Constraining the Parameters of AGN Jets

Comparisons with Herbig-Haro Jets

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November 19, 2002

Abstract. Comparing the properties AGN and Herbig-Haro jets can be a useful exercise for understanding the physical mechanisms at work in collimated outflows that propagate in such different environments. In the case of Herbig-Haro jets, the presence of emission lines in the spectra and the continuous evolution of the observation techniques greatly favor our knowledge of the physical parameters of the jets instead, for AGN jets, the process of constraining the jet parameters is hampered by the nature of the emission from these objects that is non-thermal.

I will discuss how one cannot directly constrain the basic parameters of extragalactic jets by observations but must treat and interpret the data either by statistical means or by comparing observed and simulated morphologies in order to gain some indications on the values of these parameters.

Keywords: Active Galactic Nuclei, Herbig-Haro objects, Jets, Radio Sources

1. Introduction

The main difficulty one faces when trying to comprehend the nature of jets from Active Galactic Nuclei is due to the absence of lines in the radiation spectrum of these objects. In fact, their emission is typically non-thermal emission (synchrotron or inverse Compton). This very simple fact constitutes a sort of “original sin” of AGN jets and is basically the reason why after almost five decades since the discovery of the radio emission from Cygnus A (Jennison & Das Gupta 1953), observers and theorists are still debating about very basic questions such as extragalactic jets composition, i.e. whether they are made of ordinary matter or of electron-positron pairs.

Models of AGN jets, that consider the jet overall dynamics, depend on a minimum of three parameters: the Lorentz factor, the Mach number, the jet-to-ambient density contrast. Another crucial parameter for jet modeling would be the magnetic field intensity, however one may assume, at a zeroth order approximation, that the bulk kinetic energy density in the jet dominates on the magnetic one and that the general behavior of the jet propagation can be captured by a hydrodynamic model. In any event, none of the above jet parameters can be directly constrained by observations.
In contrast, Herbig-Haro jets show copious emission lines in their spectra, in the optical and infrared bands mainly. Spectral lines give information on local temperature and density, on the bulk velocity of the jet emitting matter and on the presence of shocks along the jet. Moreover, the augmented angular resolution and sensitivity achievable with the recent telescopes (see Bacciotti, this issue) allow to investigate the velocity structure across the jet and reveal the jet characteristics close to the central source.

In this review I will present efforts to constrain the basic parameters in extragalactic jets, both by statistical and numerical means, discuss the role of these efforts in interpreting the FR I/FRII radio source dichotomy, and made comparisons with observations and interpretations of Herbig-Haro jets. For an extended review on jet modelling, I remind the reader to Ferrari (1998).

In the next Section I briefly introduce the bases of the Fanaroff-Riley classification of extragalactic radio sources and recall the interpretations proposed; in Section 3 I examine a method for deriving jet velocities; in Sections 4 and 5 I discuss the problem of constraining the jet Mach number, density and composition and in Section 6 make comparisons between Herbig-Haro and AGN jets.

2. The Fanaroff-Riley classification: Taxonomy

Historically, the extragalactic radio sources have been classified into two categories (Fanaroff & Riley 1974) based upon their radio morphology: a first class of objects, preferentially found in rich clusters and hosted by weak-lined galaxies, shows jet-dominated emission and two-sided jets and was named FR I (Fig. 1); a second one, found isolated or in poor groups and hosted by strong emission-line galaxies, presents lobe-dominated emission and one-sided jets and was called FR II (or “classical doubles”) (Fig. 2). Besides morphology, FR I and FR II radio sources were discriminated in power as well: objects below $\sim 2 \times 10^{25} h_{100}^2$ W Hz$^{-1}$ str$^{-1}$ were typically referred as FR I sources. A perhaps more illuminating criterion has been found by Owen & Ledlow (1994) who plotted the radio luminosity against the optical absolute magnitude of the host galaxy: they found the bordering line of FR I to FR II regions correlating as $L_R \propto L_{opt}^{1.7}$, i.e. in a luminous galaxy more radio power is required to form a FR II radio sources. This correlation is important since can be interpreted as an indication that the environment may play a crucial role in determining the source structure. The above argument yields the basic question of the origin of FR I/FRII dichotomy, whether intrinsic or ambient driven.
Two kind of explanations for the FR I/FR II dichotomy can be found in the literature: intrinsic and extrinsic interpretations (see the review by Wiita 2002). Among the intrinsic explanations, the jet composition was invoked to interpret this dichotomy: Celotti & Fabian (1993) argued that FR II radio jets were made of ordinary matter ($e^+ - p$) and Reynolds et al. (1996a) instead FR I jets (in particular M87) were made of $e^+ - e^-$ pairs. Another possibility was considered by Wilson & Colbert (1995) and Meier (1999) who suggested that FR II jets originated from rapidly rotating black-holes; the structure of the
accretion was also considered to explain the dichotomy: according to Reynolds et al. (1996b) when accretion is advection dominated (ADAF) FR I jets results, while standard accretion disks generate FR II jets. The extrinsic explanations assume, apart from the total power, FR I and FR II jets are basically similar close to the nucleus and that differences in the environment are able to destabilize, possibly via onset of turbulence in the flow, and decelerate FR I jets effectively, while FR II jets succeed to propagate, nearly unchanged, up to the working surface to produce the hot-spots (Bicknell 1995, Komissarov 1990, Bowman et al. 1996).

