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Active Galaxies: Unified Model

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Active Galaxies: Unified Model

Objects known as 'ACTIVE GALACTIC NUCLEI' (AGN) can be grouped into a wide variety of phenomenological subclasses that have many overlapping or similar properties. The first known 'active galaxies' were the high-surface-brightness spiral galaxies identified by Carl Seyfert in 1943. Almost two decades later, the first radio surveys of the sky led to the identification of other objects (radio galaxies, such as Centaurus A, and quasars, such as 3C 48) that we now also think of as active galaxies, though the similarities between the radio sources and Seyfert's spirals were not obvious at the time of discovery. Early failure to recognize the underlying similarities of these objects was largely because the different identification techniques used isolated extreme members of the active-galaxy population: radio-source identifications tended to yield relatively high-luminosity, high-redshift quasars (short for 'quasistellar radio sources'), often members of the 'blazar' class (see BL LACERTAE OBJECTS), in which beamed emission from a relativistic jet dominates most of the observed spectrum. On the other hand, identification of bright galactic cores led to identification of the spatially common, relatively low-luminosity radio-quiet Seyfert nuclei (see ACTIVE GALAXIES: OBSERVATIONS).

It was only in the late 1960s and 1970s that optical, color-based detection criteria (either multiple-color broad-band photometry or low-dispersion spectroscopy) began to yield large enough samples of both high- and low-luminosity AGN that the fundamental similarities began to become clear. Indeed, color-based selection of AGN led to the discovery that most high-luminosity AGN are not of the 'radio-loud' quasar variety, but are 'radio-quiet' sources that came to be known as 'QUASISTELLAR OBJECTS' (QSOs). Despite the emerging similarities between Seyfert galaxies and QSOs, important differences among types of AGN were also identified, leading to a broad and fairly complex AGN taxonomy (see ACTIVE GALAXIES: OVERVIEW).

Comparison of various types of AGN should help us understand which phenomena are fundamental to nuclear activity and which are somehow incidental or secondary. In some cases, as we will see below, differences among various types can be used to infer source structure on scales too small to resolve directly. Some of the important questions that arise in this context include the following. Why are only $\sim$10% of active galaxies radio-loud? Why are broad emission lines weak or absent in the UV–optical spectra of BL Lac objects? Why do some Seyfert galaxies have no broad emission lines?

Unification

Principles

In attempting to explain the differences among various classes of AGN, our goal is to explain the widest variety of phenomena using the simplest model that is consistent with the data. A simple hypothesis to explain much of AGN phenomenology is that the differences among various types of AGN arise from orientation dependence; simply put, we try to 'unify' various AGN types in terms of a single basic source structure whose appearance to the observer depends strongly on viewing angle. There is indeed abundant direct evidence that AGN have axisymmetric structure and thus radiate anisotropically; the observable properties of a particular source will thus depend on the location of the observer. It is therefore postulated in such 'AGN unification' schemes that the different appearance of one class compared with a second is the result of viewing the same type of object at a different angle. Properties that may depend on viewing angle and may so contribute to intrinsic anisotropy in these sources include absorption by dust or optically thick gas in any non-spherically symmetric distribution and relativistic motion which leads to Doppler boosting of the emission which peaks in the direction of this motion. Unification schemes incorporating one or both of these intrinsic source properties seek to explain at least part of the wide diversity we observe in AGN in terms of these differences in viewing angle. There are several unification schemes seeking to unify two or more classes of AGN that have met with some degree of success; several of these are outlined in table 1 and will be described below.

Table 1. Possible simple unifications.

Radio properties	Orientation	
	Face on	Edge on
Radio quiet	Seyfert 1 QSO	Seyfert 2 ULIRG?
Radio loud	BLRG Core dominated BL Lac Quasar–OVV	NLRG Lobe dominated FR I FR II

An obvious key element in any unification scheme is proof of its plausibility. If we hypothesize, for example, that some specific type of AGN (say, BL Lacertae objects) are members of some particular broad class or 'parent population' (say, Fanaroff–Riley class I radio sources[1]), then the space density of the subclass must be consistent with the space density of the parent population times the probability of observing a member of the parent population at a suitable orientation. Determining the space density of the parent population is often a difficult task in itself and must rely on source identifications based on some property which is supposed to be isotropic. Hard x-ray emission, for example, is thought to be emitted approximately isotropically by non-blazar AGN, and in principle hard x-ray emission may be the best way to

