The AGN Paradigm for Radio-Loud Objects

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Abstract. Radio-loud AGN are characterized by relativistic jets originating near the central supermassive black hole and forming large-scale radio sources at parsec to kiloparsec to Megaparsec distances. The jets are energetically significant, in many cases representing the bulk of the energy extracted from the accretion process. Host galaxies are apparently normal luminous ellipticals, supporting the “Grand Unification” scenario wherein AGN are a transient phase in the evolution of every galaxy. Black hole mass appears to be largely uncorrelated with bolometric luminosity, Eddington ratio, radio luminosity, or radio loudness.

1. Accepted Wisdom

According to the paradigm for active galactic nuclei (AGN), illustrated in Figure 1, gravitational potential energy is converted to radiation and kinetic power via accretion of matter onto a central supermassive black hole. We observe thermal emission from the disk in the optical, ultraviolet, and X-ray; Compton scattered X-rays from a hot corona; Thomson scattering of the nuclear continuum in an extended corona (Antonucci & Miller 1985); and broad and narrow emission lines. From some directions, the nuclear continuum and broad lines are obscured by a torus or warped disk; whether the torus geometry changes with luminosity and/or redshift will be settled by upcoming SIRTF searches for highly obscured quasars at redshift $z \sim 2 - 3$. These characteristics of AGN are independent of radio loudness.

The distinguishing feature of radio-loud AGN is a pair of relativistic jets, originating within a few tens of Schwarzschild radii of the black hole. The relativistic potential well of a black hole — whether a supermassive black hole at the center of a distant galaxy or a few-solar-mass black hole in our Galaxy — appears to lead naturally to relativistic jet speeds. Weaker jets disrupt sooner and thus have a diffuse appearance (these are Fanaroff-Riley type 1 sources), while the most powerful jets remain well collimated to large distances from the nucleus, where they form large double radio lobes with hot spots (Fanaroff-Riley type 2 sources). It is possible that radio-quiet AGN have such weak jets that they are quenched before developing into observable extended radio sources.

Probably the black hole spin (or accretion disk rotation) defines an axis of symmetry along which material is ejected to form the jets. In some cases, this axis must be stable over very long times, allowing the jets to extend to a Megaparsec or more (e.g., NGC 6251). In other cases, precession of the black hole,
Figure 1. Schematic drawing of the key elements of an active galactic nucleus: central supermassive black hole, accretion disk, broad-line region surrounded by a dusty torus or warped disk, extended corona of hot electrons, extended narrow-line region, and, at least for radio-loud AGN, a pair of relativistically outflowing jets which originate near the black hole and eventually decelerate on large scales.

or its motion through a dense environment, are detectable from the distorted shapes of the jets (e.g., Wide-Angle Tail sources). AGN with jets viewed end-on are classified as blazars (either BL Lac objects or Optically Violently Variable quasars), while ordinary quasars are viewed at larger angles from the jet axis, and radio galaxies have jets more nearly in the plane of the sky.

Jets are relativistic on parsec scales, as attested by the ubiquity of superluminal motion in blazars. Systematic VLBI (& VSOP) surveys of core-dominated radio sources confirm this: in addition to bright cores, these radio sources have high optical polarization, jet pc-kpc misalignments, one-sided morphologies, and intraday variability (in the radio), all characteristics explained naturally by relativistic beaming (see Lister et al., this conference).

Jets are very likely relativistic on kiloparsec scales as well. Large-scale relativistic proper motions have been directly observed in the nearby radio galaxy M 87 (Biretta et al. 1995). Jet one-sidedness is common (Bridle & Perley 1984), and correlates well with VLBI one-sidedness (which is surely due to relativistic beaming) and with depolarization asymmetry (Laing 1988; Garrington and Conway 1991). More recently, the most plausible explanation of some of the newly discovered extended X-ray jets requires that the plasma have bulk relativistic motions on scales of hundreds of kiloparsecs (Tavecchio et al. 2001, Celotti et al. 2001, Sambruna et al. 2002).

