Seeing the Nuclei of Active Galaxies

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The refurbishment of the Hubble Space Telescope (HST) is complete, and new optics are in place to correct the defective primary mirror. A great number of scientific goals have been fulfilled by this powerful but flawed telescope since its launch on 24 April 1990 (*1*, *2*). Although burdened with the much publicized spherical aberration, HST nevertheless has the highest spatial resolution of any optical telescope currently available to astronomers, thanks to the sharp and narrow spike in the distribution of light [the point spread function (PSF)] produced by the telescope. Even with the present HST optics, the peak in the PSF allows high-resolution imaging of bright, extended objects such as active galactic nuclei (AGN). In addition, the location of HST above Earth's atmosphere allows observations in the ultraviolet wave bands, unavailable from ground-based observatories.

For comparison, note that a ground-based PSF taken under the best conditions, with the atmosphere stable to disturbances on scales of 0.5 arc sec and larger, contains 50% of the energy within a radius of 0.5 arc sec, but contains no information at smaller scales. The current PSF of HST contains 15% of the energy within a radius of 0.1 arc sec, thus providing information on the 0.1–arc sec scale. The present HST PSF does spill energy out to a radius of 1.5 arc sec, so that the distant, faint universe has been lost to the telescope before refurbishment. The successful deployment of the Corrective Optics Space Telescope Axial Replacement instrument (COSTAR) will result in a PSF that contains 70% of the energy within 0.1 arc sec, thus restoring the telescope to its original optical specifications, enabling HST to observe the most distant regions of the universe.

Active galaxies contain exceptionally bright and compact nuclei, exhibiting in their spectra emission lines from gas in a wide range of ionization states. The AGN are separated into two basic types according to the velocity widths of their permitted emission lines of hydrogen, helium, and other elements. Both types of AGN display narrow forbidden lines and the narrow component of the permitted lines, but the first type, Seyfert 1s (Sy1) and Broad-Line Radio Galaxies (BLRG), display velocity-broadened permitted lines, and the second type, Seyfert 2s (Sy2) and Narrow-Line Radio Galaxies (NLRG), display only narrow permitted lines. There is a two-parameter matrix in the phenomenology of AGN, the first being the velocity width of the permitted emission lines (Sy1 and BLRG versus Sy2 and NLRG) and the second parameter being the strength of the radio emission (Sy1 and Sy2 versus BLRG and NRLG). Whereas the radio fluxes of the radio weak versus the radio-powerful AGN differ by factors of up to 10^5, with the radio-powerful AGN displaying magnificent extended radio jets, the optical spectra of the radio-weak and the radio-powerful AGN are virtually indistinguishable.

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Fig. 1. Dusty tori with cones of ionizing radiation at different orientations relative to the disk of their host galaxies. The orientation of the dusty torus to the galaxy disk may be an important factor in the determination of the appearance of an AGN. If the torus (shown at greatly enhanced scale relative to the galaxy disk) is aligned with the plane of the disk, the ionizing cone (and in the case of a radio-powerful AGN, the radio jet) has little interaction with the galaxy disk. If the torus is aligned perpendicular to the disk, the ionizing cone (and in the case of a radio-powerful AGN, the radio jet) is directed into the plane of the galaxy, depositing large amounts of energy in the disk of the galaxy.

A unifying scheme that allows astronomers to understand the difference between the narrow line AGN and the broad line AGN has been developed in the last few years and is both supported and expanded by observations with HST (astronomers do not have such a unifying scheme for understanding the relation between the radio-weak and the radio-powerful AGN). The high-resolution HST images of nuclear regions of AGN do suggest that an additional parameter is important in the unified scheme. The HST observations also address the origin of the activity in AGN. The observational evidence comes out against the origin being the "normal" events of supernovae in a tight stellar cluster at the galaxy center. The evidence comes out in favor of the origin being related to mergers or cannibalism between galaxies. The gas from the merger remnant would be driven into the center of the galaxy by nonequilibrium gas dynamics to "feed the monster." Such a picture is favored by cosmologies dominated by cold dark matter. Finally, a brain teaser is presented in the form of a high-resolution image of the nucleus of a well-known, nearby quiescent galaxy that contains a double nucleus, suggestive of merging but with no accompanying signs of activity.

