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Perspective

Active galactic nuclei

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Active galactic nuclei are the most powerful, long-lived objects in the Universe. Recent data confirm the theoretical idea that the power source is accretion into a massive black hole. The common occurrence of obscuration and outflows probably means that the contribution of active galactic nuclei to the power density of the Universe has been generally underestimated.

Active galactic nuclei (AGN) involve the most powerful, steady sources of luminosity in the Universe. They range from the nuclei of some nearby galaxies emitting about 10^{40} erg·s^{-1} (1 erg = 0.1 μJ) to distant quasars emitting more than 10^{47} erg·s^{-1}. The emission is spread widely across the electromagnetic spectrum, often peaking in the UV, but with significant luminosity in the x-ray and infrared bands. It is spatially unresolved except in the radio band, where there is sometimes evidence for collimated outflows at relativistic speeds. The power output of AGN is often variable on time scales of years and sometimes on time scales of days, hours, or even minutes.

Causality implies that an object that varies rapidly in time t must be smaller than the light-crossing time of the object, ct (where c is the speed of light) and thus must be spatially small; if not, the variation would appear smoothed. High luminosities imply high masses such that gravity can combat radiation pressure, which would otherwise blow the object apart (that is, the luminosity must be less than the Eddington limit). AGN therefore are of very high mass density, and it has long been assumed that they consist of a massive black hole, of say 10^8 solar masses ($M_\odot$) or more, accreting the gas and dust at the center of a galaxy. The gravitational energy liberated during accretion onto a black hole is ≈10% of the rest mass energy of that matter and is the most efficient mass–energy conversion process known involving normal matter (that is, ignoring the use of antimatter; nuclear burning releases at most 0.7% of the mass-energy). Indeed, the rapid variations seen in some powerful AGN argue for some high efficiency process, more efficient than nuclear burning (Fig. 1).

The accreting matter probably has some angular momentum, which causes it to orbit the black hole and, through dissipation of energy, flatten to form a disk within which magnetic viscosity transfers the angular momentum outward and the mass inward. Unless the accretion rate is either high or very low, it is likely that the gravitational energy liberated is radiated locally, much of it as thermal radiation from the surface of the disk, peaking in the UV as expected. Some energy, however, is probably stored temporarily in magnetic fields before being released in flares, which make the x-ray emission particularly variable.

Classifying Active Galactic Nuclei

AGN have been classified in many ways. Three important classes are: (*i*) the Seyfert galaxies, which have modest luminosities but tend to be the best studied since they generally lie near to us; (*ii*) the quasars, which are more luminous than the host galaxy and are particularly numerous at a redshift of ≈2, when the Universe was about one third its present age; and (*iii*) the blazars. About 10% of quasars are radio-loud; the rest are radio-quiet, although not silent. Radio loudness is generally associated either directly with a collimated relativistic outflow or jet or with regions where a jet has collided with surrounding material. A blazar is seen when our line of sight lies close to the direction of a jet.

An important issue is the obscuration of AGN by dust and gas along the line of sight, which can change or hide the spectrum of an AGN. Seyferts have long been divided into types I and II, in which the second type clearly are obscured versions of the first type (in some, the characteristic broad optical lines of type I are seen in the polarized, scattered component of type II). There are several unification schemes where the classification of an object depends on its orientation. The local number density of Seyfert II galaxies is several times that of Seyfert I galaxies. What is not yet clear is whether quasars can or should be similarly divided. There are no good examples of a type II quasar, although there are many obscured powerful objects that may host accreting black holes, such as the ultraluminous infrared galaxies.

One strong indication that much of the accretion in the Universe is obscured, whatever the name of the objects, is the x-ray background. The spectrum of this background radiation is harder than that of any unobscured objects, and it can only be successfully explained by synthesizing it from objects that are strongly absorbed, that is, surrounded by absorbing gas or dust. A simple global analysis of its spectrum (1) then suggests that as much as 85% of the accretion power in the Universe may be absorbed and reradiated at longer wavelengths (mostly in the infrared).

The evolution of quasars is fairly well understood from numerous optical and other surveys (2). Most nearby galaxies probably hosted a quasar at or near their center in the past. Indeed, estimates of the mass accreted into black holes required to explain quasar counts and the x-ray background are in rough agreement with the local space density of massive black holes. Quasar activity peaked roughly when star formation activity associated with galaxy formation peaked, and it is of course likely that these processes are related (3). Both require an abundance of gas in deep gravitational potential wells.