A possible clue for discriminating among these two kind of interpretations (Gopal-Krishna & Wiita 2000) was the observations of six HYbrid MO Morphology Radio Sources (HYMORS) that show FR I morphology on one side of the core and FR II morphology on the other one: this is a clear indication that the environment play a basic role in determining the radio source appearance.

3. The Jet Velocity

As discussed before, none of the basic parameters (Mach number, jet-ambient density ratio and jet Lorentz factor) required for analytical and numerical modeling of jets can be directly constrained by observations of radio sources. Observers must therefore interpret their data relying upon statistical analyzes and look at these data through an assumed basic model. This procedure is typically employed for the interpretation of the jet one-sideness and superluminal velocities that are observed in several radio sources at milliarcsecond scales using VLBI techniques. The basic model adopted can be synthesized as follows: responsible for the emission is a distribution of relativistic electrons that are advected at relativistic speed by the jet, assuming homogeneous and isotropic jets the flux ratio of the approaching jet to the receding one (Doppler boosting) is:

$$\frac{F_a}{F_r} = \left( \frac{1 + \beta_j \cos \theta}{1 - \beta_j \cos \theta} \right)^{2+\alpha},$$

(1)

Where $F_a$, $F_r$ are the fluxes of the approaching and receding jet respectively, $\beta_j$ is the jet bulk velocity in units of $c$, $\theta$ is the angle between the jet axis and the line of sight and $F \propto \nu^{-\alpha}$, with $\alpha \sim 0.5$ typically. If the emission region moves towards the observer at the jet speed with the angle $\theta$, photons emitted at a later time must travel a distance to the observer that is shorter than for photons emitted earlier, this makes the apparent time interval of the emission smaller and thus the
apparent speed $\beta_{\text{app}}$ possibly larger than one:
\[
\beta_{\text{app}} = \frac{\beta_j \sin \theta}{1 - \beta_j \cos \theta}.
\] (2)

The observation of the jet-counterjet flux ratio $F_a/F_r$ and of $\beta_{\text{app}}$ in a source would yield the actual jet speed and inclination. Unfortunately this is not possible in most cases: typically the counterjet is too faint to be visible and superluminal proper motions are detected in a relatively few objects only.

Jets in AGNs are clearly highly non isotropic objects, accordingly their appearance crucially depends on the viewing angle. This question is discussed in the unified model for AGNs (Antonucci 1993, Urry & Padovani 1995). According to this model the appearance of an AGN is dictated by the jet axis orientation with respect to the line of sight: radio-loud quasars and FR II radio galaxies are the same kind of objects seen with increasing angle (high-luminosity unified scheme), while BL Lac objects and FR I radio sources also belong to the same class viewed at increasing angles (low-luminosity unified scheme). Therefore one may ask the following question: when observing with the highest possible resolution, i.e. with VLBI techniques, a sample of different kind on AGNs jets showing mixed FR I and FR II morphologies at kpc-scales, is their jet Lorentz factor distribution mirroring the various large scale morphologies or not?

For attempting to answer this question a possible way, as mentioned before, is to employ a statistical analysis. Giovannini et al. (1988) collected a sample of 187 radio galaxies, observed with the VLA, and plotted their core (5 GHz) against total (408 MHz) power. Arguing that the objects of this large sample had jets randomly oriented with the line of sight, they expected that data were scattered about a best-fit line that correlated core against total radio power and corresponded to the mean orientation angle of 60° to the line of sight. The correlation found was:
\[
\log P_c(60^\circ) = 0.62 \log P_t + 7.6.
\] (3)

