LINERs (Low-Ionization Nuclear Emission-Line Regions), which are in at least some cases a lower-luminosity version of the processes seen in more traditional active nuclei. For example, NGC 4579, shown here, has a very faint Seyfert 1-like broad component to its H-alpha emission, and a modestly bright ultraviolet central source. Finally, a normal galaxy spectrum (of an early-type spiral, NGC 3368) is shown for comparison. Most of its spectrum shows the combined absorption features from the atmospheres of
individual stars, with weak emission lines from gas in star-forming regions ionized by hot young stars.

The QSO and BL Lacertae object spectra have good data only in the bluer range, so that they are plotted only from 3500-6000 Angstroms, rather than 3500-7000 as for the other kinds of object. The NGC 4151 spectrum is from the composite data set depicted in full on slide 5. NGC 4579 and NGC 4941 are from observations at Mt. Lemmon Observatory described by Keel in ApJ 269, 466 (1983). Cygnus A was observed with the 4-meter telescope of Kitt Peak National Observatory, as published by Owen, O'Dea, and Keel in ApJ 352, 44 (1990). Charles Lawrence provided his spectra, obtained with the 5-m Hale telescope at Palomar, for 0814+425 and 3C 390.3 (described by Lawrence et al. in ApJ Suppl 107, 541, 1996). The "mean quasar" spectrum is from a composite generated by Paul Francis and colleagues (see Francis et al. ApJ 373, 465, 1991). The normal-galaxy spectrum of NGC 3368 is from the spectroscopic atlas of galaxies produced by Rob Kennicutt (ApJ Suppl ) with data available through the Astronomical Data Center at NASA Goddard.

Back to QSO and AGN Gallery

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Active nuclei are among the few kinds of astronomical objects which are prominent across the whole electromagnetic spectrum. This montage illustrates the detection of a BL Lacertae object, Markarian 421, from the radio to extreme gamma-ray regimes. The graph shows the energy received per decade of frequency, keyed to images in these wavebands across the top. The spectrum is separated into two parts, believed to be related to each other through the interaction of radiation with high-energy particles either close to a central black hole or in a relativistically-moving jet of particles pointed almost toward our line of sight. The higher-energy bump in the spectrum (prominent in gamma rays) consists of radiation scattered to higher energies by collisions with particles (predominantly electrons) moving close to the speed of light. Measurements are shown when the object was in both bright (flaring) and faint states; the higher-energy part of the spectrum follows suit, giving strong support to this upward scattering picture for its origin. The green curves all have exactly the same shape, shifted to give a schematic match to the spectra at bright and faint levels and for direct and scattered radiation in each case. The observation of high-energy gamma rays was crucial to making this connection; they gamma-ray regime occupies nearly a third of the graph.
The images were produced through a variety of techniques. The radio map is from the Very Large Array, at a wavelength of 20 cm; this particular section is from the FIRST sky-survey project. The optical image was obtained with the Hubble Space Telescope, showing the surrounding host galaxy UGC 6132 and a companion galaxy as well as the brilliant point-like nucleus. The ultraviolet photograph is from the Shuttle-based Ultraviolet Imaging Telescope, working at a wavelength of 1500 Angstroms and showing the foreground A-type star to the northeast of Markarian 421. In the extreme ultraviolet, past the "valley" from 912 to about 100 Angstroms where gas in our own Galaxy absorbs virtually all the light, there is a 1-degree-square image produced from the sky survey carried out by the Extreme Ultraviolet Explorer (EUV) in this case covering the range from 44-240 Angstroms. The X-ray image is from the ROSAT satellite, sensitive to X-rays of energy 0.5 to 2 keV. Finally, this object is unusual in having a wide range of gamma-ray energies detected, both a space-based one from the EGRET system on the Compton Gamma-Ray Observatory (CGRO) and a ground-based measurement at the highest energies yet observed in astronomy, near 1 TeV (tera-electron-volt, trillion electron volts in U.S. usage) using the Earth's atmosphere as a detector and measuring the extremely short pulses of light produced when such photons interact with the upper atmosphere. These images are all presented in pseudocolor, where a monochrome (black-and-white) image is mapped into various shades of color to make fine shadings more apparent. They cover a large span of areas, from the 35-arcsecond field of the HST image to 10 degrees for the satellite gamma-ray measurement.

This is one of the few objects which have been measured across such a wide wavelength range, most of which is accessible only to spaceborne observatories. For many active galactic nuclei, most of their energy emerges in X-rays or even gamma rays, to which we would remain oblivious if astronomy were still confined to the Earth's surface.

Markarian 421 is located at 11 04 25.6 +38 12 47 (2000 coordinates). The EUVE image is from the all-sky survey, giving 1275 net seconds of exposure here. The object was detected in the highest-energy passband (where foreground absorption is lowest), through the Lexan filter which gives a nominal passband from 44-240 Angstroms. The image covers 1 degree, with 1' pixels, and has been smoothed with a Gaussian of 1.5' standard deviation. The HST image shows the 35" field of the Planetary Camera CCD, in a red-light image of total exposure 240 seconds, courtesy of Meg Urry and Riccardo Scarpa at STScI. The UIT image is a 1430- second exposure in the B1 filter at 1500 Angstroms taken during the Astro-2 mission, provided by Mike Fanelli and the UIT Team. The VLA map is part of the FIRST survey, working at a wavelength of 20 cm, and a region slightly less than 5' square is shown here. The X-ray image of this intense source is from the Position-Sensitive Proportional Counter (PSPC) on board the ROSAT satellite, representing 14 hours of total observation over a two-day period in May 1992, and covers a region about 40 arcminutes square. The EGRET image was obtained by the Compton Gamma-Ray Observatory, and covers a region 10 degrees on a side with a resolution of about 1 degree. The Mt. Hopkins atmospheric-pair telescope data are courtesy of J.Buckley, Washington University.

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Variability of Active Galactic Nuclei in various spectral domains

Quasars, BL Lacertae objects, and Seyfert galaxies show prominent variability at many wavelengths, which has been used to provide clues to the sizes and structure of the region producing the radiation. This graph compares three objects showing characteristic kinds of variability. The most complete variation history shown is for BL Lacertae itself from a long-running monitoring program at the University of Michigan Radio Observatory, observed at a frequency of 8 GHz (wavelength 3.8 cm). Averaging all measurements within each five-day interval gives 792 data points over a 28-year period. This shows why the radio behavior of such violently-variable objects is often spoken of as a series of flares, sometimes overlapping in time.

A recent discovery has been that the class of Seyfert nuclei known as narrow-line Seyfert 1 are continually and strongly variable in the X-ray range, as seen in the ROSAT data series of the Seyfert IRAS 13224-3809. These objects were originally defined from their optical spectra, as having the broad lines of type 1 Seyferts but with some of the narrowest widths ever seen for these lines. They may be a special subset of Seyferts, or perhaps ordinary Seyferts seen from a particular direction such as along the pole of a disk-shaped gas structure. For these data, statistical error bars are indicated on each measurement to indicate how significant these huge changes are.
Several Seyfert galaxies have been the subjects of intense spectroscopic campaigns to enable reverberation mapping of their nuclei. This approach uses the notion that any change in the ionizing continuum source will be reflected in the emission-line gas, after a delay that corresponds closely to the extra light-travel time from the nucleus to each gas parcel and then on to us compared to that directly from the nucleus. The data here are from a series of IUE observations of NGC 5548, (DATES) with the continuum measured at three ultraviolet wavelengths compared to three strong emission lines which have very different ionization levels and so might be expected to arise in quite different regions. The continuum is most variable in the deep ultraviolet, as can be seen by comparing the three continuum bands. The Lyman alpha and C IV emission lines follow the continuum changes closely, indicating that they come from areas a few light-days in extent, while Mg II hardly changes at all, coming from a region at least light-months in radius. More sophisticated modelling suggests that the shapes as well as sizes of these regions differ as well.