[1] Fanaroff and Riley showed that extended radio sources can be divided into two luminosity classes that have different morphologies. Class I (FR I) are less luminous sources, $L_\nu(1.4\ \mathrm{GHz}) \lesssim 10^{32}\ \mathrm{erg\ s^{-1}\ Hz^{-1}}$, that are brightest in the center with decreasing surface brightness towards the edges. Class II (FR II) sources are the more luminous sources, which are limb-brightened or have non-central regions of enhanced emission.

find a homogeneous sample of AGN. Indeed hard x-rays are probably the *sine qua non* of an active nucleus. In practice, however, relatively low hard x-ray sensitivities have limited detection of AGN to those that are relatively nearby and thus apparently bright. For radio sources (which includes blazars), radiation from the optically thin extended lobes is assumed to be emitted isotropically and in principle can be used to identify objects with intrinsically similar luminosities.

The basic model

The current AGN paradigm is built around an axisymmetric central engine that consists of an accretion disk surrounding a supermassive ($\gtrsim 10^6 M_\odot$) black hole (see SUPERMASSIVE BLACK HOLES IN AGN). The UV–optical continuum emission is supposed to arise primarily in the accretion disk. Bi-directional relativistic jets emerge from this system along the disk axis, emitting Doppler-boosted radiation via synchrotron and inverse Compton mechanisms. Both the jets and the accretion disk structure are thought to contribute to the x-ray emission. The broad emission lines (whose width can be characterized in terms of the full width at half-maximum, FWHM $\approx$ 1500–10 000 km s^{-1}) that are so prominent in the UV–optical spectra of AGN are produced in relatively dense (electron densities $n_e \approx 10^{11}$ cm^{-3}) gas clouds at distances from the black hole of several hundred to several thousand gravitational radii ($R_{grav} = GM/c^2$, where M is the mass of the central black hole, G is the gravitational constant, and c is the speed of light). On parsec scales, this entire system is embedded in a dusty torus that is opaque over most of the electromagnetic spectrum; this torus plays a key role in AGN unification models since it shields both the accretion disk, broad-line region, and inner jet structure from the direct view of external observers in the torus plane. The torus absorbs radiation from the central source and re-emits this energy in the infrared. Narrow emission lines (FWHM $\lesssim$ 300–800 km s^{-1}) arise in low-density clouds at the torus scale and beyond, mostly driven by radiation from the central source, and therefore largely constrained to lie along the system axis.

AGN unification schemes

Seyfert types

Probably the best known unification scheme is that between the two types of SEYFERT GALAXIES. In the mid-1970s, Khachikian and Weedman found that Seyfert galaxies fell into two spectroscopic classes, those with both narrow and broad emission lines (type 1 or Sy1) and those with narrow lines only (type 2 or Sy2). The narrow-line spectra of types 1 and 2 are statistically indistinguishable from one another, so Sy2s seem to be Sy1s without the broad lines. Moreover, Sy2s are typically less luminous than Sy1s by about 1 magnitude in the optical part of the spectrum. This led to unification hypotheses in which Sy2s are intrinsically Sy1s whose continuum and broad-line emission is attenuated in the direction of the observer. While simple and attractive, this hypothesis had two major difficulties: first, why is the AGN continuum source extinguished by only a factor of a few, but the broad lines by an apparently larger factor? Second, the shape of the Sy2 continuum does not look like a dust-attenuated Sy1 AGN continuum, i.e. Sy2 continua do not appear to be highly reddened by passage through a medium in which the absorption or scattering cross-section decreases with increasing wavelength.

A breakthrough occurred in the early 1980s when Antonucci and Miller found that the polarization spectra of some Sy2 galaxies such as NGC 1068 (see the articles on NGC 1068 and POLARIZATION IN ACTIVE GALAXIES) contained broad emission lines like those seen in Sy1 spectra. At least some Sy2 galaxies contain broad emission lines, but with their strength greatly reduced such that they are dominated by the continuum and narrow lines except when viewed in polarized light. Since the most common cause of polarization is scattering of light by either dust or electrons, this observation led to an interpretation of Sy2 galaxies as edge-on Sy1 galaxies where optically thick material in a flattened, disk-like geometry obscures our direct view of the broad emission-line region, as described above and illustrated in figure 1. The broad lines are visible in polarized light when they are scattered into our line of sight by dust or electrons above and/or below this material. In the case of NGC 1068, the AGN continuum light is ~16% polarized, independent of wavelength through the UV–optical spectrum, which argues that the scattering mechanism is electrons rather than dust, since the Thomson scattering cross-section is wavelength independent while dust scattering is strongly wavelength dependent. In other polarized Sy2s, however, there is evidence that dust scattering also plays a role. The polarization spectra of these Sy2s also show that the emission lines are more strongly polarized than the continuum. There is apparently a second unpolarized component to the featureless AGN continuum that constitutes some 60–90% of the total continuum and has approximately the same spectral shape as the polarized component. The origin of the unpolarized component is unclear, although it may arise from free–free emission in the scattering region itself. In any case, the existence of this component explains why the non-stellar continuum in Sy2s is not as thoroughly suppressed as the broad lines.