In powerful radio sources, jets are straight and remain relativistic to large distances (a well-known example is the radio galaxy Cygnus A). In less powerful radio sources (for example, M 87), jets become sub-relativistic closer to the radio core, but they likely are still relativistic initially (Giovannini et al. 1998). There are systematic differences in the emission line properties of AGN as a function of radio power: low-luminosity (FR 1) sources have low excitation lines, while high-
luminosity (FR 2) sources are more diverse, having a range of ionization states and line strengths (Laing et al. 1994; Chiaberge et al. 2002 and this conference). Clearly, some unify (through orientation) with luminous BL Lacs, while others are quasars. Interestingly, there appears to be an analogous situation among radio-quiet objects, in that some Seyfert 2s have hidden (strong) broad-line regions while others simply have intrinsically weak lines (Tran 2001).

Population statistics confirm that relativistic beaming is an essential feature of radio-loud AGN. Luminosity functions and number counts for blazars are commensurate with their being beaming-dominated, aligned versions of normal radio galaxies (Urry & Padovani 1995). The bulk Lorentz factors are $\Gamma \sim 5 - 10$, similar to those inferred from superluminal motion. Some have speculated that OVV quasars might evolve into BL Lac objects, which is equivalent to saying that powerful FR 2 radio sources evolve into FR 1 radio sources (Vagnetti et al. 1991, Maraschi & Rovetti 1994, Jackson & Wall 1999).

2. Underlying Physics and Jet Energy

Orientation is obviously a major influence on observed properties of radio-loud AGN. The jet brightness can vary by factors of a million or more, depending on whether it is approaching, receding, or in the plane of the sky. Yet intrinsic physical differences among AGN are clearly present, and are the interesting part of the story. How do we get at these intrinsic AGN characteristics? Probably the most important are mass accretion rate, efficiency of converting gravitational potential energy to radiation and kinetic outflows, and black hole mass. A
combination of the first two can be guessed from thermal emission from the accretion disk (or equivalent) – UV bump, lines, etc.

In evaluating the extraction of energy from accretion, however, one needs to account not only for the observed radiation but for the power channeled into the jet, which is considerable (Celotti & Fabian 1993). In many cases, the kinetic power dominates the total power budget.

Jets must be produced with a range of power, possibly even a bimodal distribution (Meier 2001). Observationally, however, the distribution of jet powers is not really known. It is an important constraint on models for jet formation, and an essential ingredient in models that explain the large-scale morphologies of radio galaxies. It may be possible to infer the distribution of jet powers from studies of blazar jets, and a number of such studies are underway.

There is clear evidence (Fig. 2) that the morphologies of radio sources depend on both intrinsic jet power and on the density of surrounding medium (Owen & Ledlow 1994), and indeed models have been successfully developed along these lines (Bicknell 1985, De Young 1993).

3. Host Galaxies, AGN Formation, and Black Hole Growth

The most powerful radio galaxies formed at high redshifts, judging from the colors of their host galaxies. They are similar to the host galaxies of nearby, less powerful radio galaxies, apart from passive stellar evolution. Ultraviolet images of local radio galaxies are very similar to the rest-frame ultraviolet images of distant radio galaxies, apart from their lower luminosity. Probably radio-loud AGN have more luminous host galaxies than radio-quiet objects.

There is evidence that the onset of radio activity — namely, the formation of jets — is associated with the clearing of dense gas and dust, based on associated CIV absorption (Baker et al. 2002). The frequent association of AGN and starbursts is also commensurate with an emerging picture wherein the onset of accretion (and thus extraction of energy from the central black hole) coincides with formation of the galactic bulge (a dissipative collapse, possibly merger induced) and with the ensuing starburst activity. These events may be truly simultaneous in cosmic terms (Kormendy & Gebhardt 2000).

4. Radio-Quiet and Radio-Loud AGN

It is entirely possible that relativistic jets are produced in the centers of all AGN, including radio-quiet objects; in the latter sources, they simply become sub-relativistic much sooner. There is some tentative evidence for this. There are suggestions that relativistic beaming is important in intermediate radio-loudness objects (namely, those with flat-spectrum radio cores; Falcke et al. 1996), and superluminal motion has been reported in two radio-quiet objects (Blundell 1998, Brunthaler et al. 2000).

