Spectra and power of blazar jets

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Abstract. The spectra of blazars form a sequence which can be parametrized in term of their observed bolometric luminosity. At the most powerful extreme of the sequence we find objects whose jet power can rival the power extracted by accretion, while at the low power end of the sequence we find TeV and TeV candidate blazars, whose spectral properties can give information on the particle acceleration mechanism and can help to measure the IR background. Most of the emission of blazars is produced at a distance of few hundreds Schwarzschild radii from the center, and must be a small fraction of the kinetic power carried by the jet itself: most of the jet energy must be transported outwards, to power the extended radio structures. The radiation produced by jets can be the result of internal shocks between shells of plasma with different bulk Lorentz factors. This mechanism, thought to be at the origin of the gamma–rays observed in gamma–ray bursts, can work even better in blazars, explaining the observed main characteristics of these objects. Chandra very recently discovered large scale X–ray jets both in blazars and in radio–galaxies, which can be explained by enhanced Compton emission with respect to a pure synchrotron self Compton model. In fact, besides the local synchrotron emission, the radiation coming from the sub–pc jet core and the cosmic background radiation can provide seed photons for the scattering process, enhancing the large scale jet X–ray emission in radio–galaxies and blazars, respectively.

1. Introduction

The discovery that blazars are strong $\gamma$–ray emitters is certainly one of the great achievements of the Compton Gamma Ray Observatory mission (e.g. Hartmann et al., 1999) and the ground based Cherenkov telescopes (e.g. Weekes et al. 1996; Petry et al. 1996) This has allowed to study relativistic jets knowing, at last, the total amount of radiative power produced by them, and at which frequencies their spectra peak. But also X–ray observations have been, and will be, very revealing, for two main reasons: firstly, in this band, we have the contributions of both the radiation processes (synchrotron and inverse Compton) thought to originate the overall continuum of blazars. In this respect BeppoSAX with its 0.1–100 keV band has been particularly revealing. Secondly, the superior angular resolution of the Chandra satellite is giving us pictures of the large scale jets, which, somewhat unexpectedly, are very bright in X–rays.
We are now beginning to construct a coherent picture of the blazar phenomenon, which is important not only *per se* but especially to understand how the relativistic jets work and what originates them. Their emitted radiation is and must be (in order to power the extended radio structures) only a small fraction (a few per cent) of the power they carry. In the most powerful jet sources, the estimated limits on the jet power rivals the power that can be extracted by accretion. The machine which forms and powers the jets in radio sources is therefore as important as accretion: this is why the study of blazars is important.

The $\gamma$–ray radiation we see is intense and variable. This suffices to constrain where this radiation is produced: it cannot be a region too compact or too close to the accretion disk and its X–ray corona, to let $\gamma$–rays survive against the $\gamma \to e^\pm$ absorption process, and it cannot be too large in order to vary rapidly (Ghisellini & Madau 1996).

Furthermore, we know that the Spectral Energy Distribution (SED) of blazars is always characterized by two broad peaks, thought to be produced by the two main radiation processes, i.e. synchrotron at low frequencies and inverse Compton at high energies (see e.g. Sikora 1994 for a review, but see e.g. Mannheim 1993 for a different view). The relative importance of the two peaks (i.e. processes) and their location in frequency appear to be a function of the total power of blazars (Fossati et al., 1998, Ghisellini et al., 1998), leading to a *blazar sequence*. Giommi & Padovani (1994) were the first to notice that the different flavors of blazars corresponded to a different location of their synchrotron peak, and called LBL and HBL the BL Lac objects having the synchrotron peak at low or high frequency, respectively, and I will use in the following the more “colorful” division in red, green and blue blazars (proposed by L. Maraschi) where the color obviously refers to the frequency of the peaks.

### 2. Red blazars

These powerful blazars include flat spectrum radio quasars with relatively strong emission lines, and several BL Lacs of the LBL–type. The synchrotron peak is in the mm–far IR band, while the high energy peak is in the MeV band, and is largely dominating the power output. In Fig. 1 we show two “extremely red” sources, 1428+4217 and 0836+710, which are among the most powerful sources known (if isotropic, the emitted power would exceed $10^{49}$ erg s$^{-1}$). These blazars are important because these are the second most powerful engines to produce bulk kinetic energy, after Gamma–Ray Bursts. By dividing the observed luminosity by the square of the Lorentz factor we can estimate a lower limit on the jet power, assuming that the jet carries more power than what it produces in radiation (i.e. that the emission process is more or less continuous, with no accumulation and rapid release of random energy). In this way we derive jet powers for these sources of the order of $P_{\text{jet}} \sim 10^{47} L_{49}/\Gamma_1^2$ erg s$^{-1}$.

