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Relativistic jets in AGNs

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Abstract. I present some of the recent progress in the study of relativistic jets in Active Galactic Nuclei, discussing in particular the importance of the observations in the high-energy band of the spectrum (X-rays and γ-rays) for the understanding of the innermost and the outer regions of jets.

Key words. Relativistic jets – High energy emission

1. Introduction

Although present in a tiny minority of galaxies, extragalactic relativistic jets (Begelman, Blandford & Rees 1984) are the subject of intense investigation, since their comprehension could help in shedding light on several fundamental issues in astrophysics. In the recent past the study of relativistic jets has received a great impulse by the possibility to extend the observations from the "classical" radio band to other regions of the spectrum, especially in the X-rays and in γ-rays. Despite this intense effort numerous questions remains unsolved, especially those related to the processes responsible for the acceleration and collimation of these outflows and even to the composition of the jet (normal plasma, pair plasma, magnetic field).

The current picture can be sketched as follows: in the vicinity of the supermassive Black Hole in the core of an AGN ($d \sim 10^{13-14}$ cm) the flow is accelerated and collimated. In the first part of its path the jet is almost dissipationless (Ghisellini & Madau 1996), until it reaches distances of the order of ~ 0.1 pc, where about 10% of its kinetic power is released through radiation (in some sources a large fraction at high energy). Then the jet continues its way through the galactic and intergalactic medium, starting to interact with the external environment. Recent *Chandra* observation revealed that even at large scales (> 10 kpc) jets a large fraction of its radiative luminosity is released at large frequencies. In the following I mainly focus the discussion on the innermost (subpc) and outer regions of the jet.

2. Blazars: the innermost jet

EGRET onboard *CGRO* first discovered that *blazars*, which form the most active class of AGNs, are bright emitters of γ-rays in the MeV-GeV domain. The discovery of such an intense flux of γ-rays definitively confirmed the twenty years old proposal (Blandford & Rees 1978) that the emission from blazars, dominated by a smooth non-thermal continuum from radio to γ-rays, is produced within a relativistic jet, close to the central BH, pointing

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close to the line of sight. To avoid absorption of γ-rays through the photon-photon process (producing electron-positron pairs), the compactness of the source must be small, condition that directly implies that the emission is beamed (Maraschi, Ghisellini & Celotti 1992), with values of the Doppler beaming factor $\delta = [\Gamma(1-\beta\cos\theta)]^{-1}$ (where Γ is the bulk Lorentz factor of the flow, $\beta = v/c$ and θ is the viewing angle) larger than 5-10.

The typical Spectral Energy Distribution (SED) of blazars (an example is reported in Fig.1) shows two broad bumps, the first located in the IR-optical-UV band, the second one peaking in the γ-rays. The most popular models interpret the double-humped SED as due to synchrotron emission at low energy and IC emission at large energy coming from the same electron population (for a different view see e.g. Mannheim 1993). The most abundant soft photons interviening in the IC process can be either those produced by synchrotron mechanism (Synchrotron Self Compton models, Maraschi, Ghisellini & Celotti 1992; Tavecchio, Maraschi & Ghisellini 1998) or those coming from the external region of the jet (External Compton models, Dermer & Schlickeiser 1993, Sikora, Begelman, & Rees 1994).

The SEDs of the blazars follow a clear trend with the (radio) luminosity, as found by Fossati et al. (1998). The most luminous blazars (showing the typical emission lines of quasars) have the synchrotron peak in the IR band and the high-energy peak in the MeV region. The less luminous sources (BL Lac objects, showing almost featurless optical spectra) have the first component peaking in the UV or even in the X-rays, while the high-energy peak can extend in the TeV band. The interpretation of this trend (Ghisellini et al. 1998) assumes that the energy of the electrons emitting at the peak is determined by the balance between acceleration and cooling timescales. The latter is determined by the energy density in radiation and magnetic field, much larger in the more luminous objects.