Whether Seyfert galaxies are the endpoint of powerful quasars is doubtful, given that many quasars, both radio-loud and radio-quiet, lie in elliptical galaxies (4), whereas many Seyferts are in spiral galaxies, the latter of which are typically less massive and younger than the former.

Evidence for Black Holes in AGN

Although accretion onto a massive black hole has long been seen as the explanation for AGN, obtaining unambiguous proof has been difficult. A black hole, by its very nature, is observationally elusive. Progress has, however, been made on several fronts over the past few years. Optical, infrared, and radio studies of the nuclei of several galaxies, including our own, have revealed the presence of large masses within small radii that can only plausibly be black holes. X-ray studies have revealed spectral features from the innermost accretion flow of several Seyfert galaxies. The enormous Doppler shifts and gravitational redshifts of the features show for the first time the strong gravity near the event horizon.

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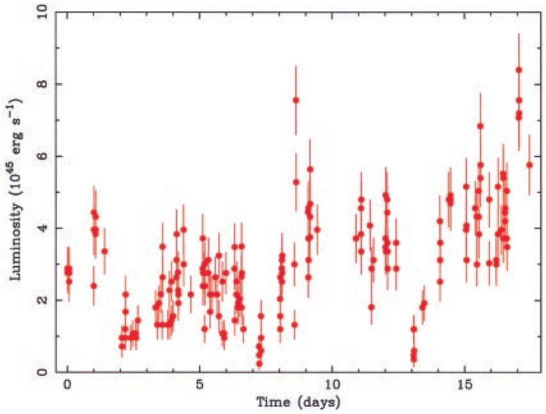

FIG. 1. X-ray lightcurve of the powerful, radio-quiet AGN PHL1092 (18). Note the persistent large variability. A remarkable flare on day 8 shows a change in luminosity exceeding 10^{42} erg·s^{-2}. This requires a mass-to-energy conversion efficiency exceeding 0.6 and cannot be associated with stellar processes. Mildly relativistic motions close to a black hole have probably amplified the apparent variability.

Radio observations of the nucleus of the nearby galaxy NGC 4258 show the presence of a water maser there. This can be resolved with very long baseline interferometry into several water masers roughly along a line extending from either side of the nucleus. The frequency of each maser can be measured accurately and shows that they lie in an edge-on disk orbiting the nucleus, which itself is a continuum radio source. The velocity and radius of the orbiting masers yields a central mass of 3.6×10^7 $M_\odot$ (5).

Near-infrared observations of the nucleus of our own Galaxy show the proper motion (that is, motion perpendicular to the line of sight) of stars there. This motion increases toward the position of the Galactic Center, which is coincident with the radio source Sgr A*. The stars are presumably in orbit about the Galactic Center that must then have a mass of 2.5×10^6 $M_\odot$ (6, 7).

While both of these examples, and others that make use of the Doppler velocity profile of optical line-emitting gas or stars near galactic nuclei (8), strongly indicate the existence of black holes, they do not reveal the effects of strong gravity expected from a black hole. Indeed, the matter observed is not in a gravitational field much stronger than that on the surface of the Sun. Other techniques are thus required to probe the innermost regions where water no longer exists and any stars have been tidally shredded.

Seyfert galaxies, and quasars, are typical x-ray sources with ≈10% of the bolometric luminosity emerging as x-rays. The emission from Seyferts is often variable and likely to be due to magnetic flares above the accretion disk. This supposition is strengthened by similarities with stellar mass black-hole candidates such as Cygnus X-1. The x-ray spectrum of Seyfert I galaxies is consistent with a power-law shape and its reflection spectrum. The reflection would be expected if the power-law spectrum is emitted above a cool, flat surface of gas with element abundance typical of a galaxy. At photon energies above ≈20 keV many of the photons incident on the surface are backscattered by electrons. Photoelectric absorption is increasingly important below ≈20 keV, and the "reflected" continuum becomes much weaker. The crucial feature that emerges here is the fluorescent iron line, at 6.4 keV. Iron has both a high fluorescent yield and abundance, relative to elements of lower atomic weight.