The first theories explaining the difference between narrow line and broad line AGN were based on either differences of orientation of the angle at which the objects were being viewed or differences in intrinsic physical conditions in the AGN; the second theory is difficult to support because of the many similarities between the galaxies hosting the activity. The breakthrough in these theories came through observations of polarized light. A narrow line AGN, the Sy2 galaxy NGC 1068, was observed in polarized light and was detected as a broad-line AGN, or Sy1 galaxy (*3*). The observers were initially puzzled but then realized that by observing the polarized light, they were observing light scattered into their line of sight by an as yet unidentified scattering medium. The narrow line AGN was hiding a broad line AGN. Observing in polarized light isolates the reflected light component in much the same way that polarized sunglasses isolate the reflected light component from the hood of a car. Further observations in polarized light of a number of Sy2s and NLRGs showed that they are also hiding broad line AGN. Thus, the picture has developed that the central source and the region in which the velocity-broadened permitted emission lines are produced are blocked from view by a dusty and opaque torus. The narrow forbidden lines come from an extended region that is ionized by the continuum emission from the central source as that ionizing emission escapes from the opening angle of the torus. If the opaque torus is observed face-on, the AGN appears as a broad line AGN (Sy1 or BLRG). If the opaque torus is observed edge-on in unpolarized light, the AGN appears as a narrow line AGN (Sy2 or NLRG). Early evidence supporting this picture came in the form of images taken at the wavelengths of forbidden lines, showing biconical structure and emission line regions extended in the same direction as the radio jets. This implies that the collimation of the ionizing radiation is the same as the collimation of the radio jets.

Spectra taken with HST in polarized light in the ultraviolet provides strong support for this model (*4*). When NGC 1068 is observed at ultraviolet wavelengths, where the starlight from the host galaxy cannot dilute the polarized spectrum by HST, the continuum polarization is constant at 16%, indicating that the scattering medium is electrons, which scatter in a wavelength-independent manner at these energies. In addition, the narrow forbidden emission lines are much less polarized than the continuum, and the broad permitted emission line of CIII] λ 1909 (bracket denotes a semiforbidden transition, and λ indicates wavelength in angstroms) is seen in the polarized flux.

The AGN images taken at the wavelength of emission lines with HST have revealed aesthetically pleasing images of biconical structure at high spatial resolution for a number of galaxies, such as NGC 1068 (*5*), NGC 5728 (*6*), NGC 4151 (*7*), and Mrk 78 (*8*). These images support the unified scheme and show that the biconical structure continues down to the smallest observable scales. The narrow band HST images also suggest that there is one more parameter relevant to the phenomenology of AGN: the angle of the opaque torus, and thus the angle of the cone of ionizing radiation and the angle of the radio jet, to the disk of the galaxy (Fig. 1) (the angle of radio jets are observed to be at random directions relative to their host galaxy disks, lending further support to this picture). A number of images of Sy1 galaxies seem to represent the extreme case (Fig. 1, left) where the cone of ionizing radiation faces directly out of the disk of the galaxy. The HST images of the Sy1 galaxies NGC 1566 (*9*) and NGC 3783 show unresolved point source nuclei with no evidence of any extended emission line region, implying that their ionizing cones are pointed directly out of their galaxies. Several images of Sy2 galaxies seem to represent the case where the ionizing cone lies partly in the plane of the disk. Both NGC 1068 (Fig. 2A) and Mrk 3 (Fig. 2B) show extended regions of narrow emission lines most likely produced by tori oriented at an intermediate angle relative to their host galaxy disk. In addition, Mrk 3 shows evidence for influence from a rotating interstellar medium on the radio and optical emission features, which appear as an "S" shape.

The galaxy M51, observed with Wide Field Planetary Camera of HST (Fig. 2C), may be an example of when a dusty torus is oriented perpendicular to the disk of the galaxy (Fig. 1, right). It is a transition between a type of galaxy with low-ionization emission lines and an AGN and thus appears to represent a lower level of activity in galaxies. The nucleus of M51 contains a dark bar about 30 pc across that lies perpendicular to the direction of the emission line cones. This may be a dusty torus observed edge-on, a conclusion that is strengthened by the fact that the radio jet emerges perpendicular to the dark bar. An additional bar is seen, which together with the edge-on dusty torus forms an "X" in the galactic nuclei (Fig. 2C). The second bar may be a dust lane reminiscent of that in Centaurus A, a galaxy that mixes the stellar morphology of an elliptical galaxy with a dust lane typical of a spiral galaxy. Orientation of the dusty torus perpendicular to the disk of the galaxy would likely result in a mixed brand of galaxy such as M51.

