Abstract.

Observations made with the VLBA have led to fundamental advances in our understanding of how radio jets in AGN evolve from parsec-scales out to distances exceeding several hundred kiloparsecs. In this review I discuss current models of young radio source evolution, as well as the observational evidence for a rapid change in jet properties on scales of $\sim 1$ kpc. A central topic of current debate is the relative importance of intermittent jet fueling versus jet-environment interactions in causing a drop-off in powerful radio sources at this critical evolutionary stage. Recent 3-D hydrodynamical jet simulations suggest that dense environments and cloud collisions can temporarily stifle, but not completely halt powerful relativistic jets. Several VLBA studies of jet-ISM interactions in both blazars and weak Seyfert jets have indicated that collimated outflows are indeed possible in dense environments. At present, the bulk of the evidence favors intermittent AGN accretion as the dominant factor in determining the evolutionary path of large numbers of AGN jets.

1. Introduction

One of the most fundamental questions that can be asked about jets associated with active galactic nuclei (AGN) is how do they evolve from their dense, gas-rich parsec-scale environments out to scales of hundreds of kiloparsecs, well outside their host galaxies. The capability of radio wavelength interferometers to penetrate the dense gas and dust in the centers of AGN host galaxies at high resolution has brought us tantalizingly close to fully answering this question. In this review, I briefly describe our current understanding of young radio jet evolution, and the relative role played by jet-environment interactions. I begin in §2 by discussing what has been learned from statistical population studies, and devote Sections 3 and 4 to numerical jet simulations and individual VLBA case studies that have improved our understanding of interactions between AGN jets and their parsec-scale environments.

2. Evolution of young AGN jets

Our current knowledge of radio jet evolution owes a great deal to the gigahertz-peaked spectrum (GPS) class of radio source, which comprise approximately $\sim 10\%$ of flux-limited samples at cm-wavelengths. Originally classified in early surveys as 'compact doubles' by Phillips & Mutel (1982), subsequent improvements in VLBI capabilities revealed weak central components, and in some cases faint bridges of emission connecting them with bright outer features. It was
soon recognized that these AGN were miniature versions of the classical kpc-scale lobe-core-lobe radio galaxies, with similar total radio powers, but over a thousand times smaller in extent.

Based on observed size trends in GPS and compact steep spectrum (CSS) sources (e.g., Jeyakumar & Saikia 2002), self-similar expansion models (e.g., Begelman 1996; Bicknell et al. 1997) were developed in which the overall linear extent of the jets grow in proportion with their hotspot diameters. These hotspots remain in ram pressure equilibrium with the external medium, which implies that the evolution of the source is strongly dictated by the density profile of the ISM. Numerical simulations (see § 3) of jets expanding into power-law external density profiles confirmed that a large bow shock forms ahead of the hotspot, allowing the latter to expand smoothly and propagate outward relatively unimpeded. Unlike the dentist drill model for kpc-scale lobes, very little side-to-side motion is expected for the pc-scale hotspot. Spectacular confirmation of these models came with the first measurements of hotspot proper motions in GPS radio galaxies (e.g., Owsianik et al. 1999), which displayed predominantly outward (non-transverse) motion. The derived kinematic ages, based on constant expansion, were typically $\sim 1000$ y (Gugliucci et al. 2005), confirming that these were in fact recently launched jets.

The first problems with the standard scenario arose with detailed studies of population statistics. In a steady-state population, one would expect a rather flat distribution of kinematic ages, but in fact, the observed one is peaked at young ages (Gugliucci et al. 2005). A similar conclusion had been reached previously by independent authors who considered the luminosity functions of GPS sources (e.g., Begelman 1996; Readhead et al. 1996). Given their high luminosities, the young radio sources were too numerous compared to their more aged radio galaxy cousins, implying that must either dim rapidly, or die out completely before reaching sizes of a few kpc. A lingering issue of current debate is the relative importance of AGN fueling and environmental interactions in dictating the evolution of radio jets at this critical evolutionary stage.