The iron line and reflection component are clearly seen in the x-ray spectra of many Seyfert I galaxies. The important point is the spectral shape of the iron line, which is broadened and redshifted by the high orbital velocities of the disk and the deep gravitational potential. The ASCA satellite, using charge-coupled device (CCD) detectors, was the first to clearly resolve this line. The best example is that derived from a 4.5-day observation of the Seyfert galaxy MCG–6-30-15 (Fig. 2*A*; ref. 9). The line data show an abrupt drop at an energy level of ≈6.5 keV, which indicates that the disk is being observed at an inclination of approximately 30°. The line extends to ≈4 keV, which indicates that most of the emission originates from ≈6–40 gravitational radii (that is, 6–40 GM/c^2). The event horizon of a nonspinning black hole is at 2 gravitational radii and is less for one that is spinning.

The line is robust in a time-averaged sense since it appeared roughly similar when observed some 3 years later (Fig. 2*B*; ref. 10). During each observation the line does, however, show changes that suggest the center of gravity of the emission moves about across the disk. This can be expected if the emission is due to flares. At one point in the first observation, the continuum was weak and the iron line was strong and appeared to shift even further to the red (11). This requires that the disk extend to within 6 gravitational radii of the black hole. This is best accounted for by assuming that the black hole is spinning rapidly, presumably because the material it has accreted had significant angular momentum in the same direction.

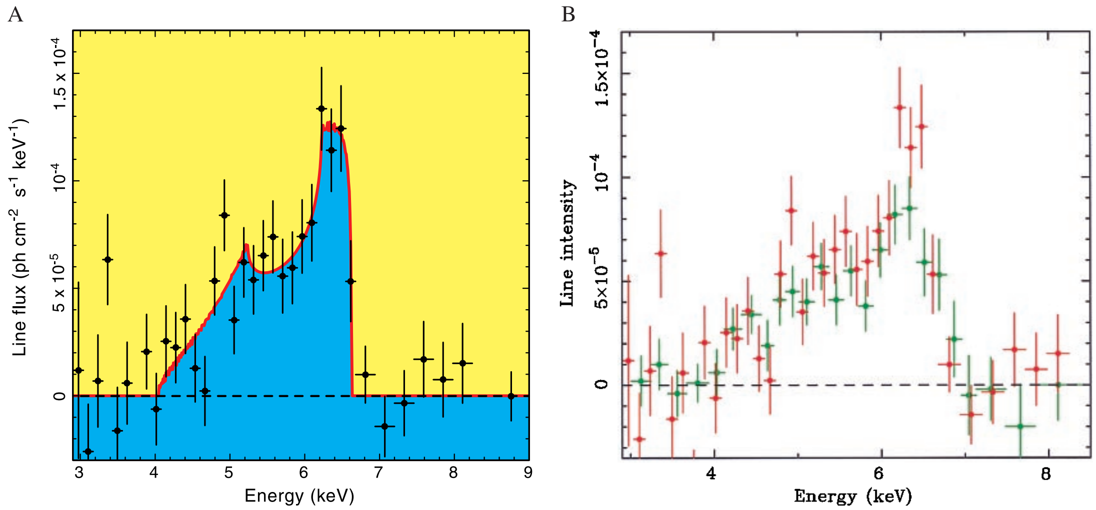

FIG. 2. The left panel shows the broad iron line seen in the Seyfert I galaxy MCG–6-30-15. The line would be very narrow and centered at 6.35 keV if the emitter were at rest in the galaxy but is clearly highly distorted and skewed to lower energies. The model compared with the data (solid line) assumes that the emitter is orbiting in a disk lying between 6 and 40 GM/c^2, inclined at 30°. Gravitational redshift due to the deep potential well accounts for part of the skewness. The right panel compares the data taken in 1994 (red dots, also shown in *A*) with that from 1997. The line profile is robust.