The BL Lacertae data were retrieved via the WWW archive of the University of Michigan's Radio Observatory, which has operated a long-running program of monitoring variable radio sources with NSF support. The ROSAT data for IRAS 13224-3809 were provided by Thomas Boller, and were described by Boller et al. in MNRAS 289, 393 (1997). The NGC 5548 continuum and emission-line light curves are from the International AGN Watch, and can be retrieved from their WWW site at Ohio State University supported by Brad Peterson.

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A Selection of Seyfert Galaxies

This montage uses ground-based wide-field images to exhibit the variety of types and environments in which Seyfert are found. Of these, IC 4329A, NGC 3516, and Markarian 279 are type 1 Seyferts, NGC 3786 is an intermediate "type 1.5" nucleus", and NGC 5728 and NGC 7674 are type 2 objects. This set includes fairly isolated galaxies (NGC 3516 and 5728) as well as several undergoing gravitational interactions with close neighbors, which has been widely suspected of contributing to the Seyfert phenomenon. IC 4329A is found in a rich cluster, with a giant elliptical galaxy seen in the field. This galaxy is noteworthy for being among the handful of known Seyfert galaxies seen edge-on, where the brilliant nuclear radiation manages to be attention-getting even after passing through the galaxy's entire dusty disk. NGC 3786 is interacting with its neighbor NGC 3788, as seen both from the plume of stars ejected from NGC 3788 and the asymmetric disk of NGC 3786 itself. Markarian 279 is part of a small group of galaxies, as is NGC 7674; this galaxy is in the midst of a complex interaction as shown by its two long, thin tidal tails stretching across the image. All these galaxies show the characteristic intense, pointlike nucleus originally remarked for this class by Carl Seyfert. The galaxies' Hubble types are also representative for Seyfert galaxies as a group, dominated by early-type spirals (Sa and Sb, with both barred and nonbarred representatives) and S0 systems.

These are V-band images taken using a Texas Instruments CCD at the 1.1-m Hall telescope of Lowell Observatory, described in detail by Keel in the Astronomical Journal (vol. 111, p. 696, 1996). All have north at the top and east to the left except NGC 3786, which has north to the right to fit in the montage.
The areas shown range from 2.0x3.5 arcminutes for Mkn 279 and NGC 7674, through 3.5 arcminutes square for NGC 3516 and 5728, to 3.5x4.7 for IC 4329A and NGC 3786. A logarithmic intensity mapping was used to enhance the visibility of both bright and faint structure.

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Closeup views of Seyfert nuclei from HST

Seyfert galaxies were originally noted as having unusually bright, compact (starlike) nuclei. The surroundings of this brilliant nucleus can take a variety of forms, perhaps carrying clues to how the central engine is fed or triggered. Some of these are shown in this selection of closeups taken with the high-resolution Planetary Camera (PC) CCD on HST's Wide Field Planetary Camera 2. Some of these nuclei are surrounded by either tight rings or annuli of star formation (NGC 1019, NGC 7469), and others show intricate dust structures around the nucleus that are not apparent from ground-based images (NGC 3516). The spiral pattern around the nucleus of NGC 3393 comes from ionized gas, rather than stars, and is excited to shine upon absorption of the intense ultraviolet light from the nucleus. Markarian 1376 shows a cone of gas similarly illuminated by the nucleus; any counterpart on the other side is hidden by the prominent absorbing dust in the galaxy. The closeup of IC 4329A shows that we see its nucleus just through the edge of dust farther out in its disk. In many of these, the nuclei are strongly overexposed to show the surrounding galaxy, producing diagonal diffraction spikes and other image artifacts.

These images are from the inner part of the high-resolution Planetary Camera CCD in the WFPC2 on HST, covering regions 9.1 arcsecond square. The data are from Matt Malkan's "snapshot" program,
which delivered short red-light exposures of numerous active galactic nuclei. The arrow indicates the
direction of north. A logarithmic intensity scale was used to show the fainter surrounding structure; the
nuclei themselves are so bright that they saturated even these short exposures, and in some cases charge
bleeding produces linear artifacts from the nuclei. The data are described by Malkan, Gorjian, and Tam

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Seyfert galaxies were originally noted for the strength and broadening of their emission lines, and as a class were later characterized by the high ionization states of many of the atomic and ionized species producing these lines. This composite spectrum of the archetypal Seyfert NGC 4151 shows the wide variety of emission lines present, from the Lyman limit at 912 Å to the mid-infrared at about 9 microns. It uses spectra taken with apertures several arcseconds in size, so as to reproduce the usual spectrum mixing broad and narrow-line components. From 912-1800 Å, the data come from the Shuttle-borne Hopkins Ultraviolet Telescope; from 1800-3200 Å, from the mean of three measurements by the International Ultraviolet Explorer (IUE) taken at similar brightness levels; from 3200-4000Å, from an observation at Kitt Peak National Observatory, with the continuum rescaled to match the adjacent spectra; from 4000-8000 Å, a CCD observation obtained at the Lick Observatory 3-m Shane telescope by Alexei Filippenko; from 8000 Å to 1 microns, an observation using the same telescope by Donald Osterbrock and collaborators, carefully corrected for atmospheric absorption; from 0.9-2.4 microns, measurements by Rodger Thompson at Steward Observatory’s 2.3-m Bok telescope, and on into the infrared, from the Infrared Space Observatory provided by Eckhard Sturm. Because NGC 4151 is irregularly variable, some of the spectral components have been scaled to make the various pieces match for this presentation (so the relative strengths of lines in very different spectral regions may not be accurate). Even so, I may not have gotten the IUE data spliced in quite right between the HUT and
Some of the most prominent emission lines are marked for reference. The permitted lines - those that can be produced at high densities by astronomical standards - show both broad and narrow components. The strongest of these are the hydrogen recombination lines, such as Lyman alpha at 1216 Å, H-beta at 4861, and H-alpha at 6563, plus the strong ultraviolet lines of C IV at 1549 and Mg II at 2800. Other features produced only by very rarefied gas at densities of 1000 atoms per cubic centimeter or so - the forbidden lines, denoted by brackets - arise in regions with less velocity structure and are narrower. Some strong examples are [O III] at 4959 and 5007 Å, [O II] at 3727, [Ne V] at 3426, and [S III] at 9060 and 9532.

NGC 4151 is a bit unusual in showing strong absorption in several lines, especially Lyman alpha and C IV. The absorption is blueshifted with respect to the line centers, so that it arises in some kind of wind or other gaseous outflow.

The spectra of active galactic nuclei are noteworthy in showing species with a large range in ionization at once, from neutral ions such as [O I] and [N I] to highly ionized cases such as [Ne V] and [O VI]. Even hot stars such as light up gaseous nebulae in our galaxy cannot ionize gas as highly as these ions require, so that both a strong source of hard radiation and a wide range in gas density must be present to see such spectra.