Red blazars are not very conspicuous in the optical, since their synchrotron peak is at lower frequencies, and they are the sources with the largest X–ray to optical flux ratio. The two sources shown in Fig. 1 surely have their jets pointing at us, and therefore their radiation is maximally boosted by beaming. Other blazars should exist with somewhat larger viewing angles (but not too large, not to appear as a radio–galaxy) which are less powerful and even redder.
Figure 1. Examples of red blazars. **Left:** SED of 1428+4217 with the recent BeppoSAX observations, revealing that the X–ray spectrum, likely due to the inverse Compton process, is dominating the power output. Note that this is the most distant radio–loud quasar known. The solid line refers to a one zone homogeneous synchrotron inverse Compton model. Adapted from Fabian et al., 2000. **Right:** SED of PKS 0836+710. Again, the power output in this $z = 2.17$ blazar is dominated by the high energy emission, as revealed by BeppoSAX and EGRET. From Tavecchio et al., 2000.

3. **Green blazars**

Fig. 2 shows two examples of “green” blazars, ON 231 and BL Lac, which are blazars with intermediate properties. Most of them are classified as LBL blazars, and often their X–ray spectrum shows both a steep power law energy component (identified as the high energy tail of the synchrotron emission) and a very hard high energy power law (identified as the emerging of the inverse Compton component). During the BeppoSAX observations of BL Lac, the source had a very rapid variability (timescales of 20 minutes) in the soft energy band, absent at high energies. We expect this behavior to be typical in this class of sources, and could be due to different emitting zones or to the different cooling times of the radiating electron (the most energetic are producing the synchrotron tail while the hard X–rays are produced by electrons with much less energy and longer cooling times).

4. **Blue blazars**

These are the less powerful blazars, with the synchrotron peak located above the optical band, and sometimes reaching the hard X–ray band, as in 1ES 1426+428 and Mkn 501, whose SEDs are shown in Fig. 3.

High energy (especially in the X–ray and TeV bands) observations are important in these sources because there we see the radiation produced by the most energetic electrons (with random Lorentz factors $\gamma > 10^6$), which can then
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Figure 2. Examples of green blazars. **Left:** SED of ON231 with the recent *Beppo* SAX observations, revealing that the X–ray spectrum is nicely described by the high energy tail of the synchrotron at lower energies, while above a few keV, the self Compton process strongly hardens the spectrum. From Tagliaferri et al., 2000. **Right:** SED of BL Lac in the flaring state of summer 1997 and in the more recent *Beppo* SAX observation in 1999. During the latter observation, the optical flux was as high as during the 1997 flare, but the X–ray emission was much lower, revealing both the synchrotron and the inverse Compton components. From Tagliaferri et al., 2000.

Figure 3. Examples of blue blazars. **Left:** SED of 1ES 1426+428 with the recent *Beppo* SAX observations, revealing a synchrotron peak located at or above 100 keV. The solid line refers to a one zone homogeneous SSC model. Adapted from Costamante et al., 2000. **Right:** SED of Mkn 501 during a quiescent state and during the flaring state of 1997. Adapted from Pian et al., 1998. Solid lines are SSC models as discussed in Ghisellini 1998.
reveal some properties of the acceleration mechanism at its extreme. Furthermore, these sources are the best candidates to emit copiously in the TeV band, as in the case of Mkn 421, Mkn 501, PKS 2155–304 and 1ES 2344+514. Besides giving information on the emission and acceleration mechanism, TeV–band data can also allow the measurement of the amount of absorption (through the $\gamma\gamma \rightarrow e^\pm$ process) both local to the source and the one due to the infrared background radiation (see e.g. Stecker & De Jager, 1997).

One can ask if sources even more extreme than Mkn 501 and 1ES 1426+428 can exist, with the synchrotron peak in the MeV range. Shock theory does not prevent it, since the intrinsic maximum predicted synchrotron energy is $\sim 70$ MeV. According to our proposed sequence, these sources should be low power objects and modest in all bands but the MeV one, since they should be radio–weak and dominated by the light of the galaxy in the optical. Even in the “usual” 2–10 keV X–ray band their synchrotron emission, while rising, would still be weak. The self Compton emission in the TeV (and beyond) could be intrinsically faint because of Klein Nishina effects. Therefore there may be many of these sources, hidden in normal elliptical galaxy, with jets of overall low power pointing at us, emitting most of their emission in the MeV band. Future INTEGRAL (in the MeV band) and VERITAS (in the TeV band) observations seem the most promising to discover these “synchrotron MeV BL Lacs” (or UV blazars).