Predictions of the relative numbers of each class provide an important test but are very sensitive to assumptions such as the opening angle of the torus and the angular dependence of the luminosity. Within these limitations the relative numbers are consistent with expectations and indicate torus semi-opening angles of ~60°. As more Sy2 galaxies and lower-luminosity AGN, such as LINERs (low-ionization nuclei emission region galaxies), are observed in polarized light, more edge-on Sy1 galaxies are discovered. It is not yet clear, however, whether all AGN, or even all Seyfert galaxies, fit into this scheme. Current studies show a detection rate for polarized broad lines in Sy2 galaxies of ~50%, implying that many Sy2 galaxies either do not possess a scattering region or that they have no broad-line region.

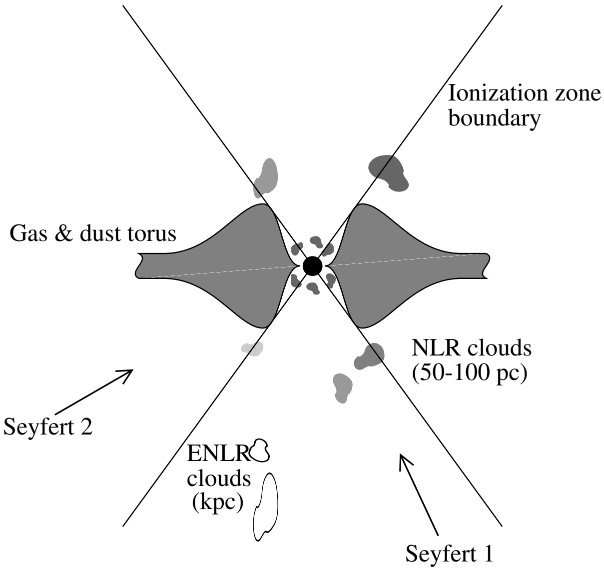

Figure 1. The conceptual scheme for unification of Sy1 and Sy2 galaxies (not to scale) with an optically thick torus of cool material surrounding the continuum source (central circle) and the broad emission-line region (BLR, small 'clouds' surrounding continuum source). From Peterson (1997), originally from R W Pogge.

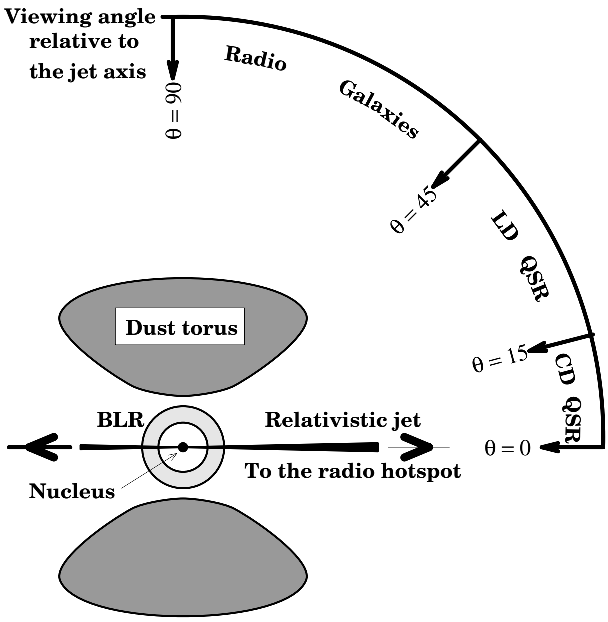

Figure 2. A scheme for unification of strong-line (BLRG, NLRG and quasars (QSR)) radio sources. Compare with figure 1 (rotated through 90°). Here the BLR is shown as a shaded shell around the continuum source (circular spot). From Kembhavi and Narlikar (1999), originally from R Athreya.