The deep-UV HUT data were provided by Gerry Kriss, as described by Kriss et al. 1995, ApJL 454, L7. Between 1800 and 2500 Å, the mean of three IUE spectra at similar brightness levels was used, while an HST FOS spectrum is shown between 2500 and 3300 Å. From there to 4250 Å, I used a spectrum I took at Kitt Peak National Observatory adjusted to the mean brightness of neighboring pieces, and from 4250-8000 Å the plot shows an observation by Alex Filippenko taken at the 3-m Shane telescope of Lick Observatory. From 8000-9900 Å, data from the same telescope by Osterbrock, Shaw, and Veilleux (1990 ApJ 352, 561) are shown, adjusted to match the variability stage of the neighboring optical data; their reduction included careful accounting for the complex absorption that our own atmosphere produces in this range. So did the infrared echelle spectrum by Thompson (1995 ApJ 445, 700) using the 2.3-m Bok telescope at Steward Observatory, shown from 1.0-2.4 microns, which I have done a grave injustice by averaging and degrading in resolution to make this plot more easily legible. Finally, the remaining infrared data are from an ISO observation provided by Eckhard Sturm. ISO scanned the wavelengths of strong emission lines in great detail, but skipped most of the intervening wavelengths, accounting for the blocky appearance of the deep infrared spectrum.

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One of the most curious of Seyfert's original sample of galaxies remains NGC 1275, which has some of the properties associated with Seyfert nuclei, radio galaxies, and even BL Lacertae objects. One of its oddest properties is this extensive system of ionized gas filaments, which has variously been interpreted as evidence for an explosive outflow, slow inflow as gas in the surrounding cluster of galaxies cools, and even for heating by a high-speed collision with another galaxy. This image provided a wide-angle contrast to the following HST view.

This CCD image was obtained using the 4-m Mayall telescope at Kitt Peak with the Cryogenic Camera,
through a narrow-band filter emphasizing the emission line at the redshift of NGC 1275 itself (thus rejecting gas in the foreground high-velocity system). The field of view is 2.6 arcminutes across. Details were provided in Keel, AJ 88, 1579 (1983).

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An HST view of the enigmatic spectacle
NGC 1275

What's going on here? In fact, how many different things are going on here? NGC 1275 has been called, at various times and not always by different astronomers, a Seyfert galaxy, radio galaxy, and even blazar... Carl Seyfert listed it in his 1943 paper on the galaxies now bearing his name, and NGC 1275 has long been an oddball among bright Seyferts - whatever the host galaxy is, it is distinctly not a spiral. It is a strong radio source (3C 84), and shows variability that has occasionally been attributed to seeing a BL Lacertae-like object "off the beam". Adding to the confusion, there is clearly something rich in gas and dust in front of NGC 1275, though the interloper's redshift is 3000 km/s higher than that of NGC 1275 itself. It shows up as a network of dusty patches with some associated blue star clusters in this view, and can also be detected absorbing radio emission at certain frequencies from the nucleus itself (it is the absorption which guarantees it to be in front of NGC 125 and its active nucleus). In the rich environment of the Perseus cluster of galaxies (Abell 426, which is more or less centered on NGC 1275) such high velocities might rarely occur as galaxies mill around in their mutual gravity, but the foreground object looks, if anything, like a skeletal view of a spiral or irregular galaxy, which are virtually absent in the Perseus cluster. Despite the fact that it hasn't yet actually hit NGC 1275, could this mystery object be related to the nuclear fireworks? And the cluster itself - does being centered in the slowly cooling and
shrinking central flow of hot X-ray gas have anything to do with fuelling the monster in NGC 1275?

This is an excellent example of a galaxy rich in young blue star clusters - so bright that they have been termed super star clusters. Such clusters are often linked to galaxy collisions and mergers, an interpretation strengthened in this case by the ripples superimposed on the smooth stellar distribution of NGC 1275. If NGC 1275 has been involved in a major accident, is this also responsible in some way for the pronounced activity at the nucleus itself?

This color composite is from exposures at 4500 and 7500 Angstroms with WFPC2 obtained on 16 November 1995, with total exposures 1-1.5 hours. This was part of the instrument team's observing program led by J. Trauger. The dark cross or windowpane pattern shows the boundaries of the field of view of each of the WFPC2 individual CCD chips; their edges don't mesh perfectly in a mosaic without some loss of light. The effect becomes noticeable when a large object like NGC 1275 fills most of the field.

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A hidden AGN - infrared images of IC 5063
While many active nuclei announce their presence from a tiny, intense source of blue and ultraviolet light, some are hidden from our view by intervening dust - either surrounding the central engine or happening to lie somewhere else in front of it. Sometimes we have a clue to its existence, by seeing the effects of a strong source of ultraviolet and X-radiation on surrounding gas. IC 5063 exemplifies this situation, being known from optical observations as a type 2 Seyfert galaxy. This series of near-infrared images from NICMOS and the Hubble Space Telescope unveils a bright, heavily reddened central source. The absorbing effects of dust drop rapidly at longer wavelengths, as can be seen from the dust structure visible at the shortest wavelength (1.1 microns) and invisible at 2.2 microns. Only the flattened central concentration of stars appears at 1.1 and 1.6 microns, but at 2.2 microns, a brilliant central source appears. The source is bright enough to show diffraction rings, easily seen since the size of the diffraction pattern limiting the camera's resolution grows with wavelength. The investigators suggest that this infrared source may still not be the nucleus proper, but the immediately surrounding dust emitting at the high temperatures produced so close to the central object itself.

Data courtesy Varsha Kulkarni (Univ. of Arizona), Daniela Calzetti (Space Telescope Science Institute), STScI NICMOS Team, NICMOS Instrument Definition Team, and NASA. Their analysis was published in the Astrophysical Journal Letters 492, L121, 1998. The images have long dimensions of 19.2 arcseconds and are oriented with north at about 27 degrees clockwise from the top.
The interaction of jets and clouds in NGC 4151

These images both depict the same area - the region of ionized gas around the nucleus of the bright Seyfert galaxy NGC 4151. In one case, the observations used a narrow-band filter to isolate the bright gaseous emission of doubly ionized oxygen - [O III] - at 5007 Angstroms, while the other used a diffraction grating to spread the light at each point into a spectrum. The color coding was used to indicate this and to show the direction of spectral dispersion, though the wavelength range spanned by the observation would not produce a vivid color range visually. The brilliant nucleus is spread into a horizontal line, producing radiation at all wavelengths in the form of a continuum. In the dispersed image, a single cloud of gas with small internal motions will have a single Doppler shift, and will have the same appearance as in the filtered image, perhaps with a position shift due to its overall Doppler shift with respect to the average. However, a parcel of gas with a large velocity dispersion, such as one might see in a turbulent situation or near a shock front, will be preferentially smeared along the wavelength direction (left-right in this depiction). Careful comparison of these two images shows that there are many such regions, mostly located in the locations close to where the galaxy’s small radio jets emerge from the nucleus. These radio jets lie approximately along the axes of the twin emission-line cones. This connection between rapid local gas motions and the emerging jets has been interpreted as evidence that much of the "turbulent" motion in the outer regions of Seyfert nuclei is powered by the radio jets, as they
transfer energy to their surroundings.