The application of the emission models to the data allows the robust determination of the physical quantities of the jet, providing the

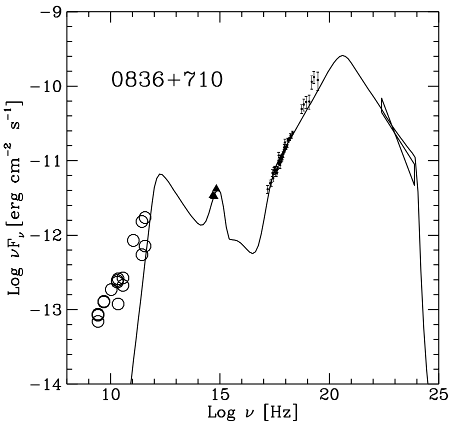

Fig. 1. Spectral Energy Distribution of the quasar 0836+710. The solid line is the synchrotron-Inverse Compton model used to reproduce the data (from Tavecchio et al. 2000a)

possibility to address some of the basic issues related to the jet physics, such as their composition and the determination of the power transported by the different components (pairs, protons, magnetic field). Fig.2 (Ghisellini & Celotti 2002) reports these estimate for a group of blazars. It is evident that electrons alone cannot transport the totality of the power required by the emitted luminosity. The magnetic field estimated in the emitting region is of the order of the equipartition value with electrons and thus cannot provide a viable alternative. Therefore a proton component seems to be the most direct candidate carrier of the jet power.

A quite interesting subgroup of blazars is that of TeV sources. The discovery (possible thanks to the advent of atmosferic Cherenkov telescopes) of bright, strongly variable TeV emission from a handful of blazars (see the recent review by Krawczynski 2004) initiated renewed efforts devoted to enlarge the number of known TeV sources, especially those located at relatively large distance ($z > 0.1$), since they can be used to probe the poor known infrared

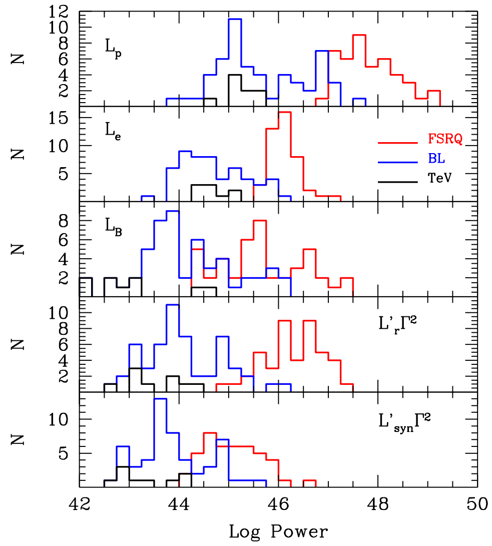

Fig. 2. Histograms of the kinetic powers separately derived for (from top to bottom) protons, electrons, magnetic field (from Ghisellini & Celotti 2002). The fourth and the last panels report the total radiative output and that of the synchrotron component, respectively. Appears evident that electrons and magnetic fields only account for the emitted power: therefore to permit the jet to exit the galaxy and feed the lobes, another carrier (protons) must be admitted.

background in the 1-20 μm range (de Jager & Stecker 2002). A recent census reports 6 sources with a firm detection in the TeV band, but in the very near future the TeV family is expected to be greatly enlarged by the (already operative) new generation of Cherenkov telescopes (Horan & Weekes 2004).

Since thermal features are almost absent in the optical spectra, SSC is the favourite explanation for the observed TeV emission. However the existing data already seem to challenge the SSC model in its simplest form. Indded the Doppler factor estimated in the emission region can reach extremely large value ($\delta \sim 50$), when the IR absorption is properly taken into account (Krawczynski et al. 2002, Konopelko et al. 2003). Moreover, the detailed study of temporal behaviour of the emission during single flares reveals that the TeV flux varies more than the X-ray flux, a behaviour difficult to reconcile within the accepted scheme (Katarzynski et al., submitted).

3. Multifrequency emission from large scale jets

Although very common in the radio band, before the launch of the *Chandra* satellite in 1999 only a handful of extragalactic kpc scale jets were known to emit X-rays. Among them the bright and prominent jets in 3C273, M87, Cen A, studied with *EINSTEIN* and *ROSAT*. With the superior sensitivity and, especially, spatial resolution of *Chandra* numerous jets have been recently detected, triggering a new intense theoretical and observational work. Even in the source selected for the first light, the distant ($z = 0.6$) quasar PKS 0637-752, a prominent jet has been discovered (Chartas et al. 2000).

