Observational Properties of Jets in Active Galactic Nuclei

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Abstract. Parsec scale jet properties are shortly presented and discussed. Observational data are used to derive constraints on the jet velocity and orientation, the presence of velocity structures, and the connection between the pc and kpc scale. Two peculiar sources with limb-brightened jets: 1144+35 and Mkn 501 are discussed in detail.

Keywords: AGN, jet, VLBI

1. Introduction

Jets are present in many galactic and extragalactic objects and may have different origin and properties. I will focus here to extragalactic radio jets from the parsec (pc) to the kiloparsec (kpc) scale. These jets are among the largest coherent fluid flow patterns in the universe. They can have very different working surface (from pc to Mpc), and they can grow of a factor $\sim 10^6$. Moreover the strength of the magnetic field in the jet and the particle density can change of a large factor ($\sim 10^4$).

To study jet properties, their origin and evolution we need to start from the pc scale region and to follow their properties up to the Mpc scale. At present only Very Long Baseline Interferometry (VLBI) observations in the radio band can have the angular resolution to obtain pc scale images in extragalactic radio sources. With these technique radio telescopes across continents are combined to form a global virtual radio telescope with a size of the earth which provides the highest resolution achievable in astronomy.

Thanks to VLBI observations I will present and discuss here observational properties of pc scale jets and I will compare these results with kpc scale jet properties in low and high power radio sources.

2. Jet Morphology

To get new insight in the study of radio jets at pc resolution, it is important to select source samples from low frequency catalogues, where the
source properties are dominated by the unbeamed extended emission and are not affected by observational biases related to orientation effects. To this aim, we undertook a project of observations of a complete sample of radio galaxies selected from the B2 and 3CR catalogs with $z < 0.1$ (i.e. no constrain on the core flux density): the Complete Bologna Sample (CBS; Giovannini et al. in preparation). This sample consists of 95 sources. At present 53 on 95 sources have been studied with VLBI observations. I will use published results and these preliminary data to discuss the jet properties on the pc scale.

Many of the extended FR I and FR II sources have a one-sided structure on the pc scale (18 (34%) FR I and 15 (28%) FR II). From these high resolution images, we note that high and low power sources appear very similar. Parsec scale images are very similar and it is not possible to discriminate FR I from FR II sources using VLBI images. In high and low power sources with relatively faint radio cores, the number of two-sided sources increases as expected from unified scheme models.

![Figure 1. VLBI image of 3C382, a Broad Line FR II RG and 3C 66B a FR I RG.](image)

Among the observed sources from our sample there are 7 FR I and 4 FR II galaxies with two-sided jets (21%). In contrast, there are 7/65 (11%) symmetric sources in the Pearson-Readhead sample (Pearson & Readhead 1988) and 18/411 (4.4%) in the combined PR and CJ samples (Taylor et. al 1994; Polatidis et al. 1995).

We note that all two-sided FR II radio galaxies are Narrow Line (NL) objects confirming that Broad Line Radio Galaxies (BLRG) are oriented at least as close to the line-of-sight as quasars.
In most sources we find a good agreement between the pc and kpc scale structures. The comparison between the VLA and VLBA jet Position Angle (PA) shows only in one source a large difference in the jet orientation (\(\sim 90^\circ\)) and in 2 other sources a difference of 50 and 30 degrees. This result support the model where the large distortions detected in BL-Lac sources and quasars are due to small bendings amplified by the small angle of orientation of these objects.

We have also compared the correlated flux in the shortest VLBA baselines with the core arcsecond flux density. In 6 sources this comparison was not possible because of the too large variability or to the presence of compact steep spectrum structures, among the other 47 sources, 33 (70\%) have a correlated flux larger than 70\% of the arcsecond core flux density. Therefore in these sources we have mapped most of the small scale structure and we are able to properly connect...
the pc to the kpc structure. In the remaining 14 (30%) sources we are missing in the VLBA images a relevant fraction of the arcsecond core flux density (larger than 90% in a few cases). This result suggests the presence of relevant sub-arcsecond structures not visible in VLBA images because of the lack of short baselines and unresolved in VLA images.