X-ray observations of AGN also generally support this unification picture. The x-ray luminosities of Sy2 galaxies are lower than those of Sy1 galaxies. Moreover, Sy2 galaxies have significantly larger amounts of soft x-ray absorption, corresponding to equivalent columns of neutral hydrogen, $N_{\rm H} \approx 10^{22-23}$ cm^{-2}, in comparison with $N_{\rm H} \approx 10^{20-21}$ cm^{-2} for Sy1 galaxies. This is consistent with our line of sight through the AGN being through an optically thick torus of cold material.

A similar unification scheme probably explains the difference between 'broad-line radio galaxies' (BLRGs), which might be described to first-order accuracy as radio-loud Sy1, and 'narrow-line radio galaxies' (NLRGs), which have Sy2-like optical spectra. A schematic of the geometry to unify the strong-lined radio galaxies is shown in figure 2.

A remaining puzzle is the apparent lack of an equivalent bifurcation in the higher-luminosity QSOs; there is no generally accepted class of 'QSO 2s' which would correspond to the low-luminosity Sy2 galaxies. The most likely candidates for dust-obscured QSOs are near IR-selected AGN, some of which do show broad lines in polarized light, or the cooler, ultraluminous IR galaxies (ULIRGs) whose emission may be predominantly due to reprocessing by cool dust. At the present time, it is clear that some ULIRGs harbor unseen AGN, but others are powered by starbursts, not by *bone fide* AGN.

Core- and lobe-dominated quasars and radio galaxies

As noted earlier, only about 10% of AGN are strong radio sources. Within this subset, there is a wide range of radio morphological structures (see also RADIO EMISSION FROM BINARY STARS) from classical double-radio sources on scales as large as megaparsecs to small, core-dominated sources with little or no extended structure. The core-dominated sources commonly show superluminal motion indicating relativistic outflow velocities close to our line of sight (see SUPERLUMINAL MOTION). Classical double sources often have one-sided, highly collimated jet structures extending from their compact core towards one of the extended lobes. The one-sided nature of the jets can be understood in a relativistic scenario whereby an approaching jet and an oppositely directed receding jet are respectively Doppler boosted and dimmed by relativistic effects. Thus both of these properties are consistent with relativistic jets originating in the core of a radio source and feeding the outer lobes. This suggests that the main variable governing the observed morphology of a radio AGN is its orientation to our line of sight. In core-dominated sources we are looking down the relativistic jet, while in double sources the jet is projected onto the plane of the sky.

A prime test of this unification scheme is to compare the relative numbers of core- and lobe-dominated sources and the distribution of projected sizes for radio AGN with the model predictions. The jet is highly collimated so that the main uncertainty is the amount of boosting due to the relativistic motion in the jet, determined by the bulk Lorentz factor $\gamma = (1 - V^2/c^2)^{-1/2}$, where V is the outflow velocity and c the velocity of light. It is thus difficult to match core- and lobe-dominated objects in intrinsic luminosity and so ensure that relativistic beaming effects are not a factor in any comparative studies. In general, these studies show that there are too many core-dominated sources compared with the lobe-dominated ones and that the former are too large when de-projected based on the observed Lorentz factor. There is also a lack of two-sided jets, i.e. sources aligned with the plane of the sky. Many of these inconsistencies can be solved if the highly luminous FR II radio galaxies (BLRGs and NLRGs) are included in the unification. In this case, the lobe-dominated, radio-loud QSOs are viewed at an angle intermediate between those of the radio galaxies, and the QSOs and the larger size of the radio galaxies matches that of the de-projected core-dominated sources. However this solution introduces a new problem, namely that the narrow [O III] $\lambda\lambda$ 4959, 5007 line emission is significantly (by a factor of 4–10) weaker in radio galaxies than in quasars, which requires that these lines also be emitted anisotropically for unification to work. The similar strength of the lower ionization [O II] λ 3727 line in the two classes supports this scenario since it originates at larger distances from the AGN core and so is expected to be emitted more isotropically.

Within the context of this orientation picture, the inclination of a radio source is related to the ratio of core to lobe luminosity, largely as a result of the relativistic boosting of the core luminosity. This parameter, known as core dominance R, can then be used to study the dependence of other parameters on inclination. For example the widths of the broad Hβ and C IV emission lines indicate that face-on (core-dominated) objects tend to have relatively narrow broad lines (FWHM $\approx$ 1000–5000 km s^{-1} while edge-on (lobe-dominated) have a wider range of line width (FWHM $\approx$ 1000–10000 km s^{-1}). This result suggests that the orientations of the broad emission-line region and the obscuring torus are similar.