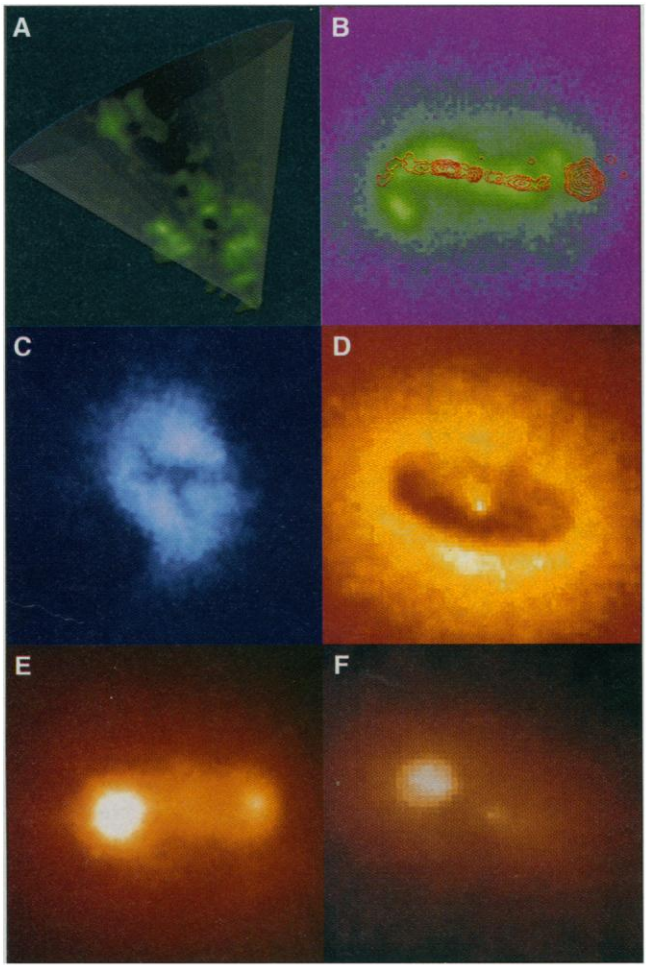

Fig. 2. (**A**) The emission line knots in the central 50 pc of the core of NGC 1068, observed in the light of [OIII] (brackets denote a forbidden transition). A schematic representation of the cone of ionizing radiation has been artificially added to illustrate the beaming direction. The radio knots overlay directly onto the emission line knots (*5*). (**B**) The raw image of the central 2.6 arc sec of Mrk 3 with the radio emission overlaid (*12, 13*). (**C**) The nucleus of M51 (*14*). (**D**) The central 4.3 arc sec of NGC 4261 (*15*). (**E**) The nucleus of Mrk 315 (*16*). (**F**) The nucleus of M31 (*17*). [H. C. Ford, Z. Tsvetanov, W. Jaffe, J. MacKenty, and T. Lauer, National Aeronautics and Space Administration.]

The HST image of the radio-powerful AGN NGC 4261 reveals a structure much discussed and much hypothesized in astronomy but never before observed—a disk in a galaxy nucleus. The opaque disk has orientation and structure directly linked to both the nuclear activity of the AGN and the large-scale radio jets (Fig. 2D). The galaxy's bright nucleus is obscured by the opaque disk, which lies slightly offset from the nucleus. The disk is consistent in size with the dusty, opaque disks of the unified scheme, about 300 light years in diameter. As with the other active galaxies observed with HST, the extended radio jets lie perpendicular to the orientation of the disk, suggesting a common source of alignment for disk and jet.

To what degree is the activity in AGN caused by "normal" events, such as the explosion of supernovae in a cluster of hot and massive stars (a starburst) collected in the central region of a galaxy? This picture (*10*) gets strength from the fact that some supernovae are observed to have spectra that bear a strong resemblance to the spectra of AGN. However, when optical images and ultraviolet spectra are taken of the nearest example of an AGN, NGC 4395 (*11*), no evidence for starburst activity is seen. Most especially, the strong ultraviolet absorption lines of hot stars are completely lacking in the spectrum of this low luminosity AGN. Thus, the ultraviolet spectra with HST lend no support for starburst activity as the origin of activity in AGN.

Mrk 315 is a Seyfert galaxy with evidence for tidal interactions from ground-based images. When observed at high resolution with HST (Fig. 2E), the central region is observed to have a double nucleus about 2000 pc apart. The double nuclei together with the tidal tails of material observed at greater distances from the center suggest that a recently captured galaxy remnant, which has not yet had time to settle into the more massive galaxy nucleus, may be the cause for the activity seen in the AGN.

Finally, an image of the center of the sister galaxy to our Milky Way, the spiral galaxy Andromeda (Fig. 2F), reveals not one but two nuclei, separated by about 2 pc. This spiral galaxy shows virtually no signs of being active and shows no signs of recent tidal activity. The lifetime of the secondary nucleus against orbital decay resulting from dynamical friction and tidal forces is thought to be incredibly short by astronomical standards (less than 10^5 years), so the the system is either being observed at a very unique time or some mechanism that is not well understood may be stablizing the double nucleus against orbital decay. This image of the closest spiral galaxy serves as a reminder that even so-called normal galaxies are not yet well understood.