The emission-line image shows clearly the biconical region where most of the ionized gas appears, in support of a `beaming picture" for the various kinds of Seyfert nuclei. It poses an interesting puzzle, however, because to get this plan view we must be outside the cones, but we see the broad-line region and thus classify NGC 4151 as a type 1 Seyfert - in fact, it was the prototype of the class. Thus, there are directions outside these cones where we can have a fairly clear view of the core, so the simple mental picture of a solid torus and clear views along its axis cannot be taken quite literally.

These data were among the earliest taken with the Space Telescope Imaging Spectrograph (STIS), installed on the Hubble Space Telescope in February 1997 by the crew of the space shuttle Discovery during STS-82. These data are courtesy of John Hutchings, with a full discussion published by Hutchings et al. in Astrophysical Journal Letters 492, L115 (1998). Normal astronomical practice involves using a narrow slit to limit the area of sky being investigated and so avoid confusing overlap between spectra of different areas, but in a case like this of structure in a single strong emission line, slitless spectroscopy such as this may be very revealing and much less time-consuming than mapping the whole object with narrow slit locations. These images show a region about 12" top-to-bottom, corresponding to roughly 750 parsecs (2500 light-years) at the distance of NGC 4151.

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Measurements of the polarization of the light near the nucleus of NGC 1068, a nearby and prototypical type 2 Seyfert, provided strong evidence that it actually contain a type 1 nucleus which is blocked from our direct view by an obscuring ring or torus of material. The nucleus produces a radio jet at right angles to this hypothesized torus, which must lie almost at right angles to the galaxy's disk plane. Recent VLBI observations may have detected this torus, as shown in this montage. HST images are used to show the galaxy as a whole and the conelike illumination pattern of highly ionized gas which must see the nucleus directly, then the radio jet and finally a tiny structure which has the right size, orientation, and temperature to be the obscuring disk. If this in fact the obscuring material, this is an important piece of evidence for the unified scheme for Seyfert galaxies. This is simply the notion that many type 2 Seyferts would be type 1 objects if we could see them from the proper direction, nearly along the axis of the torus so that our view is not blocked. These special directions are often marked by both radio jets and cones of intense radiation, which we see either as they ionize ambient gas or are reflected from clouds rich in dust that happen to lie within the cones.
The radio data include a VLBI image from 10 elements of the VLBA plus the phased VLA for the inner torus and a MERLIN observation of the radio jet, provided by Jack Gallimore and discussed by Gallimore, Baum, and O'Dea in Nature 388, 852 (1997). The optical images are from HST, including the FOC image of the inner emission region that was released publicly immediately after the 1993 servicing mission.
A crucial development in understanding Seyfert galaxies came with the recognition that at least some type 2 Seyfert nuclei are in fact type 1 objects for which our view of the innermost region is blocked by a dust- and gas-rich obscuring torus. The key observations involved measurements of polarization - the fraction of the energy carried by light waves with the electric and magnetic fields oriented in various directions. Light may be polarized in several ways, the most familiar of which is by scattering or incoherent reflection - the way polarizing sunglasses work. In NGC 1068, combination of polarization and spectroscopic measurements (spectropolarimetry) produced the remarkable fact that the polarized light from the nucleus resembles a type 1 Seyfert, complete with broad Balmer lines of hydrogen and forests of blended Fe II emission at 4500 and 5300 Angstroms, while the ordinary intensity spectrum is the original type 2 with virtually no Fe II and much narrower hydrogen lines. This was interpreted as coming from dusty clouds that are placed directly in the radiation field of the nucleus, so that we see the nuclear light scattered by dust. A striking confirmation that the nucleus is responsible comes from an HST measurement of the polarization at every point near the nucleus. Shown as electric-field direction vectors superimposed on the image, they show the characteristic pattern of concentric arcs which results
from scattering by a source in the center, and points to the same center as the radio jets and tracing backwards from the conical distribution of ionized gas around the nucleus. Recent radio observations may have in fact seen the obscuring material (slide 11).

The spectropolarimetry is taken from Miller, Goodrich, and Mathews 1991 (ApJ 378,47), with the data provided by Bob Goodrich. The HST imaging polarimetry came from Capetti et al 1995 (ApJLett 452, L27), and was kindly provided by Alessandro Capetti.
Radio structure in radio galaxies

Radio galaxies are best known for their extensive double radio sources, shining by synchrotron radiation as electrons spiral through magnetic fields at relativistic speeds. These objects show a remarkable variety of forms and symmetries, as shown in this montage of radio images of radio galaxies. These are of so-called Fanaroff-Riley (FR) type I, with radio lobes decreasing smoothly in intensity outwards from the central source - for the contrasting case of an FR II source, see the Cygnus A slide. Ordinary, symmetric double structure is seen in Fornax A, 3C 219, and 3C 285. Hydra A (3C 218) exhibits an interesting corkscrew form, sometimes seen as suggesting a long-term precession of the jets feeding outwards from the nucleus, while 3C 449 shows a very long and extended set of helical twists more or less symmetric about the core. The radio source of 3C 315 is so tightly twisted that it takes on the shape nicknamed by Jacques Vallee and his Francophone collaborators as Papillon - the butterfly.

In each case, the optical galaxy spans only a small part of the range of the radio source. In Fornax A, it fills the gap between the two lobes, and in the other cases the visible galaxies are much smaller compared to the radio source extent.

Data for Fornax A, 3C 285, 3C 315, and 3C 219 were taken from the "Images from the Invisible

Universe" CD-ROM distributed by NRAO. Of these, all but 3C 219 are VLA maps at 21 cm, while 3C 219 was mapped at 11 cm using the interferometer of the Mullard Radio Astronomy Observatory in the UK. The Fornax A data were presented by E. Fomalont, K. Ebneter, W. van Bregel, & R. Ekers in ApJL 346, L17 (1989), and the data for 3C 285, 219, and 315 are from a study by P. Alexander and J.P. Leahy in MNRAS 225, 1 (1987). The data for 3C 449 span a 0.15-degree field and are from the NRAO VLA Sky Survey (NVSS) via WWW retrieval.

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One remarkable finding from HST images, barely anticipated from the ground, is that dust structures close to the nucleus are prevalent in radio galaxies. These structures often take the form of disks or rings, at right angles to the radio jets and thus fitting with the general picture of jets collimated by the influence of an accretion disk surrounding the central objects. These are far too large to be the active, hot accretion disk itself, which should extend to no more than light-months in radius, but may represent material which has already settled into its orbital plane and will eventually migrate inwards into such an accretion disk. These dust features are difficult to resolve from the ground, with diameters from 0.95 arcsecond in 3C 296 to 3.5 in 3C 449. These correspond to linear diameters of 170 parsecs (3C 272.1) to 3.7 kiloparsecs in 3C 285, so that we are seeing a wide range of physical phenomena. One common interpretation is that many of these galaxies have undergone mergers or strong interactions, so that new gas and dust has been introduced into the system, which we see as it settles into a disk around the central region of the radio galaxy, possibly fuelling the nuclear activity.

These are red-light (about 7000-Angstrom) images taken largely as part of a "snapshot" imaging program using the PC chip of WFPC2 on HST, provided by Stefi Baum and Andre' Martel. The areas shown here
are either 11.6 or 23.3 arcseconds on a side, with north in each case at the top. A logarithmic intensity scale is used to make detail visible over a wide brightness range. The scale bars indicate one arcsecond.