The notion of a distinct bimodality in radio loudness of AGN — that is, the separate categories “radio-quiet” and “radio-loud” — is based largely on the radio properties of the PG sample of quasars (Kellerman et al. 1989). But the statistics of that sample were not overwhelming and indeed the data are com-
Radio-Loud AGN

5

Figure 3. Distributions of radio loudness for two quasar samples. Left: PG quasars (Kellerman et al. 1989); right: FIRST quasars (White et al. 2001). These distributions are not convincing evidence of bimodality in radio loudness; indeed, the FIRST distribution suggests a continuous distribution of radio loudness, and thus no sharp division between radio-loud and radio-quiet AGN.

compatible with a roughly Gaussian peak at low radio-to-optical ratio (representing the 90% of AGN that are radio-quiet) plus an extended tail to higher values (the 10% of AGN that are radio-loud). The FIRST bright quasar sample, which probes much lower radio fluxes, indeed shows no signs of a bimodal distribution in radio loudness (White et al. 2001). Figure 3 shows the two distributions.¹

5. Black Hole Masses

Black hole mass is a fundamental property of AGN, and must be related, in an as-yet unknown way, to the individual characteristics of AGN. In recent years there has been a flurry of activity on this front.

Black hole mass can be estimated in several ways. Direct dynamical methods — for example, measuring orbital motions of gas very near the black hole — are possibly only for a few very local AGN (e.g., NGC4258; Miyoshi et al. 1995). More generally, one can apply the virial theorem to the broad emission line clouds, provided the distance from the black hole to the broad line region is known. This distance can be estimated most reliably from reverberation mapping, but can also be guessed from photoionization models, or from optical or ultraviolet luminosity (which appears to correlate with reverberation-mapped broad-line region size; Kaspi et al. 2000).

¹We use the standard definition of radio-loudness, $R > 10$, where $R \equiv F_{5\text{GHz}}/F_B$ (Kellerman et al. 1989).
Figure 4. Absolute R-band host galaxy versus nuclear magnitude (K-corrected and, for BL Lac nuclei, also corrected for beaming) for low-power radio-loud AGN (filled circles) and high-power radio-loud AGN (stars). The scatter in the host galaxy magnitudes is very small (rms $\sim 0.25$ in log $L_{gal}$), over a range of more than 4 orders of magnitude in nuclear luminosity. The solid line indicates an Eddington ratio of $L/L_{Edd} = 1$, and the dashed line is $L/L_{Edd} = 0.01$, obtained by assuming the host galaxy luminosity–black hole mass relation reported by Kormendy & Gebhardt (2001).

Alternatively, we can infer black hole mass from host galaxy properties, under the assumption that AGN host galaxies are intrinsically the same as non-active galaxies (the “Grand Unification” hypothesis, for which there is increasing evidence). Normal galaxies show a clear correlation between black hole mass and stellar velocity dispersion, $\sigma$, in the galaxy. Thus if one could measure $\sigma$ in AGN hosts, or infer it somehow (for example, from the morphological parameters $\mu_e$ and $r_e$, together with the fundamental plane correlation for early type galaxies), then the $M_{BH} - \sigma$ correlation yields a black hole mass estimate.

Our extensive HST survey of the host galaxies of low-luminosity radio-loud AGN (Falomo et al. 1997, 2000; Urry et al. 1999, 2000; Scarpa et al. 2000, 2001) showed that the host galaxy properties were remarkably independent of nuclear luminosity. Essentially all hosts are luminous elliptical galaxies, which follow well the Kormendy relation between half-light radius and surface brightness at that radius (the $\mu_e - r_e$ anti-correlation). Comparing our sample to host galaxies of higher luminosity radio-loud AGN (quasars), we found that galaxy luminosity was remarkably uniform, despite several orders of magnitude range in nuclear luminosity (O’Dowd et al. 2002; Fig. 4).