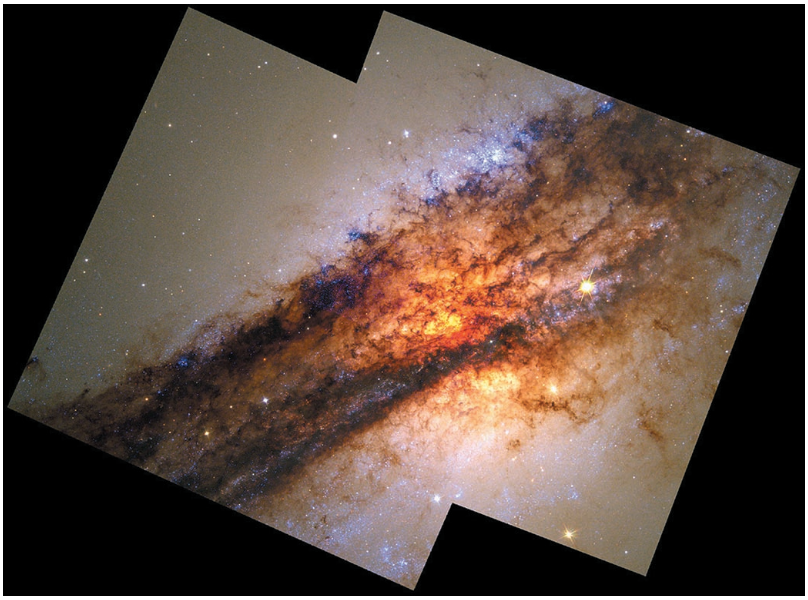

FIG. 3. Hubble Space Telescope image of the core of the nearest radio galaxy, Centaurus A (19). A billion $M_\odot$ black hole in the center of this galaxy squirts jets to the upper left and lower right, which dissipate in large radio lobes (not visible in this optical image). Note the high level of obscuration evident in the image, which is common for radio galaxies and Seyfert II galaxies. The nearest two Seyfert galaxies to us, NGC 4945 and the Circinus galaxy, at about the same distance as Centaurus A but in different directions, also show large levels of obscuration.

More data on MCG–6-30-15, and other Seyfert galaxies, are needed before details like reverberation of the iron line in response to changes in the continuum, which can yield the black hole mass, can be observed. ASCA data do nevertheless show that the broad iron line is common in Seyfert I galaxies and that it has the shape expected for matter close to a black hole (12).

Curiously, few iron lines have been found in the spectra of quasars or luminous AGN. This may be due to their disks being more highly ionized (13).

Jets and Outflows

Approximately 10% of AGN are radio-loud, which means that the nucleus produces a relativistic outflow of material. The exact composition of the outflow—electrons and positrons or electrons and protons—is uncertain. Shocks in the jet lead to emission of photons, which is principally synchrotron radiation in the radio band and Compton-upscattered emission (of either the synchrotron radiation or external optical/UV photons) at shorter wavelengths. The bulk Lorentz factor of a typical jet may be $\approx$20, which leads to considerable beaming of radiation along the jet direction (14). If viewed from that direction, as a blazar, then the object may appear as a strong γ-ray emitter, sometimes with photons of energy up to a TeV.

Much of the energy of jets is not radiated but accumulates in the surrounding medium. The many radio galaxies in the sky are such objects. The total kinetic power of a jet may rival the accretion power itself. What powers jets and why they only appear in a small fraction of sources is unclear. It has been long suggested that magnetic fields enable the spin energy of the black hole to be tapped and liberated as kinetic energy in jets. Nevertheless, it is debatable whether sufficiently strong magnetic fields can be maintained by the surrounding accretion disk for this process to liberate much spin power (15, 16).

It is possible that radio-quiet AGN also have outflows, which may only be poorly collimated and nonrelativistic. The incidence of photoelectric absorption features (so-called warm absorbers) in the x-ray spectra of Seyferts indicates significant columns of highly ionized gas occur close to the nucleus (17). Its general motion is not known but could represent the base of an outflow.

The strong UV radiation field of the central engine of most AGN photoionizes much of the gas in the vicinity ($\approx 10^5$ GM/c^2), causing the cool and warm components to emit bright emission lines. The shape and smoothness of these lines and their response to continuum changes has been a major source of information of both the UV spectrum and the near environment of AGN.

The Future

Many AGN are already known across the sky. Many more will be found over the next few years by the SLOAN Digital Sky Survey, which will also take optical spectra of all AGN found, by x-ray imaging by the Chandra x-ray Observatory and XMM, and by the Sky Survey to be carried out by ABRIXAS. These surveys will both reduce the statistical uncertainties on the properties, number density and evolution of the typical AGN and reveal unusual AGN. Of great interest will be AGN at high redshift. Already the SLOAN Survey has found a quasar at redshift 5, and more are expected.

What can be learned from these studies is how and when massive black holes formed and what their evolution is. Did they form before or after the first galaxies? The matter of obscuration is also crucial (Fig. 3), for it may be that both rapid star formation and black hole accretion occur roughly together and the dust formed rapidly from the metals ejected by massive stars has quickly obscured both the massive stars and many of the AGN.

Studies of nearby objects will continue as the black hole content of more galaxies is assessed and the properties of AGN are explored in detail. Ultimately, x-ray reverberation studies of the iron line with missions such as Constellation-X will enable a mass and spin census of low redshift black holes and reveal the full details of the inner accretion flow around massive black holes.

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