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High-redshift radio galaxies in the early Universe

Radio galaxies have been popular tracers of galaxy evolution, because they were long the easiest galaxies to pick out at high redshift - a faint galaxy with an associated radio source is more likely to be an intrinsically luminous galaxy far away than is a similarly faint galaxy without a radio source, most of which will be genuinely small and dim galaxies in the foreground. Indeed, radio galaxies have frequently held the record for highest known galaxy redshift. Detailed examination has shown that many of these high-redshift radio galaxies, seen when the Universe was half of its present age or less, have bizarre structures. They are very elongated, often consisting of chains of distinct clumps. This has led to serious questions about how representative they are of the galaxy population in general - is this appearance due to youth, the powerful radio source, or that fact that we are observing them preferentially in their own ultraviolet range?

This collection compares several radio galaxies from the 3C catalog as imaged with HST. The redshifts range from $z=0.635$ for 3C 337 to $z=1.575$ for 3C 68.2. All are shown to the same angular scale (the
transformation to linear scale depends heavily on what cosmological model is used. These images are all in the emitted ultraviolet, where seeing any bright structure in a galaxy marks it as unusual either in star formation rate or having a powerful active nucleus. Among these galaxies, the lowest-redshift examples of 3C 247 and 3C 337 are the most "normal", much like ellipticals in nearby cluster environments, while the higher-redshift objects such as 3C 368 and 3C68.2 are the strangest by our present-epoch standards.

The radio sources all have elongated structures with the brightest parts being twin lobes or "hot spots" of radio emission. It is a remarkable correlation for high-redshift radio galaxies that when the optical galaxy is elongated, it preferentially aligns with the radio source (the "alignment effect"), while there is no such tendency for nearby, lower-power radio galaxies. The radio lobes are just inside the area shown for 3C 247, 3C 266, 3C 280, 3C 337, and 3C 368, and well beyond it for 3C 68.2 and 3C 265.

All these sources are among the brightest radio sources in the sky at low frequencies, having been discovered in the Third Cambridge (3C) survey, revised and completed in 1962. This list was long the richest compilation of powerful and distant radio galaxies, despite being confined to such strong levels of observed radio brightness. These are among the most powerful radio sources in the Universe.

These data were provided by Philip Best and Malcolm Longair, as described in the paper by Best, Longair, and Roettgering, MNRAS 292, 758 (1997). The color images are composites based on images through V-band (5550 Angstroms) and near-infrared I-band (8500 Angstroms) filters plus a synthetic intermediate one, and represent the colors as seen in our observed reference frame. The part of the emitted spectrum we are seeing here ranges from blue (for the lowest redshifts) to ultraviolet at the highest redshifts.

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One important lesson from radio galaxies is that the central engine continues to eject material in nearly the same direction for at least several million years, based on the fact that the tiny parsec-scale jets in the core regions point in the same direction as the very extended radio structure which may stretch several million light-years (and thus took at least that many years to form). The nearby radio galaxy NGC 6251 is an excellent example. The largest structures are seen in a map made with the Westerbork Synthesis Array Telescope in the Netherlands, which can map somewhat larger objects than the VLA, working in this case at a wavelength of 49 cm. This image spans almost a full degree (56 arcminutes) east-to-west. Closing in toward the nucleus are two maps made with the VLA at 20 centimeters wavelengths, showing the extraordinary straight and narrow jet feeding toward the northwest radio lobe, spanning 308 and 188 arcseconds. Finally, the innermost core is shown in a VLBI map with a resolution of only 3 milliarcseconds (0.003 arcsecond), showing that knots are still moving outward from the nucleus in nearly the same direction. The VLA and VLBI maps have been rotated to make the jet horizontal for
convenience. The WSRT map shows the faint counterjet opposite the bright jet; its weakness may indicate that the jet is in relativistic motion more or less toward us, so that Doppler boosting makes it appear dramatically brighter than its counterpart.

The Westerbork data were provided by Karl-Heinz Mack, as presented by Mack, U. Klein, C.P. O'Dea, and A.G. Willis 1997 A&AS 123,423. Rick Perley furnished the VLA data, and Dayton Jones made his 11-station VLBI image available.
The first hint of the important role that ejection of matter can take from active nuclei came, in retrospect, in the discovery of the jet (described at the time as a "curious straight ray") on photographs taken with Lick Observatory's 0.9-m Crossley reflector in 1918. Its importance became clear only with the identification of M87 with the radio source Virgo A, and the recognition that many radio galaxies and quasars show jets with similar radio properties. However, none has emission in visible light remotely as bright as that from M87, and none can be easily studied in such exquisite detail. These structures are shown well in this composite HST image - the sudden broadening of the jet at its brightest knot, bright arcs resembling shock waves, and intricate helical patterns near the nucleus. Detailed comparison of
these images with radio observations should fill out our picture of where the jet particles get their energy and how fast they are moving outwards, two of the most important unknowns in studying the flow of mass and energy from active nuclei.

This image was provided by John Biretta. It is a color composite from stacked HST WFPC2 images in the near-UV and near-IR (at about 2900 and 8000 Angstroms), so the color mix isn't quite what a purely visual filter selection would produce. However, the color difference between the old stars dominating the galaxy and the bluer light of the jet (tending to violet in this rendition) is clear. The small objects scattered around the field of view are are a few of the thousands of globular star clusters in M87 itself.

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The supermassive central object in M87

Aside from its jet and radio structure, there has been special interest in the nearby radio galaxy M87 because it has long been one of the best candidates for detection of a supermassive black hole, perhaps in billions of solar masses. Confirmation of such an object would be a major development in understanding active nuclei, and would jump us well beyond the level of speculation otherwise required in dealing with them. Ground-breaking observations by Peter Young and collaborators published in 1978 showed that the motions of stars in M87 implied the existence of a central mass of several billion solar masses with no visible counterpart, easily interpreted as such a supermassive black hole. However, firm proof was elusive, since it was realized that there existed possible distributions of stellar motions which, although perhaps unlikely, could account for the M87 velocity observations without necessarily requiring a black hole. High spatial resolution is the key - the ability to isolate stars at a set of well-defined and small distances from the center without contamination from the light of stars elsewhere in the vicinity. HST provides this capability wonderfully. It turns out that M87 also has a conveniently rotating disk of gas, difficult to make out from the ground because so much else is going on in its vicinity, whose dynamics furnish strong evidence that there is indeed an enormous dark mass at the center.
This slide compares an emission-line image of this gaseous disk to a high-resolution spectrum obtained with the Faint-Object Camera on board HST, the only one of the original instruments which could deliver a fully two-dimensional spectrum in a single observation. The change in Doppler shift of the [O II] emission line at 3727 Angstroms is clear from both the spectral images and intensity crosscuts. A plot of the measured velocities compared to a model with a massive central object, including the blurring effects of motions very near the center, shows a very good fit with a central mass of 3 billion solar masses confined within a radius of 3.5 parsecs or less, which almost completely requires that this mass be a black hole. (Well away from the center, the orbital velocities around a point mass will show the Keplerian pattern of velocity falling as the inverse square root of distance, as seen for the planets in our solar system. Closer in, the measured velocities will drop as we see blends of material moving in various, and eventually opposite, directions within the same measuring aperture.) Final confirmation may come from observations with the new STIS spectrometer installed in 1997, which can track the Doppler shifts of stars as well as gas. Since interstellar gas can be moved by forces other than gravity (supernova explosions, shock waves, magnetic fields) the results from stellar motions, although much more difficult to obtain because they use absorption rather than emission lines, are considered definitive.