2.1. AGN fueling and intermittent jet activity

Although a simple argument for intermittent jet activity in AGN can be found in the fact that only $\sim 10\%$ of all AGN associated with super-massive black holes are radio loud, yet the lifetimes of individual AGN are on the order of a few hundred Myr, true ‘smoking gun’-type evidence has become available only relatively recently. The most compelling has been the discovery of the ‘double-double’ class of radio galaxy (Schoenmakers et al. 2000), of which roughly a dozen are currently known (Marecki et al. 2006). These sources contain two sets of nested radio lobes, which are symmetric with respect to a central component associated with the active nucleus. The inner double resembles in many ways a GPS source, with a peaked radio spectrum, bright hotspots, and fast expansion speed. The outer lobe structures, on the other hand, have sizes comparable to the those of the largest known radio galaxies. The notable gap in radio emission between the two components is indicative of a long quiescent period, on the order of $10^6 - 10^7$ Myr, in which the jet was presumably switched off (e.g., O’Dea et al. 2001).
Understanding intermittent jet activity in AGN is undoubtedly an important factor in building a complete model of jet evolution (e.g., \cite{Reynolds_1997}). However, it is still a nascent field in which the necessary statistical samples (needed because of the long evolutionary timescales involved) are still being gathered. As I will describe below, considerably larger progress has been made in understanding the role played by jet-ISM interactions in affecting AGN jet evolution.

2.2. Basic forms of jet-ISM interaction

Because they are relatively light compared to their external environments (density contrasts on the order of $10^{-3}$, e.g., \cite{Krause_2003}), AGN jets are highly susceptible to external interactions, which can be classified roughly into three main areas:

- **Bow shock-hotspot interaction** at the jet terminus, as in the standard models described above.

- **Cloud collisions**, which can cause bending and disruption of the flow.

- **Entrainment**, leading to shear layers, deceleration, instabilities, and possible particle acceleration at the jet boundaries.

Although much is known about the physics of entrainment in kiloparsec-scale jets, progress on parsec-scales has been limited by several factors. These include the difficulty of observing faint, diffuse emission at the jet boundaries with limited dynamic-range VLBI, as well as a paucity of bright, nearby AGN jets which we can resolve in a transverse direction to the flow. Furthermore, studies of the crucial 100-1000 milliarcsecond region where jets may undergo strong internal changes due to entrainment have been hampered by the lack of a suitable interferometer matching the sensitivity of the VLA or VLBA. For these reasons I will concentrate hereafter on the issue of jet interactions with dense clouds in the nuclear region of the host galaxy.

3. Numerical jet-cloud simulations

Numerical simulations continue to play a vital role in understanding the structure and evolution of AGN jets, by providing the ability to test various scenarios under controlled conditions. Early numerical jet-medium interaction studies were able to reproduce classical bow shock and hotspot structures by propagating supersonic outflows into external media with uniform density and pressure gradients (e.g., \cite{Hardee_1990}). The extension of MHD codes to the fully three-dimensional, relativistic regime has made it possible to robustly examine powerful jet evolution through a more realistic, non-uniform medium for the first time. I describe here two such studies (\cite{Choi_2007} and \cite{Sutherland_2007}), that are of particular relevance to young jet evolution.

The simulations of \cite{Choi_2007} employ a fully 3-D, pure hydrodynamic code to simulate the passage of the relativistic jet through a two-phase
medium. The latter consists of a single dense cloud embedded in a constant-pressure gas. They examined cases of both high (\( \Gamma = 7 \)) and low (\( \Gamma = 2.29 \)) Lorentz factor jets striking the cloud slightly off-axis. During the interaction, an oblique shock forms in the jet, causing it to bend. Unlike previous non-relativistic studies (e.g., Wang et al. 2000; Higgins et al. 1999), the flow itself does not undergo any significant deceleration or decollimation, and remains stable after the interaction event. By varying the cloud-to-ambient medium ratio, the authors find that the highest deflections occur in the case of low-Mach number jets hitting denser clouds, with cloud density being the dominant factor. Thicker clouds end up being less encompassed by the bow shock, allowing earlier interaction with the Mach disk and stronger oblique shocks in the flow. The clouds themselves can actually survive the event, provided the cloud/jet density contrast is high enough to suppress most Kelvin-Helmholtz instabilities. These regions of shocked gas may be important star formation sites (see § 4) and may play a role in creating the emission-line/jet alignment effect in AGN (e.g., McCarthy et al. 1987).

