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Vicinity of supermassive black holes probed by high-resolution radio observations

A.P. Lobanov

Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany.
e-mail: `alobanov@mpifr-bonn.mpg.de`

Abstract. Past years have brought an increasingly wider recognition of ubiquity of relativistic outflows (jets) in galactic nuclei, which has turned jets into an effective tool for investigating the physics of nuclear regions in active galactic nuclei (AGN). The emission properties, dynamics, and evolution of jets are intimately connected to the characteristics of the supermassive black hole, accretion disk and broad-line region. High-resolution radio observations access directly the regions where the jets are formed, and trace their evolution and interaction with the nuclear environment. These observations, combined with optical and X-ray studies, yield arguably the most detailed picture of the galactic nuclei. In this talk, a summary of recent results in this field of study will be given, outlining the relation between jets, supermassive black holes, accretion disks and broad-line regions in these objects.

1. Introduction

Recent years have witnessed an increasingly wider recognition of the ubiquity of relativistic outflows (jets) in galactic nuclei, which has turned them into an effective probe of nuclear regions in AGN (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 (Lobanov 2006, 2007).

In radio regime, very long baseline interferometry (VLBI) offers the best opportunity to image directly spatial scales comparable with that of the gravitational radius, $R_{\rm g} = G\,M_{\rm bh}/c^2$, of the central black holes in AGN, using observations at millimeter wavelengths (Krichbaum et al. 2008) and with space VLBI (e.g. Takahashi 2004) combining ground radio telescopes with an antenna in orbit around the Earth. Such high-resolution radio observations also 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 vicinity of supermassive black holes in AGN (Marscher 2005).

2. Ultracompact 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 angu-

Send offprint requests to: A.P. Lobanov

Table 1. Characteristic scales in the nuclear regions in active galaxies

	l $[R_g]$	l_8 [pc]	θ_{Gpc} [mas]	τ_c [yr]	τ_{orb} [yr]
Event horizon:	1–2	10^{-5}	5×10^{-6}	0.0001	0.001
Ergosphere:	1–2	10^{-5}	5×10^{-6}	0.0001	0.001
Corona:	10^1–10^2	10^{-4}–10^{-3}	5×10^{-4}	0.001–0.01	0.2–0.5
Accretion disk:	10^1–10^3	10^{-4}–10^{-2}	0.005	0.001–0.1	0.2–15
Jet formation:	$>10^2$	$>10^{-3}$	$>5\times10^{-4}$	>0.01	>0.5
Jet visible in the radio:	$>10^3$	$>10^{-2}$	>0.005	>0.1	>15
Broad line region:	10^2–10^5	10^{-3}–1	0.05	0.01–10	0.5–15000
Molecular torus:	$>10^5$	>1	>0.5	>10	>15000
Narrow line region:	$>10^6$	>10	>5	>100	>500000

Column designation: l – dimensionless scale in units of the gravitational radius, $G\,M/c^2$; l_8 – corresponding linear scale, for a black hole with a mass of $5\times10^8\,M_\odot$; θ_{Gpc} – corresponding largest angular scale at 1 Gpc distance; τ_c – rest frame light crossing time; τ_{orb} – rest frame orbital period, for a circular Keplerian orbit. Adapted from Lobanov (2006)

lar 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). Production of highly-relativistic outflows requires a large fraction of the energy to be converted to Poynting flux in the very central region (Sikora et al. 2005), which depends on the spin of the central black hole (Meier 1999).

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, ν, so that $r_c \propto \nu^{-1/k_r}$, (Königl 1981). If the core is self-absorbed and in equipartition, the power index $k_r = 1$. Changes of the core position measured between three or more frequencies can be used for determining the value of k_r and estimating the strength of the magnetic field, B_{core}, in the nuclear region and the offset, R_{core}, of the observed core positions from the true base of the jet. The combination of B_{core} and R_{core} gives an estimate for the mass of the central black hole $M_{bh} \approx 7\times10^9\,M_\odot\,(B_{core}/\mathrm{G})^{1/2}(R_{core}/\mathrm{pc})^{3/2}$. Core shift measurements provide estimates of the total (kinetic + magnetic field) power, the synchrotron luminosity, and the maximum brightness temperature, $T_{b,max}$ in the jets can be made (Lobanov 1998). The ratio of particle energy to magnetic field energy can also be estimated, from the derived $T_{b,max}$.

