Compact jets as probes for sub-parsec scale regions in AGN

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Abstract Compact relativistic jets in active galactic nuclei offer an effective tool for investigating the physics of nuclear regions in galaxies. The emission properties, dynamics, and evolution of jets in AGN are closely connected to the characteristics of the central supermassive black hole, accretion disk and broad-line region in active galaxies. Recent results from studies of the nuclear regions in several active galaxies with prominent outflows are reviewed in this contribution.

Keywords galaxies: active; galaxies: nuclei; galaxies: jets

1 Introduction

Substantial progress achieved during the past decade in studies of active galactic nuclei has brought an increasingly wider recognition of the ubiquity of relativistic outflows (jets) in galactic nuclei, turning them into an effective probe of nuclear regions in galaxies (Lobanov & Zensus 2006). Emission properties, dynamics, and evolution of an extragalactic jet are intimately connected to the characteristics of the supermassive black hole, accretion disk and broad-line region in the nucleus of the host galaxy.

High-resolution radio observations access directly the regions where the jets are formed (Junor 1999; Bach et al. 2005), and trace their evolution and interaction with the nuclear environment (Mundell et al. 2003). These studies, combined with optical and X-ray studies, yield arguably the most detailed picture of the galactic nuclei (Marscher 2003). Presented below is a brief summary of recent results in this field, outlining the relation between jets, supermassive black holes and nuclear regions in prominent active galactic nuclei (AGN). In this respect, this review is complementary to other recent reviews (Camenzind 2005; Königl 2006; Marscher 2003) focused on formation and propagation of extragalactic relativistic jets.

2 Compact jets in AGN

Jets in active galaxies are formed in the immediate vicinity of the central black hole (Camenzind 2005), and they interact with every major constituent of AGN (see Table 1). The jets carry away a fraction of the angular momentum and energy stored in the accretion flow (Hujeirat et al. 2003) or corona (in low luminosity AGN; Merloni & Fabian 2002) and in the rotation of the central black hole (Koide et al. 2002; Komissarov 2005).

The production of highly-relativistic outflows requires a large fraction of the energy to be converted to Poynting flux in the very central region (Sikora 2005). The efficiency of this process may depend on the spin of the central black hole (Meier 1999). The collimation of such a jet requires either a large scale poloidal magnetic field threading the disk (Spruit et al. 1997) or a slower and more massive MHD outflow launched at larger disk radii by centrifugal forces (Bogovalov & Tsynganos 2005).

At distances of $\sim 10^3 R_g$ ($R_g = G M/c^2$ is the gravitational radius of a black hole), the jets become visible in the radio regime, which makes high-resolution VLBI observations a tool of choice for probing directly the physical conditions in AGN on such small scales.

1 Very Long Baseline Interferometry
Recent studies indicate that at distances of $10^3$–$10^5 \, R_g$ ($\lesssim 1$ pc) the jets are likely to be dominated by pure electromagnetic processes such as Poynting flux (Sikora 2005) or have both MHD and electromagnetic components (Meier 2003). The flowing plasma is likely to be dominated by electron-positron pairs (Wardle et al. 1998; Hirotani 2005) although a dynamically significant proton component cannot be completely ruled out at the moment (Celotti 1993). How far the magnetic field dominated region extends in extragalactic jets is still a matter of debate. There are indications that this region does not extend beyond several parsecs. Parsec-scale flows show clear evidence for the presence of rapidly dissipating relativistic shocks (e.g. Lobanov & Zensus 1999) preceding the development of Kelvin-Helmholtz instability (Lobanov & Zensus 2001) dominating the flow dynamics on kiloparsec scales (Lobanov et al. 2003).

**Ultracompact jets** observed down to sub-parsec scales typically show strongly variable but weakly polarized emission (possibly due to limited resolution of the observations). Compelling evidence exists for acceleration (Bach et al. 2005) and collimation (Junor 1999) of the flows on these scales, which is most likely driven by the magnetic field (Vlahakis & Königl 2004). The ultracompact outflows are probably dominated by electromagnetic processes (Meier 2003; Sikora 2005), and they become visible in the radio regime (identified as compact “cores” of jets) at the point where the jet becomes optically thin for radio emission (Lobanov 1998; Lobanov & Zensus 1999). At this point, the jets do not appear to have strong shocks (??) and their basic properties are successfully described by quasi-stationary flows (Königl 1981). The evolution and variability of the “core” can be explained by smooth changes in particle density of the flowing plasma, associated with the nuclear flares in the central engine (Fig. 1). Intrinsic brightness temperatures of the ultracompact jets are estimated to be $(1–5) \times 10^{11} \, K$ (Lobanov et al. 2000), implying that the energy losses are dominated by the inverse-Compton process.

Quasi-periodic variability of the radio emission from the ultracompact jets is most closely related to instabilities and non-stationary processes in the accretion disks around central black holes in AGN (Igumenschev & Abramowicz 1999; Lobanov & Roland 2005). Alternative explanations involve binary black hole systems in which flares are caused by passages of the secondary through the accretion disk around the primary (Ivanov et al. 1998; Lehto & Valtonen 1996). These models however require very tight binary systems, with orbits of the secondary lying well within $10^3$ Schwarzschild radii of the primary (between 20 and 100 Schwarzschild radii, in the celebrated case of OJ 287; Lehto & Valtonen 1996), which poses inevitable problems for maintaining an accretion disk around the primary (for massive secondaries; Lobanov 2006) or rapid alignment of the secondary with the plane of the accretion disk (for small secondaries; Ivanov et al. 1999). Discrepancy between the predicted and actual epoch of the latest outburst in OJ 287 (Valtonen et al. 2006) indicates further that the observed behavior is not easy to reproduce by a binary black hole scenario and it is indeed more likely to result from a quasi-periodic process in the disk, similarly to the flaring activity observed in 3C 345 (Lobanov & Roland 2005).