Sutherland & Bicknell (2007) investigate the more general case of a jet propagating through an inhomogeneous medium in the form of a massive (\( 10^{10} \) M\(_{\odot} \)), turbulently supported disk plus a hot (\( 10^7 \) K) ISM. Like Choi et al. (2007), they use a fully 3-D pure hydrodynamic code, although in this case a non-relativistic one for which they derive relativistic scaling parameters according to Komissarov & Falle (1996). In the initial phase of their simulations of a \( \sim 10^{43} \) erg s\(^{-1} \) jet, the morphology looks strikingly different than those seen in other studies that assume a uniform ISM, in that the flow attempts to seek out and pass through the lowest-density locations in the clumpy (fractal) medium. In doing so, multiple channels are formed and reformed, followed by the formation of quasi-spherical bubbles around the jet and counter-jets that expand outward. Making simple assumptions about the gas emissivity, the authors find that these bubbles should be prominent in hard X-rays. Once the jet reaches the outer edge of the disk and clears the last obstruction, a stable, linear outflow develops, containing the standard re-collimation and bow shock structures. At this point it pierces the expanding bubble and evolves as in the uniform medium case.

The authors find a good deal of similarity between the predicted radio emission from their simulations and the compact symmetric object (CSO) 4C 31.04 (Cotton et al. 1995). This young radio source is characterized by a large asymmetry in its jet and counter-jet structure, as well as lobe spectral index gradients that are difficult to reconcile with standard models of cocoon backflow (Giroletti et al. 2003). Comparison with their simulations led Sutherland & Bicknell (2007) to suggest that the western lobe may be near the end of the breakout phase, whereas the eastern lobe is at a slightly earlier stage of evolution. The strong apparent northward deflection of the western lobe flow at the hotspot is also reminiscent of structure found in the simulations of Choi et al. (2007).

The conclusion that can be drawn from these studies is that powerful relativistic jets are not likely to be permanently stifled by neither direct jet-cloud collisions, nor a dense, clumpy external medium. Instead, it is more likely that they all pass through an evolutionary stage in which the flow may be bent and not necessarily well-collimated. The duration of this stage is largely determined
by the power of the jet, and to a lesser extent, the jet/medium density contrast. Given the good initial agreement with observed jet structure from these preliminary simulations, it suggests that through careful study of jet morphologies of young radio sources, it may be possible to identify the precursors to both high- and low-power radio galaxies, as well as to characterize their early evolutionary paths.

4. VLBA studies of jet-environment interactions

In addition to providing measurements of kinematic expansion speeds, the VLBA provides a variety of unique tools for studying jet-medium interactions on parsec scales. These include HI absorption measurements, Faraday de-polarization and electric vector rotation measurements at sub-milliarcsecond resolution levels. I discuss here several recent VLBA studies of ISM interactions in weak Seyfert jets, as well as in powerful blazars.

4.1. Seyfert galaxies

The relative proximity (15-20 Mpc) of Seyfert galaxies makes them ideal targets for investigating jet-environment effects with the VLBA at spatial resolutions approaching several thousand A.U. Given that their jet powers are typically a factor of 100-1000 smaller than radio-loud quasars (e.g., Goldschmidt et al. 1999), they are much more subject to entrainment and disruption (e.g., De Young 2006). Their sporadic accretion rate also offers the chance to examine in detail the effects of central engine disruption on jet structure.