3. Jet Velocity

3.1. Proper Motion

Many AGNs contain compact radio sources with different components which appear to move apart. Multi epoch studies of these sources allow a direct measure of the apparent jet pattern velocity ($\beta_a$). The observed distribution of the apparent velocity shows a large range of values (Vermeulen and Cohen, 1994; Kellerman et al., 2000). From the measure of $\beta_a$ we can derive constraints on $\beta_p$ and $\theta$ where $\beta_p$ is the intrinsic velocity of the pattern flow and $\theta$ is the jet orientation with respect to the line of sight:

$$\beta_p = \beta_a / (\beta_a \cos \theta + \sin \theta)$$

A main problem is to understand the difference between the bulk and pattern velocity. In few cases where proper motion is well defined and the bulk velocity is strongly constrained, there is a general agreement between the pattern velocity and the bulk velocity (see e.g. NGC 315 in Cotton et al., 1999, and 1144+35, here). However, in the same source we can have different pattern velocities as well as stationary and high velocity moving structures. Moreover, we note that in many well studied sources the jet shows a smooth and uniform surface brightness and no (or very small) proper motion (as in the case of Mkn 501, Giroletti et al. 2004, and M87 in the region at $\sim 1$ pc from the core, Junor et al., 1999).

3.2. Bulk Velocity

Assuming that the jets are intrinsically symmetric we can use relativistic effects to constrain the jet bulk velocity $\beta_c$ and orientation with respect to the line of sight ($\theta$) as following:

- jet - counterjet ratio
- core dominance
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— synchrotron Self Compton emission
— arm length ratio
— brightness temperature

I will discuss here only the first two points which are the most used in our sample and literature.

3.2.1. Jet - Counterjet ratio
Assuming that the jets are intrinsically symmetric we can use the observed jet to counter-jet brightness ratio \( R \) to constrain the jet bulk velocity \( \beta c \) and its orientation with respect to the line of sight (\( \theta \)):

\[
R = (1 + \beta \cos \theta)^{2+\alpha}(1 - \beta \cos \theta)^{-(2+\alpha)}
\]

where \( \alpha \) is the jet spectral index \( (S(\nu) \propto \nu^{-\alpha}) \). Some problems can be related to this measurement: free free absorption may affect the observed jet brightness, moreover, we cannot derive strong constraints in intrinsically low luminosity jets: e.g. in 3C264 where a well studied optical and radio jet is present (Lara et al., 1999) the highest j/cj ratio is \( R > 37 \) which implies that the source is oriented at \( \theta < 52^\circ \) with a jet moving with \( \beta > 0.62 \).

3.2.2. Core Dominance
The core radio emission measured at 5 GHz, at arcsecond resolution is dominated by the Doppler-boosted pc-scale relativistic jet. The source radio power measured at low frequency (e.g. 408 MHz), instead, is due to the extended emission, which is not affected by Doppler boosting. At low frequency the observed core radio emission is not relevant since it is mostly self-absorbed. Given the existence of a general correlation between the core and total radio power discussed in Giovannini et al., 2001, we can derive the expected intrinsic core radio power from the unboosted total radio power using the estimated best fit correlation (continuum line in Fig. 4):

\[
\log P_c = (0.62 \pm 0.04)\log P_t + (7.6 \pm 1.1)
\]

The comparison between the expected intrinsic core radio power and the observed core radio power will give constraints on the jet velocity and orientation (Giovannini et al., 2001). We note that the core radio power is best measured at 5 GHz where it is dominant because of the steep spectrum of the extended emission, self-absorption is not relevant, and high angular resolution images allow us to separate the core from the extended jet emission.
The large dispersion in the core radio power visible in Fig. 4 is expected because of the strong dependance of the observed core radio power on \( \theta \) and \( \beta \).

From the data dispersion, assuming that no selection effect is present in the source orientation (\( \theta = 0^\circ \) to \( 90^\circ \)), we can derive that the jet Lorentz factor \( \Gamma \) has to be < 10 otherwise we should observe a larger core radio power dispersion.

3.3. Results

To derive statistical properties of radio jets on the pc scale, we used all observational data for the 51 sources in our sample with VLBI data. We found that in all sources pc scale jets move at high velocity. No correlation has been found between the jet velocity and the core or total radio power. Highly relativistic parsec scale jets are present regardless of the radio source power. Sources with a different kpc scale
morphology, and total radio power have pc scale jets moving at similar velocities.

We used the estimated $\beta$ and $\theta$ to derive the Doppler factor $\delta$ for each source, and the corresponding intrinsic core radio power (assuming $\alpha = 0$):

$$P_{c-\text{observed}} = P_{c-\text{intrinsic}} \times \delta^2$$

We found a good correlation between $P_{c-\text{intrinsic}}$ and $P_t$ with a small dispersion since plotting $P_{c-\text{intrinsic}}$, we removed the spread due to the different orientation angles (Fig. 5). We found that a Lorentz factor $\Gamma$ in the range 3 to 10 is consistent with the observational data. The Lorentz factor cannot be $> 10$ for the previous considerations (Sect. 3.2). It cannot be $< 3$ to remove the dispersion due to the different source orientations. The result that sources with different $P_t$ and kpc scale morphology show the same correlation, implies that all pc scale jets have a similar velocity. Two sources do not follow the general correlation: M87 where we should have a higher jet velocity to fit with the general correlation and 3C 192 which core radio power is lower than expected (it could be in a pre-relic phase).