To extend this study to more AGN, both radio-loud and radio-quiet, we collected black hole mass estimates for a heterogeneous sample of nearly 500 AGN (Woo & Urry 2002a,b), using both the virial method and the host-galaxy method. We used published multiwavelength data to estimate bolometric luminosities for every AGN in the sample. The goal was to look for trends of
black hole mass with luminosity, Eddington ratio, radio loudness, and so on. We found no significant trends (or rather, none that could not be explained by obvious selection effects like flux limits or volume surveyed). As implied by the earlier O’Dowd work, black hole mass is not correlated with luminosity (Fig. 5a) or with Eddington ratio (Fig. 5b).

One of the most persistent and intriguing suggestions is that radio loudness is closely tied to black hole mass. In particular, it has been suggested that radio luminosity correlates with black hole mass (Franceschini et al. 1998, but see Oshlack et al. 2002), or that there might be a threshold effect such that radio loudness requires a high black hole mass ($M > 10^9 M_\odot$; Laor 2000, Lacy et al. 2001). We find no such relation. Figure 6 shows radio loudness versus black hole mass for the largest compilation of AGN to date (Woo & Urry 2002b).

6. Grand Unification of AGN and Galaxies

It seems increasingly likely that AGN are normally evolving galaxies going through a high-accretion-rate phase. This is supported by several independent lines of evidence. First, essentially all local normal galaxies (at least those with bulges) host supermassive black holes (Kormendy & Gebhardt 2001). The correlation between black hole mass (most of which must be accumulated during the high-accretion period) and the host galaxy bulge luminosity and/or stel-
Figure 6. Radio loudness versus black hole mass for 452 AGN, most at $z \lesssim 1$. There is no correlation between radio loudness and black hole mass. In particular, at high mass ($M > 10^9 M_\odot$) there are similar distributions of black hole mass for radio-loud ($R > 10$) and radio-quiet AGN. Squares: PG quasars, all at $z < 0.5$; circles: remaining AGN from Paper I, at $0 < z < 1$; triangles: high-redshift quasars ($2 < z < 2.5$) from McIntosh et al. (1999); stars: LBQS quasars, $0.5 < z < 1$; arrows: upper limits for LBQS quasars, $0.5 < z < 1$. Radio fluxes for AGN from the Parkes sample of Oshlack et al. (2002) have been revised downward to account for relativistic beaming, following Jarvis & McLure (2002).

Lar velocity dispersion directly implies at least a related evolution of AGN and galaxies. Second, equating the integrated quasar light to accreted mass (modulo some efficiency factor) requires episodic accretion to occur for $\sim 5 - 10\%$ of the time in most galaxies in order to avoid overly massive black holes (Cavaliere & Padovani 1989). Third, the host galaxies of AGN are indistinguishable from normal galaxies, at least based on present imaging data (Taylor et al. 1996; McLure et al. 1999; Urry et al. 2000; Bettoni et al. 2001). Finally, a few percent of Lyman-break galaxies have emission lines, and appear to be some sort of AGN (Steidel et al. 2002).

Suppose AGN and galaxies are precisely the same population, with AGN simply representing a particular phase of normal galaxy evolution. We call this the “Grand Unification” hypothesis. The AGN phase in individual galaxies would occur when episodes of high accretion are triggered, and could be influenced by interactions or mergers. As many have pointed out, this explains naturally why there are more AGN at high redshift, where the galaxy density is far higher and interactions are more common.

Obviously, for the better understanding of our Universe, it is of great interest to test the Grand Unification hypothesis thoroughly. One key issue is whether AGN host galaxies are indeed indistinguishable from normal galaxies. Most such inferences are based on imaging data; measuring the stellar velocity dispersions
in AGN host galaxies — a project that several groups are now undertaking — is a critical next step.

In the presently preferred scenario, black hole accretion coincides with bulge formation and starburst activity (Kormendy & Gebhardt 2001). Jets may be generated in most or all galactic nuclei, with a broad distribution of initial kinetic power (cf. Meier 2001). Weak jets would be most prevalent by far, and would lead to radio-quiet AGN, possibly with jet-initiated winds and outflows, of the kind seen in many Seyfert galaxies. More powerful jets would evolve into luminous radio sources once the dense gas associated with the starburst has cleared (Baker et al. 2002). Testing this Grand Unified picture is the next step in understanding AGN.

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