### 3 Jets and nuclear regions in AGN

A number of recent studies have used the ultracompact jets as probes of physical conditions in the central
regions of AGN. These studies have focused on basic characteristics of relativistic flows and atomic, physical properties of the molecular material in circumnuclear regions of AGN, and connection between relativistic outflows and accretion disks and broad-line emitting regions.

Synchrotron self-absorption and external absorption in the ultracompact jets (VLBI “cores”) can be used effectively for determining the properties of the flow itself and its environment (Lobanov 1998). Absolute position of the core, \( r_c \), varies with the observing frequency, \( \nu \), so that \( r_c \propto \nu^{-1/k_t} \) (Königl 1981). If the core is self-absorbed and in equipartition, the power index \( k_t = 1 \) (Blandford & Königl 1979). Changes of the core position measured between three or more frequencies can be used for determining the value of \( k_t \) and estimating the strength of the magnetic field, \( B_{\text{core}} \), in the nuclear region and the offset, \( R_{\text{core}} \), of the observed core positions from the true base of the jet (see Fig. 2). The combination of \( B_{\text{core}} \) and \( R_{\text{core}} \) gives an estimate for the mass of the central black hole

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M_{\text{bh}} \approx 7 \times 10^9 M_\odot \left( \frac{B_{\text{core}}}{G} \right)^{1/2} \left( \frac{R_{\text{core}}}{\text{pc}} \right)^{3/2}.
\]

Core shift measurements provide estimates of the total (kinetic + magnetic field) power, the synchrotron luminosity, and the maximum brightness temperature, \( T_{b,\text{max}} \) in the jets can be made (\( ? \)). The ratio of particle energy to magnetic field energy can also be estimated, from the derived \( T_{b,\text{max}} \). This enables testing the original Königl model (Königl 1981) and several of its later modifications (e.g., Hutter & Mufson 1986; Bloom & Marscher 1996). The known distance from the nucleus to the jet origin will also enable constraining the self-similar jet model (Marscher 1995) and the particle-cascade model (Blandford & Levinson 1995).

Recent studies of free-free absorption in AGN indicate the presence of dense, ionized circumnuclear material with \( T_e \approx 10^4 \text{K} \) distributed within a fraction of a parsec of the central nucleus (Lobanov 1998, Walker et al. 2000). Properties of the circumnuclear material can also be studied using the variability of the power index \( k_t \) with frequency. This variability results from pressure and density gradients or absorption in the surrounding medium most likely associated with the broad-line region (BLR). Changes of \( k_t \) with frequency, if measured with required precision, can be used to es-
Opacity and absorption in the nuclear regions of AGN have been probed effectively using the non-thermal continuum emission as a background source. Absorption due to several atomic and molecular species (most notably due to HI, CO, OH, and HCO\(^+\)) has been detected in a number of extragalactic objects. OH absorption has been used to probe the conditions in warm neutral gas (Goicoechea et al. 2004, Kloeckner & Baan 2005), and CO and HI absorption were used to study the molecular tori (Conway 1999, Pedlar 2004) at a linear resolution often smaller than a parsec (Mundell et al. 2003). These observations have revealed the presence of neutral gas in a molecular torus in NGC 4151 and in a rotating outflow surrounding the relativistic jet in 1946+708 (Peck & Taylor 2001).

3.2 Jet-disk and jet-BLR connections

Connection between accretion disks and relativistic outflows (Hujeirat et al. 2003) has been explored, using correlations between variability of X-ray emission produced in the inner regions of accretion disks and ejections of relativistic plasma into the flow (Marscher et al. 2002). The jets can also play a role in the generation of broad emission lines in AGN (Fig. 4). The beamed continuum emission from relativistic jet plasma can illuminate atomic material moving in a sub-relativistic outflow from the nucleus, producing broad line emission in a conically shaped region located at a significant distance above the accretion disk (Arshakian et al. 2006). Magnetically confined outflows can also contain information about the dynamic evolution of the central engine, for instance that of a binary black hole system (Lobanov & Roland 2005). This approach can be used for explaining, within a single framework, the observed optical variability and kinematics and flux density changes of superluminal features embedded in radio jets.

4 Conclusion

Extragalactic jets are an excellent laboratory for studying physics of relativistic outflows and probing conditions in the central regions of active galaxies. Recent
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studies of extragalactic jets show that they are formed in the immediate vicinity of central black holes in galaxies and carry away a substantial fraction of the angular momentum and energy stored in the accretion flow and rotation of the black hole. The jets are most likely collimated and accelerated by electromagnetic fields. Convincing observational evidence exists connecting ejections of material into the flow with instabilities in the inner accretion disks. In radio-loud objects, continuum emission from the jets may also drive broad emission lines generated in sub-relativistic outflows surrounding the jets. Magnetically confined outflows may preserve information about the dynamics state of the central region, allowing detailed investigations of jet precession and binary black hole evolution to be made. This makes studies of extragalactic jets a powerful tool for addressing the general questions of physics and evolution of nuclear activity in galaxies.

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