![Figure 5. Observed core radio power versus total radio power (a). Intrinsic core radio power (see Sect. 3.3) versus total radio power (b)](image)

4. Acceleration and Deceleration in Jets

In some sources evidences of increasing velocity in pc scale jets have been found: e.g. M87 (Biretta et al., 1995); 3C84 (Dhawan et al., 1998); Cygnus A (Krichbaum et al., 1998). However, in these sources the jet velocity was measured from the jet apparent motion. Thus the
increasing velocity could be non intrinsic but due to a change in the jet direction or to a change in the jet pattern velocity unrelated to the jet bulk velocity. In NGC 315 Cotton et al. (1999) found an increasing jet velocity in the 5 inner pc from the core both from proper motion measurements AND from the sidedness ratio. Recently an increasing bulk velocity has been found also in NGC 6251 by Sudou et al. (2000).

In many low power sources there are observational evidences (Laing et al. 2003) that jets are relativistics at their beginning and strongly decelerate within a few kpc from the core (see e.g. 3C449, Feretti et al., 1999).

In FR II radio sources kpc scale jets are still affected by Doppler boosting effects, but the jet sidedness ratio decreases with the core distance implying a velocity decrease. Observational data are consistent with $\Gamma \sim 2$ on the kpc scale (Bridle et al., 1994).

The discovery of X-Ray emission from jets on the kpc scale is an evidence in favor of relativistic beaming even on large scales (e.g. Sambruna, 2003).

5. Velocity Structures

An evident limb-brightened jet morphology on the pc scale is present in some FR I sources as 1144+35, Mkn 501, 3C264, M87, 0331+39 (Giovannini et al., 2001), and at least in one high power radio source: 1055+018 (Attridge et al., 1999). We interpret the limb-brightened structure as due to a different Doppler boosting effect in a two-velocity relativistic jet. If the source is oriented at a relatively large angle with respect to the line of sight, the inner very high velocity spine could be strongly deboosted, while the slower external layer could be boosted and appear brighter than the inner jet region. Therefore only sources in a small range of $\theta$ will appear limb-brightened. For this reason, and for the observational difficulties of transversally resolving the radio jets, we expect that the number of sources exhibiting limb-brightened jets is low, as observed.

At present it is not clear if the velocity structure is strictly related to the jet interaction with the ISM as suggested by Giovannini et al. (2001) or it is an intrinsic jet property. The presence of this structure very near to the central core as in M87 (Junor et al., 1999) and Mkn 501 (Giroletti et al. 2004) is in favour of a jet intrinsic property in the inner region (as discussed by Meier, 2003), whereas a jet velocity decrease due to the ISM is likely to be present in an intermediate region (from the pc to the kpc scale).
6. Two laboratory sources

6.1. 1144+35

1144+35 is a giant radio galaxy which shows a strong extended jet and a short counter-jet on the pc scale (Giovannini et al., 1999). The main jet is limb-brightened with evident substructures in the external shear layer which are moving with $\beta_a \sim 2.7$ (A, B, B1, and A1 in Fig. 6). New recent observations at 8.4 GHz have allowed to measure a possible proper motion also in the counter-jet (E in Fig. 6): $\beta_{a-cj} = 0.3 \pm 0.1$ in the time range 1995 - 2002 with 4 different epochs (Giovannini et al. in preparation). According to Mirabel and Rodriguez (1994) using both the jet and counter jet proper motions we can obtain directly $\theta = 30^\circ$ and $\beta = 0.9$. From these data we can obtain a comprehensive scenario, as follows: 1) the bulk and pattern velocity are the same; 2) the shear layer Doppler factor is $\sim 2$ (being $\Gamma \sim 2.3$) while assuming $\Gamma = 15$ for the inner spine, its Doppler factor is 0.7 in agreement with the observed brightness distribution; 3) if the external shear layer started with the same velocity of the inner spine, its velocity decreased from 0.998c to 0.9c in less than 100 pc suggesting an intrinsic origin for the jet velocity structure.

6.2. Markarian 501

Markarian 501 (Mkn 501) is a nearby ($z = 0.034$) BL-Lac source well known for its X- and $\gamma$-ray emission. At parsec resolution it is one of the best observed radio sources. In a recent paper Giroletti et al. 2004 show a clear evidence of a limb-brightened jet structure visible at a distance $< 1$ mas from the core up to 50-100 mas from the core.

The presence of a velocity jet structure very near to the nuclear emission implies a strong deceleration if it is completely due to the jet interaction with the surrounding medium. In agreement with Meier 2003, we suggest that a transverse velocity gradient is intrinsic and that a further velocity decrease due to mass loading in the jet from the ISM is likely to be dominant at larger distances from the core.