NGC 4151: The nearly-face on Seyfert 1.5 galaxy NGC 4151 has been the subject of many intensive VLBI studies, due to its well-defined, two-sided, ~100 parsec-long radio jets, as well as the large quantity of neutral gas in its nuclear region. HST imaging has revealed numerous ionized gas clouds in an inner region that is extended about an axis roughly aligned with the radio jets (Hutchings et al. 1998; Kaiser et al. 2000). The spatial geometry of the narrow-line region suggests a thick molecular torus aligned perpendicular to the jet, which is confirmed by H$_2$ measurements (Fernandez 1999). VLBA absorption data have also provided evidence for an inner HI ring (Ulvestad et al. 1998; Mundell et al. 2003). The radio spectral flattening and brightness enhancement of the jet at this location led Mundell et al. (2003) to suggest that this marks a site of jet-ISM interaction. Although the VLBA images lack sufficient dynamic range to fully examine the extremely weak surface brightness structure, the jet does undergo an abrupt deviation at this point, in a manner similar to the jet-cloud simulations of Choi et al. (2007). Mundell et al. (2003) found the HI absorption line profiles to vary significantly toward different portions of the jet, indicating a medium composed of clumpy dense clouds with a variety of velocities. Although they speculate that some of the other bright knots in the jet may be the result of jet-cloud encounters, the authors rule out shock ionization as the main source of the NLR, based on its imprecise alignment with respect to the radio jet, and the presence of several low-velocity clouds very near the jet that show no signs of interaction.
NGC 3079: This is another good example of a Seyfert jet in a dense environment, albeit in this case the galaxy is viewed nearly edge-on (Sosa-Brito et al. 2001). Using a series of VLBA measurements over a six year period, Middelberg et al. (2007) have discovered complex kinematics and variable jet emission in this source. They found one bright jet knot initially moving at nearly 0.1 c, only to watch it decelerate and become virtually stationary during the final year of their observations. During this time its flux density increased and its spectrum changed to a convex free-free/synchrotron-self absorbed profile. This behavior is consistent with that expected from the jet-cloud simulations described in §3. Furthermore, the source contains several steeper spectrum features well off the main jet axis, which could perhaps be remnants of earlier flow channels as predicted by Sutherland & Bicknell (2007). NGC 3079 thus provides an excellent example of the potential of multi-epoch VLBA studies for exploring the kinematics of jet-cloud interactions at exceedingly high spatial resolution.

PKS 1345+12: The ultra-luminous infrared galaxy IRAS 13451+1232 is a recent merger system with significantly distorted optical morphology and a binary nucleus, the northwest of which has been classified as a Seyfert 2 (e.g., Scoville et al. 2000). The latter also contains a spectacular radio jet (PKS 1345+12), which extends nearly 200 pc in a continuous, sinusoidal pattern (Lister et al. 2003). The counter-jet is also visible, but only out to ~ 50 pc from the nucleus. Although these properties are consistent with the CSO class, this object is unique in the fact that Lister et al. (2003) measured speeds of 1 c in the innermost jet region, as well as high fractional polarization at the location of the southern hotspot. The latter is significant as it implies a continuous resupply of energy, i.e., the southern jet is not stifled by this very gas rich galaxy.

By fitting to the apparent ridge line, apparent speeds, and jet/counter-jet ratio, Lister et al. (2003) concluded that the jet follows a three-dimensional, conical helix aligned 82 degrees from our line of sight, with an intrinsic flow speed of ~ 0.8 c. Similar sinusoidal ridge lines seen in other CSOs and blazars have led various authors to conclude that these may be the result of growing Kelvin-Helmholtz instability modes, driven by small perturbations at the jet nozzle and excited by interaction with the medium at the jet boundaries. The northern counter-jet shows a deviation from the predicted best-fit helical path, and is truncated at the site of dense HI absorption (> 10^{22} cm^{-2}; Morganti et al. 2003). This appears therefore to be a clear case where asymmetries in the external environment have a strong differential impact on the morphology and evolutionary rates of the jet and counter-jet of a young radio source.

4.2. Blazar Jets

Despite their much larger distances, blazar jets can also serve as useful probes of parsec-scale jet interactions. First, because they are viewed directly down the opening in the obscuring torus, there is much less de-polarization, meaning that the jet polarization and magnetic field properties can be directly studied. This also means that any intervening gas can be potentially studied via Faraday rotation measures (e.g., Zavala & Taylor 2005). Second, any slight deviations in the flow that may be caused by interactions are greatly magnified by projection effects. Finally, because of Doppler effects, there are many examples of blazars
where over a century of jet evolution is compressed into a span of only a few years of observing time (e.g., Kellermann et al. 2004).