The first problem posed by these observations is the identification of the emission mechanism responsible for the production of X-rays. Since these jets are known to emit in radio, the first candidate mechanism is the extrapolation at high frequencies of the synchrotron emission. In some cases (in particular for the low power [FRI] jets) the the data are consistent with a unique synchrotron component (steepening at high frequencies because of radiatiove losses), but in numerous other cases (especially for jets in powerful quasars) this simple interpretation fails to explain the observations. This is the case of the first jet discovered in PKS 0637-0752, for which two separated emission components are clearly required by the shape of the convex radio-optical-X-ray spectrum. The SSC model cannot explain the level of the X-ray emission, since it would require very extreme conditions. Tavecchio et al. (2000b) and Celotti et al. (2001) proposed that the mechanism responsible for the observed X-ray emission is the IC scattering of the CMB radiation by relativistic electrons in the jet. The key point in this model is the assumption that the jet in these (FRII) sources is still highly relativistic (with bulk Lorentz factors $\Gamma = 5 - 10$) at these scales. It is also possible to reach the equipartition between emitting electrons and

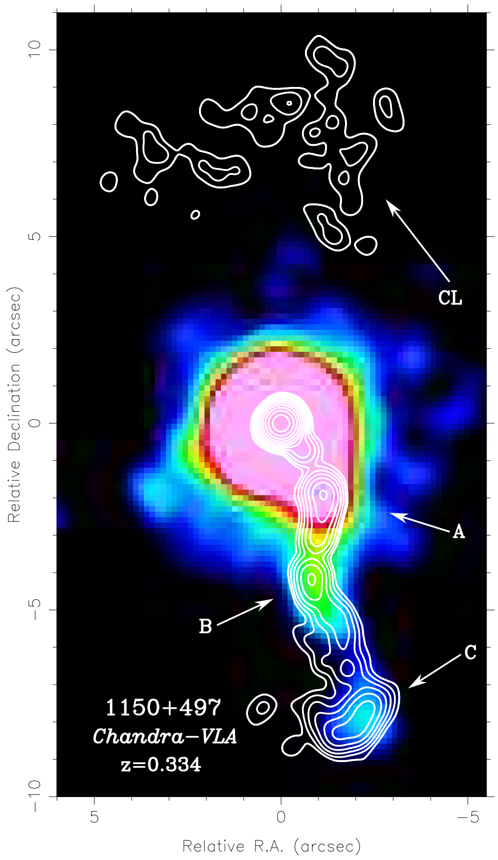

Fig. 3. X-ray (colours) and radio (contours) maps of one of the jets studied by Sambruna et al. (2004).

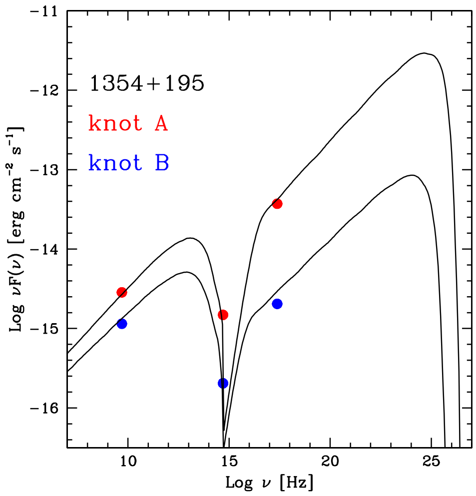

Fig. 4. SEDs of knots A and B of the jet of the quasar 1354+195. The solid lines represent the synchrotron (low frequency) and IC/CMB emission which reproduces the data (from Sambruna et al. 2002)

magnetic field, and the kinetic power is consistent with those usually derived for jets in powerful QSOs.

A problem faced by the IC/CMB model has been recently pointed out in Tavecchio, Ghisellini & Celotti (2003). In fact in this model, X-rays are due to the emission by low-energy electrons ($\gamma \sim 100$). If the cooling of electrons is due to radiative losses the lifetime of these electrons is virtually infinite. Therefore one should expect that these electrons, streaming in the jet, would produce a *continuous* emission, not concentrated in knots as observed. Even assuming adiabatic losses due to the jet expansion the result does not change. A possible solution is to admit that the emission region is not uniform, but composed by several "clumps", overpressured with respect to the environment: adiabatic losses suffered by electrons due to the expansion of these small regions should be enough to cool the particles.