For investigating the jet properties close to the AGN, Giovannini et al. (1994, 2001) examined a complete sample of 27 radio galaxies limited in flux observed with the VLBI. The sample included FR I and FR II sources in nearly the same quantity. They again plotted the observed core at 5 GHz, and affected by Doppler boosting, against the total radio power at 408 MHz, therefore not boosted, of the objects (Fig. 3), with the correlation of Eq. (3) given as a comparison. Since both proper motions and jet-counterjet flux ratios were typically not available for the sources of the sample, therefore Eqs. (1) and (2) could not be
solved for $\theta$ and $\beta_j$, Giovannini et al. (2001) fixed $\gamma$ and obtained $\theta$ from data, once assuming $\alpha = 0$, not a bad approximation for the core fluxes. In this way they could constrain the Doppler factor $\delta \equiv \left( \gamma(1 - \beta_j \cos \theta) \right)^{-1}$ and deboost the observed core power to obtain the intrinsic one, according to:

$$P_{c\,\text{obs}} = P_{c\,\text{intr}} \times \delta^2.$$  \hspace{1cm}(4)

The correlation in Eq. (3) was scaled as well in the same way to obtain the intrinsic core power and in Fig. 4 one can see the result of this procedure after having set $\gamma = 5$. Repeating the same trick for different values of $\gamma$, Giovannini et al. (2001) found that the correlation line went nicely through the data for $\gamma = 3 - 10$, outside this interval the correlation failed, as in Fig. 3, independently of the FR I/FR II type of the sources. Giovannini et al. (2001) concluded that FR I and FR II, despite showing different kpc-scale morphologies, have all the Lorentz factors in the range 3-10 on the parsec scale.

4. Jet Mach Number

According to the above reasoning, both class of AGN jets are relativistic, and thus supersonic, on parsec scale. On the kpc-scale FR II jets may still be relativistic in most cases due to the observed one-sideness, if this is interpreted as Doppler boosting. A clear indication
Figure 4. The solid line represents the correlation from Eq. (3), after the $P_c(60^\circ)$ has been scaled. Bullets show the intrinsic core power vs the total radio power. $\gamma = 5$ has been assumed for deboosting.

of supersonic speed is the presence of shocks in the FR I jets, that can be resolved in the transverse direction, and the signature of shocks is the behavior of the polarization vector. The M 87 jet is among the best studied objects since originate from the closest AGN and detailed polarization maps have been obtained in the radio and optical bands (Perelman et al. 1999). The magnetic field is parallel to the jet axis and becomes perpendicular in the regions where we see emission knots, such as knot A of the M 87 jet that is shown in detail in Fig. (5). This is a clear indication of a shock compression of the field component along the shock extent.

Jets of FR II radio sources are too faint to produce resolved polarization maps. Polarization can be easily detected in the prominent radio lobes and hot spots, where the jet terminate into the intergalactic medium. Again one expects a field direction oriented along the lobe’s border, i.e. the working surface of a supersonic jet at its terminal point. In Fig. (6) the polarization map of the western hot-spot of Pictor A is shown (Perley et al. 1997), and the projected magnetic field is perpendicular to the electric field vector shown in the figure. The magnetic field results aligned with the shocked working surface.
Figure 5. Polarization maps of the M 87 jet (the projected magnetic field is given); optical (top panel) and radio (bottom panel)

Figure 6. Polarization map of the western lobe of Pictor A (the electric field vector is given)
5. Jet Density and Composition

We have seen that jets are likely relativistic on parsec scale, and that remain supersonic on kpc scale, provided the direction and intensity of the magnetic field is correctly interpreted in terms of shock compression. A third parameter to constrain is the jet density, or more properly the jet-to-ambient density contrast. For constraining this parameter one has to rely upon numerical simulations and compare qualitatively the spatial density distribution, resulting from the calculations, with the observed brightness distributions.

In Fig. 7 I show the radio brightness distribution of the FR II source Cygnus A and point out the different regions of interest for the model interpretation: the radio hot-spots are the regions where the jets terminate (“splash points”), the lobes are the manifestation of the back-flow, and the diffuse region between the lobes is the “cocoon”, typically invisible in radio but evident in X-ray (see Smith et al. 2002).

When simulations of supersonic, underdense jets are carried out (see e.g. Massaglia et al. 1996) the overall picture that emerges from these studies can be summarized as follows (see Fig. 8): the deceleration of the jet flow at its head is accomplished through the formation of a strong shock (Mach disk), which partially thermalizes the jet bulk kinetic energy; the overpressured shocked jet material forms a back-flow along the sides of the jet and inflates a cocoon whose size becomes more prominent as the density ratio between jet and ambient material decreases; finally, a second shock (bow-shock) is driven into the external medium. Simulations of supersonic, overdense jets yield qualitatively different morphologies that are close to Herbig-Haro jets. Therefore AGN jets, at least those found in FR II sources, are underdense with respect to external medium and the density ratio can be very small ($\sim 10^{-5}$) in case pair plasma jets.