Giroletti et al. discuss also evidences of a highly relativistic pc scale jet despite of the lack of any measured proper motion. In this source from the high frequency ($\gamma$-ray) emission, Salvati et al. (1998) found that a jet with a bulk velocity $\Gamma \geq 10$ with opening angle and orientation angle $\sim 1/\Gamma$ is required. This result is in contrast with observational evidences of radio data that, as discussed in Giroletti et al., require a jet orientation angle larger than 15$^\circ$. To reconcile the radio and high frequency results we have to assume that the jet in the inner region ($< 0.03$ pc) where high frequency radiation is produced.
Figure 6. Global VLBI image of 1144+35 at 8.4 GHz. C is the source core, E the counter-jet and D B1 A1 B A are substructures in the main jet.

Figure 7. Space VLBI image of Mkn 501 at 1.6 GHz
and radio emission is negligible is oriented at $\theta \leq 5^\circ$. Over the range from 0.03 to 50 pc the jet orientation has to change from $5^\circ$ to $15^\circ - 25^\circ$. The origin of this possible gradual change it is not yet known. We recall that beyond 30 mas from the core the jet position angle becomes stable and closely aligned with the kpc scale structure.

7. Polarization

In quasar and BL-Lacs the nuclear emission is weakly polarized at a level of a few percentage with a higher fraction of polarized flux at high frequency. Radio jets have $5 - 10\%$ polarization with a tail up to a few tens of percent. No polarized emission has been found in radio galaxies at a few percent level.

About the orientation of jet polarization with respect to the jet direction conflicting data are reported in literature. It seems that quasar jets are dominated by longitudinal magnetic fields but with a large tail. BL-Lac objects have an excess of parallel oriented vectors (transverse magnetic fields) but also in this case a large tail is present.

Present more accepted interpretation is the dominance of the longitudinal or toroidal component of helical jet magnetic fields (Gabuzda, 2002). We note that most parsec scale polarization observations are sensitive only to polarization in the brightest jet regions, therefore the measured polarization percentage and orientation could not reflect the full jet magnetic field properties.

In jets where a transverse structure has been found probably due to a velocity structure (sect. 5), a parallel magnetic field is present in the shear boundary layer and a perpendicular magnetic field in the inner spine.

8. From pc to kpc

Radio jets in low power (FR I) radio galaxies are characterized on the kpc scale by a symmetric two-sided structure, a large opening angle, and the presence of a magnetic field perpendicular to the jet axis. Observational data show the presence of a strong jet deceleration within $\sim$ 5 kpc from the core (see e.g. 3C449, Feretti et al. 1999). Large scale jets are therefore low velocity jets and often show morphological distortions as oscillations or large curvatures (head-tail or wide-angle-tail radio galaxies) due to a strong interaction with the ambient medium.

Jets in high power (FR II) radio galaxies and quasars are very collimated, in many cases strongly asymmetric (one-sided), and with a
magnetic field parallel to the jet axis. Relativistic beaming affects the observational properties of pc and kpc scale jets, however peripheral regions are less dominated by Doppler boosting, suggesting a decreasing of the jet Lorentz factor from the pc to the kpc scale. A value of $\Gamma \sim 2 - 1.5$ is consistent with kpc scale properties in many large scale FR II sources (see also Arshakian and Longair, 2003).

9. Conclusions

In recent years we have seen a large improvement in number and quality of observational data of jets. From these data we can derive the following conclusions:

− The parsec scale jet velocity is highly relativistic with $\Gamma$ in the range 3 to 10 in high and low power radio sources. The jet velocity is not correlated to the total or core radio power.

− The jet morphology in the pc scale is the same in high and low power radio sources.

− In some sources the pattern and bulk velocity are the same.

− A two velocity regime is necessary to explain some observational properties in low power sources and possibly in a few high power sources. A different Doppler factor can explain the limb-brightened structure observed in some sources.

− It is not yet clear if the jet velocity structure is a jet intrinsic property or it is due to the jet interaction with the ISM. In any case at some distance from the core the jets slow down because of interaction with the ISM.

− BL-Lac sources show an excess of magnetic field perpendicular to the jet direction while Quasars show an excess of longitudinal magnetic fields, however a broad tail is present.

− In jets with a velocity structure, the boundary layer show a parallel magnetic field with respect to the jet direction, and the inner spine a perpendicular magnetic field. Radio galaxies are not polarized at a few percent level.

− Large scale jets in FR I have a low velocity and are not relativistic. They decelerate dramatically from the pc to the kpc scale. In FR II sources jets decelerate more slowly. They can move with a Lorentz Factor $\sim 2$ also at large distance (kpc scale) from the core.
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