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Recent Advances of X-ray Astronomy

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Among the great astronomical discoveries of the 1960s was the totally unexpected finding by Giacconi *et al.* (*1*) of a bright x-ray star, now known as Scorpio X-1. Because cosmic x-rays are absorbed by the Earth's atmosphere, astronomers were effectively blind in the x-ray wavelength band until they were able to send instruments into space. The discovery of Sco X-1 was truly surprising because no bright x-ray sources other than the sun were considered to exist. Since then, x-ray astronomy has developed very rapidly, especially in the last 20 years, after satellite observations became possible.

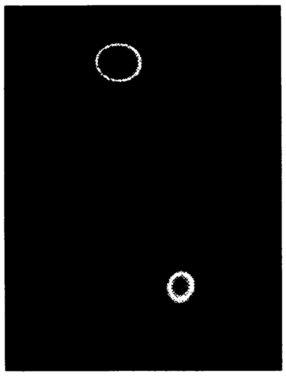

Fig. 1. X-ray image of M81 obtained with ASCA on 7 April 1993. The source near the top (north) is the nucleus. The bright source below is SN 1993J (3 arc min from the nucleus). Another source adjacent to the supernova is a probable x-ray binary in M81.

X-rays are emitted either thermally, from hot plasmas with temperatures of millions to tens of millions of kelvins, or nonthermally through relativistic processes involving high-energy electrons. Therefore, many high-energy astrophysical processes are manifested most directly in the x-ray and gamma ray bands, and x-ray observations have become indispensable for the studies of high-energy astrophysics. At present, every class of astronomical object, from nearby stars through quasars at cosmological distances, is the subject of x-ray astronomy investigations.

The first x-ray astronomy satellite, UHURU (1970), revealed a great many x-ray sources, galactic as well as extragalactic. One of UHURU's most important discoveries was that the brightest galactic x-ray sources were close binaries of which one member was a gravitationally collapsed, compact object—usually a neutron star, but possibly a black hole (*2*). The intense x-ray emission arises as matter dragged from the normal companion star falls into the extremely deep potential well of the compact object, releasing 100 MeV per nucleon of gravitational energy in the form of heat. This process, called mass accretion, produces a variety of phenomena in the x-ray band, allowing detailed investigation of the nature of these compact objects.

The richness of the x-ray sky was further disclosed as exploration progressed with succeeding x-ray satellites. The Einstein Observatory (1978) carried the first focusing x-ray telescope and had a sensitivity that was improved by several orders of magnitude over previous experiments. This enormously expanded the horizon of the x-ray sky and made x-ray studies of extragalactic sources an important branch of astronomy.

The Einstein Observatory revealed that many active galaxies, including quasars, were strong x-ray emitters (*3*). An active galaxy emits an immense quantity of electromagnetic radiation from a tiny region at the center of the host galaxy, called an active galactic nucleus (AGN). The emission is clearly of nonthermal origin, and the spectrum extends up to the gamma ray regime, indicating that complex relativistic processes are involved. From various arguments, an AGN is suspected to be a supermassive black hole, but the mechanism of the "central engine" of the AGNs still remains enigmatic.

Observations at x-ray wavelengths revealed that clusters of galaxies contain a large amount of hot (several tens of millions of kelvins) plasma (*4*). The mass of this intracluster gas is comparable with or more than the total mass of the constituent galaxies and accounts for a substantial fraction of the baryonic matter in the universe. The formation and evolution of clusters of galaxies have become increasingly important topics of x-ray astronomy.

More recently, the German x-ray satellite, the Roentgen Satellite (ROSAT), was launched in 1990. It was equipped with a larger x-ray telescope than that of the Einstein Observatory and, in the limited soft x-ray band of 0.3 to 2 keV, has the highest sensitivity of any soft x-ray telescope flown to date. Naturally, many discoveries are being made with ROSAT. The ROSAT all-sky survey vastly expanded the previous catalog to include nearly 100,000 x-ray sources.

In the past, despite great scientific need, high-energy astronomy satellites have been scarce, too few compared to the ground-based observatories. Today, fortunately, several x-ray and gamma ray satellites with unique capabilities are simultaneously in operation: ROSAT (Germany), GRANAT (Russia), the Compton Gamma-Ray Observatory (CGRO) (United States), and the most recently launched Japanese satellite, ASCA. Significant advances in high-energy astrophysics can be expected.

In the remainder of this article, I shall focus on several topics in x- ray astronomy, using recent results obtained mainly with Ginga and ASCA. Ginga (1987–1991), the Japanese x-ray satellite before ASCA, had an x-ray collecting area of 4000 cm^2, the largest of its kind, covering a wide energy range between 1 and 40 keV. Launched in February 1993, ASCA is the first x-ray observatory capable of simultaneous imaging and spectroscopic observations over the range 0.5 to 10 keV. Although the angular resolution is modest (1 arc min), the x-ray charge-coupled device (CCD) cameras provide spectra of an unprecedented energy resolution.

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