To better characterize the properties of the X-ray emission from large scale jets we proposed a large sample (17 objects) of known radio jets to be observed with *Chandra* and *HST* (the optical is critical to discriminate among synchrotron and a double spectral component). Examples of the X-ray images and the SEDs that we obtained are reported in Figs.3-4. We detected (Sambruna et al. 2004) X-ray and optical emission from about 60% of the sources. The spectral characteristics of the detected emission features are summarized in Fig.5, showing the radio-to-optical spectral index versus the optical-to-X-ray spectral index. The great majority of the sources are located in the region characterized by the condition $\alpha_{ro} > \alpha_{ox}$, indication of the presence of two different spectral components separated by the optical (that we interpreted as synchrotron and

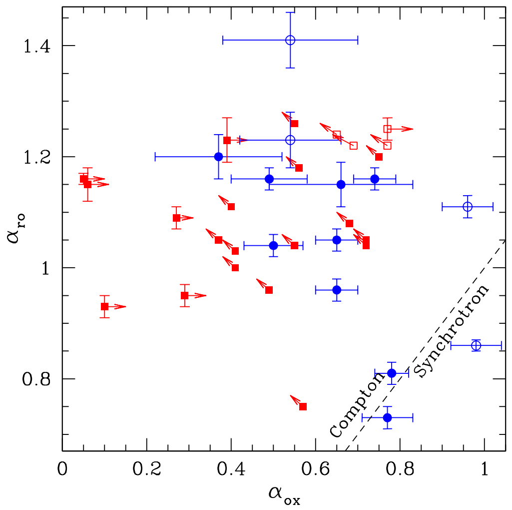

Fig. 5. Plot of the radio-to-optical spectral index, α_{ro}, versus the optical-to-X-ray index, α_{ox} (from Sambruna et al. 2004). The dashed line marks the locus where $\alpha_{ox} = \alpha_{ro}$. Knots lying above the dashed line have a concave SED, where the X-rays belong to a different spectral component than the longer wavelengths; IC likely dominates in these sources for the X-ray production. Knots below the dashed line have a convex SED, and the X-rays are interpreted as due to synchrotron emission.

IC/CMB emission). A word of caution is necessary to correctly interpret these result: indeed this sample is not a complete sample representative of all the jet population, being strongly biased toward powerful, (likely) aligned jets hosted by bright quasars. This is consistent with the large Doppler factor necessary to reproduce the bright X-ray emission with the IC/CMB model.

Once the origin of the observed emission is known, it is possible to use the available data to pose limits on the value of the main physical quantities within the jet. Moreover, when more than one knot is detected in a single jet it is possible to follow the evolution of the physical parameters along the jet. To this aim we have obtained deeper (~ 80 ksec) *Chandra* exposures and multifilter *HST* observations of two sources in our sample, 1136-135 and 1150+497. The results are still preliminary, but it is evident a clear trend of the radio emission (already present in other well observed jets, e.g. 3C273), which is continuously increasing along the jet, while the X-ray emission shows a constant or decreasing flux. The impact of these evidences for the physics of the jet are under study.

4. Conclusions: from sub-pc to kpc scale

The possibility to constrain the physical state of the plasma in the jets both at blazars and kpc scale could offer the interesting opportunity to shed some light on the evolution of the jet from very small scales, close to the central engine, to the outer regions, where the jet is starting to significantly decelerate. A case-study along these lines has been presented for a small subset of the *Chandra* jets for which good data for both regions are available (Tavecchio et al. 2004). A first important result is that the powers independently derived for both regions are very close, supporting the overall metodology and suggesting the idea that the jet does not substantially dissipate its power until its end. This result is consistent and supported by the fact that the bulk Lorentz factors independently derived at the two scales are quite close. We have accepted *Chandra* and *HST* observations of three other blazars with a prominent radio jets in the VLA maps, with which we could extende these preliminary study.

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