3. Probing the environment of SMBH

Recent studies of free-free absorption in AGN indicate the presence of dense, ionized circumnuclear material with $T_e \approx 10^4$ 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_r 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_r with frequency can be used to estimate the size, particle density and temperature of the absorbing material surrounding the jets (Lobanov 1998). Estimates of the the BLR size, obtained from the core shift measurements, can be compared with the respective estimates from the reverberation mapping.

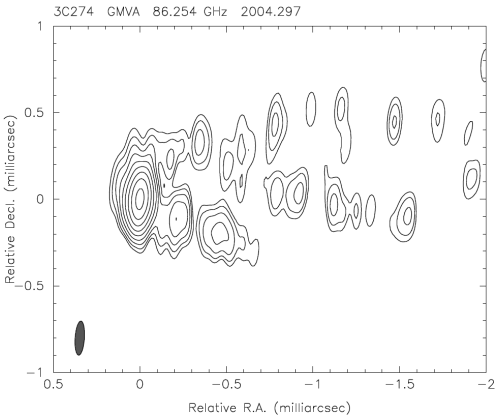

Fig. 1. VLBI image of the nucleus in M 87 at 86 GHz (corresponding to $\lambda = 3$ mm). The image has a 0.2×0.05 milliarcsecond resolution, corresponding to linear scales or less than $100\,R_g$. Reproduced from Krichbaum et al. (2008).

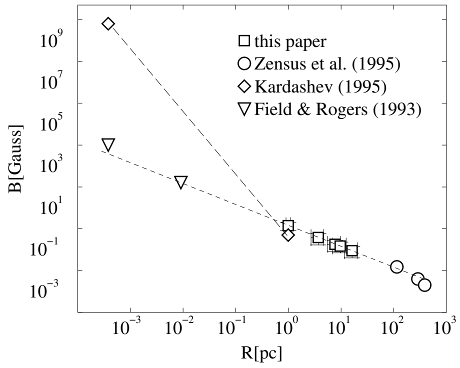

Fig. 2. Magnetic field distribution in the jet in 3C 345. Squares show the magnetic field in the compact jet derived from the frequency dependent shift of the core. Circles are the homogeneous synchrotron model estimates of magnetic field in the extended jet components. Triangles show the characteristic magnetic field values from a model of magnetized accretion disk. Diamonds are the theoretical estimates for the dipole magnetic field, similar to that expected to be found in a magnetized rotating body with hard sruface as opposed to the event horizon of a black hole. Reproduced from (Lobanov 1998).

3.1. Probing the nature of black holes

It still remains an open issue whether the central supermassive bodies in AGN indeed harbour black holes or other more exotic objects such as bozon stars (BS; Schunk & Mielke 2003) or magnetospheric eternally collapsing objects (MECO; Robertson & Leiter 2003). The major difference between these alternatives is the absence of the event horizon in BS and MECO. Direct imaging of these spatial scale is still out of reach, although it is possible at present to resolve linear dimensions of $\leq 10^2\,R_g$ (Fig. 1) using VLBI observations at 86 GHz (Krichbaum et al. 2008). Similar resolution would be achieved with the next generation space VLBI mission VSOP-2 Inoue et al. (2008) offering the possibility to detec a "shadow" of the nuclear black holes in nearby AGN Takahashi (2004).

Meanwhile, presence of the event horizon can also be probed effectively by measuring the magnetic field strength on scales of $\sim 10^3$–$10^5\,R_g$ which are accessible with the VLBI measurements of the core shift. An example of such a measurement is shown in Fig. 2.

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. 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. 2008). 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 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. 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. Direct VLBI imaging at millimeter wavlengths and with the space VLBI, as well as radio measurements of the nuclear opacity of radio emission, offer a viable way to determine the physical conditions in the immediate vicinity of supermassive black holes. This makes high-resolution VLBI observations a powerful tool for addressing the general questions of physics of SMBH and evolution of nuclear activity in galaxies.

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