The FOC spectrum is shown both as an intensity image and as a set of crosscuts across the strong [O II] feature (which is itself a blend of two close emission lines). These cuts are evenly space every 0.14 arcsecond along the slit, and have been individually scaled in intensity for ease of comparison.

The HST FOC data were provided by A. Marconi and F. Macchetto, as detailed by Macchetto et al. in ApJ 489, 579 (1997). The H-alpha image is from an STScI press release in January 1997. The FOC spectrum samples the sky at 0.028-arcsecond intervals, preserving the full angular resolution of the refurbished HST optical system.

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Beyond the jet of M87, discovered in 1918, optical detections of further jets had to wait almost half a century. The next brightest ones are a hundred times dimmer, although there are plenty of radio jets to examine. Apparently the optical radiation, from relativistic electrons spiralling at nearly the speed of light through the jets' magnetic fields, require unusually high energies or special conditions to appear, compared to the ubiquitous radio jets. A handful were detected from ground-based images, and several more have been found (often serendipitously) during analysis of HST observations. Four of the clearest examples are shown here.

PKS 0521-36 was first detected from the ground, and appeared somewhat like a larger, more distant version of M87 - complete with a bright knot at the same radius within the galaxy. The HST image shows the knot in detail. In 3C 275 (NGC 3862), the optical jet was serendipitously discovered by Phillippe Crane and colleagues in 1993; radio observations again show an excellent structural match. The other two - 3C 15 and 3C 78 - are both HST discoveries, with 3C 15 just submitted for publication at this writing. For PKS0521-36 and 3C 264, an additional image is shown after subtracting a model for the galaxy's starlight and adding pseudocolor to enhance some of the details.
These HST images were provided by Stefi Baum and Andre’ Martel. Each was a red-light exposure in the high-resolution PC CCD of the WFPC2 camera system. North is at the top for each, and the upper and lower rows have different scales as indicated.

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The powerful radio galaxy Cygnus A

This is the most powerful radio galaxy on our corner of the Universe, used as a point of departure for studying radio galaxies at great distances. At a redshift z=0.0565 (distance of about 211 Mpc or 700 million light-years), its nature remains mysterious enough. The first photographs of Cygnus A showed two clumps of luminous material, which led Walter Baade and Rudolph Minkowski to speculate that the radio emission was somehow linked to a galaxy collision. Others saw a poorly resolved version of Centaurus A, bisected by a thick dust lane. The HST image shown as an inset reveals much detail, but doesn't quite clear the matter up. We see dust and an odd Z-shaped pattern. Much of this light in some regions comes not from stars, but from gas ionized by the nucleus. This is a narrow-line radio galaxy, but infrared and polarization measurements show that from some directions it would appear as a broad-line object and perhaps as a quasar, so that there is plenty of radiation in some directions to light up the gas.

Cygnus A is an excellent example of the Fanaroff-Riley (FR) type II radio sources, characterized by faint, very narrow jets, distinct lobes, and clear hot spots at the outer edges of the lobes, often where the jets intersect the outer edges. These are in general more powerful radio sources than the FR I objects seen in slide 13, with the difference being frequently attributed to faster (relativistic?) motion of the jet material in the stronger FR II sources. The radio/optical overlay highlights the extent of the radio source

beyond the central galaxy, extending 140 kpc (500,000 light-years) if we see it sideways.

Bob Fosbury provided the HST color composite image. The wide-field optical image was taken with the 0.9-m telescope at Kitt Peak National Observatory, courtesy of Frazer Owen (as described by Owen at al. 1997 in ApJLett 488, L15). The VLA map is from the NRAO CD-ROM "Images from the Invisible Universe", as presented by Perley, Dreher, and Cowan 1984 (ApJLett 285, L35). For the overlay, both optical and radio images were displayed with logarithmic intensity scales.

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With ground-based telescopes, quasars are typically boring until you measure their spectrum. As a pretty typical example, this is the radio-loud quasar PKS 1117-248 at redshift z=0.466. I marked it to reduce puzzlement - this image shows why various subterfuges involving radio emission, X-rays, colors, or spectra are needed to pick out quasars wholesale from foreground stars. Even at this modest redshift, there's not much of a host galaxy or surrounding group visible to make it stand out.

This is a red-light CCD image taken with the 3.6-meter telescope of the European Southern Observatory. The image covers an area 2.9 by 2.9 arcminutes. The limiting magnitude is about R=23.5.
The first quasar identified and the brightest in apparent magnitude, 3C 273 is unusually luminous for being so nearby, and has by far the brightest optical jet known among quasars. This montage illustrates its appearance on Palomar Sky Survey plates, where a hint of the jet appears; on an excellent ground-based image, showing not only the jet but the fuzzy glow of the giant host galaxy around the brilliant nucleus; and an HST images detailing the complex structure of the jet itself with the nucleus safely outside the field of view. This jet is unique in its complex structure, with extensions to the side at both ends that have no radio counterparts. Indeed, unlike optical jets seen in radio galaxies, there are major differences between the radio and optical structures of this jet.

Herman-Josef Roeser provided copies of his HST images of the jet and the ground-based image from the ESO New Technology Telescope (NTT) at La Silla, Chile. The jet image used WFPC2 and a near-IR I band filter, while the NTT image is a red-light exposure.

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Gravitational lensing was long predicted by Einstein's General Theory of Relativity - if gravity can be properly viewed as a bending of space produced by mass, then light rays should change their direction upon passing a massive object. In extreme cases, we might expect to see multiple images of the same object, formed by light that has gone around opposite sides of the intervening mass. The first examples of such lensing involved quasars, as the brightest objects seen at large distances. This is the first confirmed lensing case, the double quasar 0957+561. It was found while searching for counterparts of radio sources, when two candidates showed up only 6 arcseconds apart. In a 1979 paper, Dennis Walsh, Bob Carswell, and Ray Weymann showed both to be quasars with identical redshifts and spectra, which led them to speculate that this might be a gravitational lens. Shortly thereafter, observations from Mauna Kea and Palomar showed a luminous galaxy almost in front of one quasar image, and a surrounding cluster that could also contribute to the lensing.

This system has given us more to work with, in analyzing its properties and the mass of the lensing galaxies, than any other lensed QSO. Radio sources give the parity; lensing radius, and shear of the mass distribution, we probably have the time delay for light along the two distinct paths, and may even see
microlensing effects from stars in the central galaxy. These can in principle lead to a measurement of the Hubble constant and the characteristic masses of stars and substellar objects in this very distant lens galaxy.