3C 279: The powerful jet in the quasar 3C279 was one of the first jets in which superluminal motion was witnessed, and has been the target of intensive study in a variety of wave-bands. The jet has been regularly imaged since 1994 by the 2 cm Survey (Kellermann et al. 2004) and MOJAVE (Lister & Homan 2005) programs with the VLBA at a wavelength of 2 cm. Shorter wavelength (7 mm) VLBA monitoring (Jorstad et al. 2004, 2005) has revealed a regular swing in the ejection direction of the jet close to the nozzle, over a timescale of 3 years. Homan et al. (2003) describe one prominent jet feature (C4) that was ejected in late 1984, which moved steadily along a linear path for over a decade with an apparent speed of 8 c, before suddenly undergoing an increase in brightness and change in polarization angle in 1998. These events were followed shortly thereafter by a rapid apparent acceleration to 13 c, and a change in trajectory of 26 degrees. Under the most conservative assumptions, Homan et al. (2003) found that these changes were consistent with an intrinsic bend of only 0.5 to 1 degree. Given the fact the brightening and polarization changed before the change in trajectory, the most plausible scenario is one in which C4 is interacting with the external environment. Furthermore, the direction of the new trajectory closely matches that of another feature ejected several decades previously, which rules out a random jet-cloud collision. The authors suggest instead that the event represents a collimation of the jet resulting from a jet-boundary interaction at a de-projected distance $\gtrsim 1$ kpc from the nucleus. Since this is the first such an event to be witnessed in an AGN jet, it is difficult to yet draw solid conclusions on the validity of this model. However, large intensive VLBA monitoring programs such as MOJAVE (Lister & Homan 2005) may soon provide additional examples for further study.

3C 120: Although classified as a Seyfert 1, this nearby ($z = 0.033$) broad-lined galaxy shares many properties with blazars, including superluminal motions of up to 6 c, a one-sided radio jet, and flux variability. Axon et al. (1989) found high-velocity emission line components in the host galaxy that suggested interaction between the jet and gas clouds in the NLR. The excellent spatial resolution (0.1 pc) achievable by the VLBA at 43 GHz has enabled detailed study of its jet evolution in both total intensity and linear polarization (Gomez et al. 2001, Jorstad et al. 2005). The jet is resolved perpendicular to the flow direction, and a distinct asymmetry is seen between the northern and southern edges. In particular, Gomez et al. (2001) have found a distinct region in the southern edge, approximately 8 pc (de-projected) from the base of the jet, where moving jet features show marked changes as they pass through. These include a brightening in flux density, and a rotation of their polarization electric vector position angles (EVPAs). These events are different from that witnessed in 3C 279, since in this case no accelerations are seen. Gomez et al. (2001) conclude the most likely explanation to be interaction with a cloud, which causes Faraday rotation of the EVPAs, and shocking of the jet material. There is also an indication of a slight bend at the interaction site, although the jet remains well-collimated downstream. Ideally it would be useful to study additional examples of this type of interaction, but unfortunately there are still very few known bright jets that
are close enough to be resolved transversely by the VLBA, and yet have viewing angles small enough not to be heavily de-polarized by foreground nuclear gas.

5. Summary

High-resolution radio observations of young radio jets associated with gigahertz-peaked spectrum AGN have led to considerable insight into the evolutionary processes of AGN jets. Kinematic and population studies have shown that these young radio sources undergo a significant decline in numbers when they reach sizes of $\sim 1 \text{kpc}$. VLBA studies of individual jets have provided clear evidence for interaction with clouds in their external environment, suggesting stifling by dense gas as a possible cause. However, detailed numerical simulations of jet-environment interactions indicate that dense, clumpy environments can only temporarily stifle the flow of powerful jets, even in the case of direct jet-cloud collisions. Furthermore, the discovery of 'double-double' galaxies has provided solid evidence of recurrent jet activity in powerful AGN. It therefore appears likely that variable accretion rates play a major role in determining the evolutionary paths of many AGN. The enhanced resolution and sensitivity of upcoming facilities such as VSOP-II, the EVLA, and the SKA should provide many new opportunities for studying the evolution of young radio sources and their interactions with their external environment.

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