Blazars and radio sources

With the recognition that blazar emission originates in relativistic jets towards the observer, radio galaxies with jets in the plane of the sky presented themselves as candidates for 'misaligned' blazars. Blazars themselves fall into two distinct categories, 'BL Lacs' and 'optically violent variables' (OVVs), and these seem to be drawn from different parent distributions of radio galaxies. The primary distinction between OVVs and BL Lacs is that OVVs have strong UV and optical emission lines so their UV–optical spectra resemble those of non-beamed AGN, whereas in BL Lacs other spectral features are swamped by the emission from the jet. OVVs also have higher luminosities and higher inferred Lorentz factors than BL Lacs.

It is possible to make a fairly convincing argument that BL Lacs reside in FR I radio galaxies. By disregarding the spatially unresolved blazar core emission and considering only the luminosity of the 'extended' radio source (presumably the 'lobes' seen along their axis), it is found that FR I galaxies and BL Lacs have comparable radio luminosity, supporting the notion that they are drawn from a single population. The luminosity functions and space densities are also consistent with unification of these two types of object. It should be mentioned at least in passing that BL Lacs themselves have been sometimes divided into radio-selected and x-ray-selected subcategories, and on average sources in these categories tend to have spectral energy distributions that peak, not surprisingly, at low and high frequencies, respectively. Recent work suggests that these are not, in fact, distinct classes, but rather represent the extremes of a continuous distribution in peak wavelength for the entire class of BL Lacs.

The more luminous FR II radio galaxies afford a plausible parent population for OVVs. Compared with the FR I–BL Lac unification scheme, this is more difficult to demonstrate, at least in part because the FR II population is relatively less homogeneous.

'Grand unification': radio-loud and radio-quiet AGN

One of the longest-standing questions in AGN astrophysics is why, despite being optically similar, a small minority ($\lesssim$10%) of AGN are radio loud while the remainder are radio quiet? Any unification scheme that can explain the difference between these two major classes of AGN would go a long way towards explaining the AGN phenomenon in general, and is therefore sometimes referred to as 'grand unification'. There is a clear dichotomy between the radio-loud and radio-quiet sources; for a given IR through soft x-ray luminosity, the radio-loud AGNs are 2–3 orders of magnitude more luminous in the radio than the radio-quiet objects. There are very few objects of intermediate radio luminosity so the distribution of radio power relative to power at shorter wavelengths is clearly bimodal. In other words, the evidence clearly points to two distinct AGN populations defined by relative radio luminosity.

An early suggestion advanced by Scheuer and Readhead was that the radio-loud and radio-quiet objects constitute a single population in which the radio-louds represent the sources with axes oriented towards the observer. This failed, however, to account for the lack of extended radio emission in the radio quiets.

Radio-quiet and radio-loud AGN differ in other respects. Radio-loud AGN are, on average, about a factor of 3 brighter in the mid-energy x-rays (0.2–3.5 keV) with somewhat flatter spectral slopes (i.e. relatively more high-energy photons). This is thought to be due to the presence of beamed X-ray emission related to the radio-emitting jet and provides evidence for the unification of core- and lobe-dominated radio-loud AGN discussed above. However, the difference in x-ray spectral slope would be hard to account for in a grand unification scenario.

The emission-line spectra of the two types of object also show differences, at least in a statistical sense (e.g. stronger optical Fe II blends, weaker narrow lines and narrower broad lines in the radio-quiet objects).

Until relatively recently it was believed that broad relatively blueshifted absorption-line features that are indicative of mass outflows are only found in radio-quiet AGN; it is now clear that these also occur in radio-loud AGN, although at the present time it appears that the flows in radio-loud objects have relatively lower terminal velocities. The outflowing material responsible for the absorption is generally thought to be accelerated away from the surface of the torus and so expected to be present at certain orientations in both radio-loud and radio-quiet AGN.

No satisfactory explanation for the differences between radio-loud and radio-quiet sources has yet emerged. Although hard to understand, it was for a long time thought that the nature of the host galaxy determined the radio class with radio-quiet AGN in spiral hosts and radio-loud AGN in ellipticals. However, recent observations with the Hubble Space Telescope have shown that at high luminosity nearly all AGN lie in elliptical galaxies. It is now widely suspected that the angular momentum of the central black hole might be the determining factor, since the orbital motions of charged particles around the black hole might determine whether or not electromagnetic effects will be sufficiently powerful to generate and collimate jets.

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