The question of the jet density reminds the problem of establishing whether AGN jets are made of proton and relativistic electrons or instead of relativistic electron-positron pairs. This of the jet composition is a long outstanding and yet unsolved problem for the simple reason that electrons and positron emit synchrotron radiation of identical spectrum and linear polarization. A possible observational clue for discriminating between $e^- - p$ and $e^+ - e^-$ jets is the detection of radio circular polarization (CP). In fact (see Wardle et al. 1998), the large linear polarization degree observed in AGN jets at parsec scales has survived the internal Faraday rotation process, that is mainly due to electrons with $\gamma_{\min} < 100$. Therefore $e^- - p$ jets should have relativistic electrons with $\gamma_{\min} \geq 100$, while $e^+ - e^-$ jets do not suffer Faraday rotation since electron and positron gyrate in opposite directions and
thus $\gamma_{\text{min}} \geq 1$. Values of $\gamma_{\text{min}} \ll 100$ should be a clear signature of $e^+ - e^-$ jets. Low-energy electrons can yield to Faraday conversion of linear into circular polarization, besides producing Faraday rotation. For an $e^+ - e^-$ jet internal Faraday rotation should not be present, as mentioned before, and a small but appreciable fraction (below 1%) of the linear polarization should be converted into CP by low energy electrons and positrons since this mechanism is sign-independent, being proportional to the electron gyrofrequency to the square. Observation of CP should be thus be a signature of the presence of low-energy emitting particles that do not cause Faraday rotation and maintain a high degree of LP, therefore should be $e^+ - e^-$ plasma.

CP has been indeed observed in about 20 AGN jets (Wardle & Homan 2001) and we should have a clear indication on the $e^+ - e^-$ nature of the jet composition. Unfortunately, there are other possible origins of CP, besides Faraday conversion: intrinsic CP, scintillation and coherent radiation mechanisms. Therefore the question of the jet composition remains open.

Authors have attempted different ways for solving this important and basic problem. Scheck et al. (2002) have simulated relativistic $e^+ - e^-$ and $e^- - p$ jets of given kinetic luminosities and jet-ambient density ratios: they have found that both the morphology and the dynamical behavior is almost independent of the assumed jet composition.
6. AGN and HH Jets

AGN and Herbig-Haro jets (see a recent review by Reipurth & Bally 2001) share some similarities but many basic differences, besides the different scale powers and sizes. Both are collimated outflows that originated from accretion processes and are accelerated, possibly by MHD mechanisms. Since jet velocity must be of the order of the escape velocity from the central gravitational well, AGN jets are likely to be relativistic, at least in their initial part, while HH jets have velocities comparable with stellar winds. Both kind of jets appear knotty and terminate into the ambient medium forming structures whose morphology that can be interpreted as bow-shocks, that indicates supersonic bulk velocity in the jets.

HH jets are observed in the optical and infrared bands where they emit optically thin thermal radiation. Their spectra are rich of emission lines, mainly of hydrogen, sulfur and oxygen with intensities, ratios and profiles are clearly indicative of shocks, since these observational values can be related to the predictions from plane-parallel and bow-shock models. Combining the data of shock velocities, Doppler shifts of the emission lines and proper motions it is possible to constrain the jet velocity, density and temperature (i.e. the Mach number). Typically, the jet velocity is $\sim 200 - 400$ km$^{-1}$, density $\sim 10^3 - 10^4$ cm$^{-3}$ and Mach number $\approx 20 - 40$.

AGN jets instead emit continuous, non-thermal radiation in a wide frequency range that goes from the radio up to the X-ray bands; these jets are likely relativistic on parsec scale but may decelerate down to non-relativistic speeds at kpc scales, at least in the case of FR I objects, but are likely to remain supersonic both FR I and FR II jets. The basic reason why shocks lead to thermal emission in HH objects and non-thermal radiation in AGN jets is due to about 6-8 orders of magnitude ratio in the ambient density: in the case of HH jets propagate in the high density ambient of molecular clouds, thus shocks can heat the matter and produce radiative losses, while extragalactic jets propagate
in the tenuous intergalactic or intracluster medium therefore shocks, that can be considered with good approximation adiabatic, have the main effect to accelerate relativistic particles via Fermi-like processes of the first kind that, in turn, yield synchrotron radiation in the shocked ambient magnetic field and the only possible signature we observe is the reorientation of the polarization vector of the radiation.

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