This composite comes from a combination of 3 images each in V and I filters, showing the field of view of a single WFPC2 wide-field CCD centered on the QSO images (PI was George Rhee). Each individual image had an exposure time of 2300 seconds, and they were made into a color image using a synthetic intermediate color. This filter choice means that the galaxy colors in the foreground lensing cluster are as we would see them at the cluster (that is, implicitly correcting for the passband shifting from the cluster's redshift). These exposures were long enough to saturate the bright QSO images, so some bleeding of charge in the images appears. Also, the outer halo of blue light from the inner QSO image affects the lens galaxy's appearance in the blue.
Surely the most spectacular of the 12 or so well-attested instances of gravitationally lensed quasars involves a QSO and foreground galaxy, each of which is known only by its coordinate designation 2237+030 (one prefaced by Q, the other by ZW for the Zwicky catalog in which it was first listed). This system was discovered in the course of the redshift survey carried out at Mt. Hopkins by the Center for Astrophysics, resulting in observation of an unexceptional 15th magnitude galaxy (with a redshift \( z=0.0394 \)) whose nucleus showed the spectrum of a high-redshift quasar (\( z=1.695 \)). Higher-resolution images, from the best ground-based sites, later showed the configuration that came to be called the Einstein cross - four QSO images arrayed around the nucleus of the low-redshift galaxy.
It is especially remarkable that the quasar light suffers very little reddening from interstellar dust while passing so deeply through the foreground spiral; comparison with radio observations indicates that only one image, the faintest, shows evidence for measurable dust absorption. The alignment between the QSO and the galaxy is remarkable; models show that the QSO would appear within 0.05 arcsecond of where we see the galaxy's nucleus, if we could remove the galaxy's gravitational effect.

The image of the Einstein Cross is a composite of 5 WFPC2 images in the V band (5400Å), with exposures from 200-800 seconds, obtained under the instrument team's observing program with Westphal as PI. In orientation, celestial north is about 35 degrees counterclockwise from vertical. I tried to add color information from near-UV HST images (which show only the core of the galaxy), but the results were no more informative than this black-and-white depiction. The QSO images are notably bluer than the galaxy, but that's hard to see for bright sources against a much fainter background. The image is displayed logarithmically, so that the nucleus and QSO images can be distinguished along with the much fainter bar and spiral arms.

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Many studies of the number of quasars (including radio-quiet QSOs) show that there were many more at high redshifts than we see today. Many more, that is, up to a certain point at about 1/3 of the Universe's present age. Before that there are progressively fewer, a phenomenon known as the redshift cutoff. This is illustrated here using a smooth fit to data from a recent study by Peter Shaver and collaborators. The transformation from redshift to cosmic time uses the approximation of a low-density Universe; for simplicity; changing the amount of matter in the Universe alters the deceleration parameter, and thus the exact correspondence between linear time and redshift $z$. The number of quasars per unit volume must be examined in what are known as comoving coordinates - that is, with the expansion of the Universe factored out. Otherwise, whatever kind of objects we observe would show a cubic dependence on $(1+z)$ simply because they were more squeezed together at earlier times. Instead, quasars (and for that matter, radio galaxies) were actually much more common in the early Universe.

There have naturally been numerous speculations as to how this happened. Some suggest a link to galaxy formation, perhaps through the epoch when massive black holes were being fed most effectively. If galaxy collisions are the most efficient way to feed the monster, maybe this is when collisions and
mergers were most common. The redshift cutoff has been variously addressed as due to the formation of quasar cores or as a selection effect - might we have trouble seeing quasars at higher redshifts, because of the accumulated effects of dust in foreground galaxies that are individually too dim for us to see? At this point, probably not, but the improving access and sensitivity of infrared observations should soon be able to tell us with certainty. For now, I left a question mark back there at the start of our knowledge of quasar history.

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Anomalous QSO/galaxy associations and the redshift controversy

Much of our understanding of quasars in particular hinges on our knowing their distances and luminosities. Some astronomers have repeatedly suggested that quasar redshifts are different from ordinary galaxies, and that they may have some redshift component due to their peculiar physics and not to the expansion of the Universe. Their arguments have hinged largely on whether we see more close associations between quasars at large redshifts and galaxies at small redshifts than we would expect by chance. This montage shows the kinds of association under discussion.

The case of ESO 1327-206 and the quasar PKS1327-206 is one of the most flamboyant examples. The galaxy (at redshift $z=0.018$) is obviously disturbed, sporting loops, a long tail to the north, and knotty rings going over the poles of the inner region of the galaxy. The quasar (redshift $z=1.170$) is seen (at least in projection) along one of the loops (though not actually at one end; the loop can be seen to make a full circle). The apparent loop in the tail near the top is actually a reflection of a bright star outside the field of view. The other case is of the QSO PKS 2020-370 at $z=1.048$ and the galaxy group Klemola 31. Both spiral and elliptical galaxies are present close to the quasar line of sight, at $z=0.0288$. In both of these instances, absorption lines close to the galaxies' redshifts are seen against the quasars.

These are composites from BVR CCD images taken with the EFOSC system at the European Southern Observatory's 3.6m telescope at La Silla, Chile. Some of the stars have colored edges on one side due to
slight focus shifts during the observations.
All quasars at high redshift exhibit huge numbers of narrow absorption lines starting at the wavelength of the quasar's own Lyman alpha emission line and extending blueward. These are Lyman alpha absorption from foreground structures, in which the quasar light probes an otherwise invisible component of cosmic gas. This component evolves strongly with cosmic time, since we see dramatically more absorbers (be they clouds, filaments, or even crowding in velocity rather than in space) toward higher redshifts. However, they have not completely disappeared. When the launch of HST provided the first capability of measuring Lyman alpha at low redshifts to the required accuracy, it was found that a few of these absorbers remain in the local Universe. They are generally but not specifically associated with galaxies - for instance, 3C 273 lies behind the Virgo cluster of galaxies, and has a couple of absorbers in the cluster's redshift range, but they cannot be cleanly identified in position and redshift with specific neighboring galaxies. The evolution of the Lyman-alpha forest may be intimately connected with the history of galaxy formation.

This panel compares two quasars at very different redshifts, 3C 273 at z=0.158 and 1422+2309 at
z=3.62, shifted to a common scale in emitted wavelength. The strong and broad emission peak is Lyman alpha, which is almost chopped in half by the onset of the Lyman alpha forest in the high-redshift quasar. At low redshift, 3C 273 shows only a handful (but distinctly more than zero) Lyman alpha absorbers, including the strong and broad absorption from its light intercepting the disk of a foreground spiral galaxy (ours). Our galaxy also produces absorption in the C IV lines around 1550 A, which appear at 1337 A in the quasar's emitted frame. Hundreds of lines can be identified in the spectrum of 1422+2309, with the densest concentration near the quasar redshift - this is a very general feature showing how the density of Lyman alpha absorbers decreases with cosmic time. An increase appears again crossing 1026 A as the corresponding Lyman beta lines appear as well as new Lyman alpha lines.

The 3C 273 data are the average of two pre-refurbishment exposures totalling 49 minutes with HST's Faint-Object Spectrograph. The spectacular data for 1422+2309 come from 7-hour Keck I HIRES spectrum at resolution of 6.6 km/s, which comprised 94,000 spectral pixels in the original data provided by Mike Rauch. The data have been averaged down to more closely match the 3C 273 results, and make the graph a little more legible.

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An absorption-line galaxy in front of the quasar 3C 196
Not only disembodied hydrogen clouds can be found producing absorption in the spectra of QSOs - bona fide galaxies do as well, and produce quite different signatures. They produce broader and stronger hydrogen absorption, plus in many cases from heavier elements such as carbon and magnesium (the so-called metal-line systems). This example was first discovered as an absorption in redshifted 21-cm hydrogen radiation, implying a redshift $z=0.437$ for the foreground object. Recent HST images show that the foreground object is a clear barred spiral galaxy. Detailed radio studies show that the hydrogen is located not in front of the quasar core, but in front of the extended radio structure which indeed lies partly behind the galaxy's disk and spiral arms. The galaxy is at about half the quasar's distance in this case - the redshifts are $z=0.437$ and 0.871.

The H I profile was measured with the NRAO 43-m radio telescope at Green Bank, West Virginia, as observed by R. Brown et al. (ApJ 329, 138, 1988). The HST image was taken with WFPC2 in a filter centered near 7000 Angstroms; this frame shows a 25-arcsecond region centered on 3C 196, with a total exposure time of 20 minutes. The images were retrieved from the HST archive, originally obtained as part of the GHRS instrument team's observations and reported by Cohen et al (ApJ 456, 132, 1996).

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The search for the galaxies that quasars are imbedded in - the host galaxies - was long thought to be important, first, for establishing whether quasars are in fact as distant and luminous as we think they are, and second, for clues as to what can produce such an energetic phenomenon. By definition, typical ground-based telescopes don't see the surrounding galaxies against the quasar's intense light - if they did, we'd call it a Seyfert nucleus instead of a quasar. Impressive progress had been made from the best ground-based sites before the advent (and refurbishment) of HST, showing that many low-redshift quasars (the ones where we might expect to see a surrounding galaxy peeking around the edges of the blurred nuclear light) do in fact have fuzzy glows about the size and brightness of a decent galaxy, and in some cases it was even possible to measure the redshift of the surrounding galaxy from spectral features produced by their constituent stars. It had thus been established that many quasars do live in recognizable galaxies.

In most instances, though, the detection and detailed study of quasar host galaxies awaited the sharp images from HST, which could separate the brilliant nucleus from the faint glow of its host galaxy far more accurately than any other instrument. These images have revealed a great variety in size,
brightness, and form of the galaxies. At one point there was a popular scheme, based on observations of
nearby radio galaxies and Seyfert galaxies, suggesting that radio-loud quasars would live in elliptical
galaxies and radio-quiet ones would be found in spirals. Only one part of this really works - radio-loud
objects don't seem to be found in spiral galaxies. However, radio-loud and radio-quiet objects can be
found in elliptical galaxies or merging systems, so the distinction isn't as clear-cut as we might have
liked. One important pattern has emerged - a striking tendency for quasar host galaxies to have
extraordinarily compact, close companion galaxies, which may fit with reports of a tendency for Seyfert
and radio galaxies to show more signs of interaction than would be expected from chance.

The arrangement of objects here is intended to show parallel kinds of galaxies for radio-loud and
radio-quiet QSOs where they have even found - including ellipticals, ellipticals with compact and close
companions, and merging systems. The bottom two, spiral galaxies around radio-quiet nuclei, are not
(yet) known to have counterparts for radio-loud quasars, so that this much of the analogy with Seyferts
and radio galaxies seems to hold true. The objects shown here are at redshifts from $z=0.155$ (PG
0052+251) to $z=0.371$ for 3C 351.

Most of these data are from HST observations by John Bahcall, Sofia Kirhakos, and Donald Schneider,
published in Astrophysical Journal 479, 642 (1997). They have subtracted a model for the quasar's own
light in each case, based on observations of stars with the same filters, so that the much fainter
surrounding details are more obvious. Using a contrasting approach centering on the higher resolution of
the PC CCD, Peter Boyce and Mike Disney provided their image of 3C 351 as published by Disney et al.
(Nature 376, 150, 1995). All are shown at the same angular scale, which for most of the quasars
 corresponds to a similar linear scale since they are concentrated at redshifts $z=0.15$ to 0.20.

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The superluminal radio source in the gamma-ray blazar 3C 279
One of the greatest surprises provided by very-long baseline interferometry (VLBI) observations was the fact that some quasars, radio galaxies, and BL Lacertae objects exhibit motion along their jets which works out to several times faster than light. Motion of material at such velocities is forbidden by relativity (which otherwise checks out perfectly, to the chagrin of some diehard science-fiction fans), but relativity also provides a way in which we can see such blobs appear to move faster than light (that is, superluminally). If we see a train of objects moving close to the speed of light and moving almost exactly toward us, tracking the apparent position in our time frame will make them appear to move sideways much faster than they actually do. And the sources with superluminal motion are typically just those most likely to be pointed toward us - they are bright because of Doppler boosting, and there also seems to be a connection between strong gamma-ray emission and superluminal radio structure. This series of VLBI images, with pseudocolor intensity coding to make the structures easier to see, follows the quasar or blazar 3C 279 over a three-year period. The prominent outer knots are moving with an apparent speed of 4c, typical for superluminal sources.

Just what we are seeing here remains unclear. Some objects show twisted paths for the emerging knots, fitting with theoretical expectations that material may move along helical twists (driven by instabilities in the jets and their imbedded magnetic fields). This montage may show some support for this idea, with complex structure changing rapidly between the brightest knots. It is also unclear whether the knots that we see are physical objects, clumps of gas moving together along the jet, or bunchings of material in which the constituent matter constantly changes, as we see in waterfalls and waves.

These images were provided by Ann Wehrle and Steve Unwin, described in a paper in press in the ApJ by Wehrle et al. They have been rotated by 30 degrees to make the jet horizontal, and vertically displaced according to the date of observation. The observations here were taken from 1991-1994; more recent regular monitoring has been done with the VLBA. The resolution is about 0.2 milliarcsecond, corresponding to about 2 light-years at this distance. These data were obtained at a frequency of 22 GHz (wavelength 1.3 cm).

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William C. Keel

Bill Keel makes a hobby of getting photons wherever he can, having made appearances at Kitt Peak, Cerro Tololo, La Palma, La Silla, the MMT, the 6-meter Bolshoi Teleskop Azimutal'nyi, the IRTF, and the VLA. He has slowly becoming multispectral, using data from Voyager 2, IUE, IRAS, Einstein, ROSAT, ISO, UIT, and HST. These data support studies of the effects of interactions on galaxies, the history of galaxy merging, triggering of star formation and nuclear activity in galaxies, and too many other projects that have struck his fancy. In the more socially respectable part of his job, he teaches at the University of Alabama; mostly introductory astronomy courses with occasional forays into extragalactic astronomy and observational techniques at the graduate level. Unlike many professional astronomers, he got his start in the back yard many years ago and retains a soft spot for eyeballing the Universe.

Education:

- B.A., Vanderbilt University 1978
- Ph.D., University of California, Santa Cruz 1982
Places I've been since then:

- Kitt Peak National Observatory (1982-1985)
- Sterrewacht Leiden, Netherlands (1985-1987)
- University of Alabama, Tuscaloosa (since 1987)

Research Interests:

Galaxies: their interactions and evolution. Active galactic nuclei, extragalactic jets.

Now for the stuff you are probably here for:

Some of my research interests:

High-redshift galaxies  Dust in galaxies  Galaxy interactions

- Intro astronomy course resources
- Current publication list
- PostScript preprints
- Travel status (Where is he?)
- Useful data files
- Link to my pretty-picture collection
- WWW slide gallery on quasars and active galactic nuclei
- Science/religion article from Mercury
- Astronomy students say the strangest things
- ...and so do professionals
- The family page (mostly for grandparents...)
- I also manage the WWW site for the UA Christian Faculty/Staff Fellowship
Disclaimer (the UA legal folks only took about 2 years to get around to this requirement): (ostentatious throat-clearing) "The views, opinions, and conclusions expressed in this page are those of the author and not necessarily those of The University of Alabama or its officers and trustees. The content of this page has not been reviewed or approved by The University of Alabama, and the author is solely responsible for its content."

As if anyone might confuse the two!

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Last changes: August 1998