5. What controls the SED of blazars?

In the previous sections we have seen some examples of the variety of the SEDs of blazars. From these examples there seems to be a link between the “color” of a blazar (i.e. the location of its peaks) and its overall luminosity. This impression has been confirmed by a much more detailed study by Fossati et al. (1998), who considered the largest complete blazar samples known at that time, and divided the sources with respect to their radio luminosity (thought to trace well the bolometric power).

As a result we found that blazars come in a sequence, whose main parameter is the observed power: with increasing power blazars tend to be redder, with a more dominating high energy peak. At first sight this is surprising, since the observed power is enhanced by beaming by orders of magnitude, and changes in viewing angle and/or bulk Lorentz factor can dramatically change the observed flux, hence the power. If the beaming factor is $\delta$, the observed bolometric flux is $\propto \delta^4$ while the peak frequencies is $\propto \delta$: note that beaming tends to give a correlation opposite to the one observed: more powerful object should be bluer, not redder. Therefore one interesting conclusion is that blazars are characterized by the same degree of beaming, i.e. the bulk Lorentz factors are contained in a narrow range. The viewing angles should be similar in all blazars as well, and this counter–intuitive conclusion may suggest that the emitting plasma in jets is moving in a fan, not always parallel to the jet axis, and we perhaps call blazars those sources observed within the jet opening angle.

Ghisellini et al. (1998) applied to all blazars detected by EGRET (with known distance and $\gamma$–ray spectral shape), a simple, one–zone, homogeneous synchrotron inverse Compton model including the possible contribution to the
inverse Compton process of photons produced externally to the jet. This enabled us to estimate the intrinsic parameters of the source, such as the magnetic field, the radiation energy density, the size, the beaming factor and the energy of the electrons emitting at the two peaks of the SED, or, equivalently, their random Lorentz factor $\gamma_{\text{peak}}$. We found a remarkable correlation between $\gamma_{\text{peak}}$ and the total energy density $U$ (radiative plus magnetic) as seen in the comoving frame (see Fig. 4, left panel). The slope of this correlation $\gamma_{\text{peak}} \propto U^{-0.6}$ strongly suggests that radiative cooling is playing a crucial role in determining this correlation. The radiative cooling rate scales as $\dot{\gamma} \propto U\gamma^2$ and the found correlation slope implies that, at $\gamma_{\text{peak}}$, all sources have the same cooling rate.

The model we used for the fitting assumed that there is a continuous injection of relativistic particles throughout the source, at a rate $Q(\gamma) \propto \gamma^{-s}$ above some random Lorentz factor $\gamma_{\min}$. We then assumed that radiative cooling was dominating at all energies, resulting in a steady particle distribution characterized (in the absence of Klein Nishina effects) by a broken power law, being $\propto \gamma^{-2}$ at low energies, up to $\gamma_{\min}$, and $\propto \gamma^{-(s+1)}$ above. In this case (since $s$ was larger than 2), the peaks of the spectrum are due to electrons with $\gamma_{\text{peak}} = \gamma_{\min}$.

More recently, we (Ghisellini & Celotti, in prep.) have investigated in more detail this issue, testing if this correlation holds also for more extreme sources,
i.e. extremely blue blazars. Many sources of this class have been observed recently by *BeppoSAX*, and for them we can construct meaningful SED even if we ignore the location of the high energy peak (these sources have not been detected by *EGRET*, nor by Cherenkov telescopes).

Despite the uncertainties introduced by the unknown level of the Compton emission, the intrinsic parameters resulting from the fits are limited in a given range which is not compatible with the $\gamma_{\text{peak}} \propto U^{-0.6}$ relation. For these extreme sources the relation is steeper (i.e. $\gamma_{\text{peak}} \propto U^{-1}$, see Fig. 4, right panel).

We then fitted the SED with a slightly different model, in which the particle energy distribution takes into account the relative importance of adiabatic vs radiative cooling. We then find that for powerful blazars the radiative cooling is always dominating (and then find the same results as above), but for blue blazars adiabatic can dominate over radiative cooling even at energies $\gamma > \gamma_{\text{min}}$. In this case the peak of the emission is produced by electrons for which the two cooling processes are equal. This effect should be responsible of the $\gamma_{\text{peak}} \propto U^{-1}$ relation we find for blue blazars (Ghisellini & Celotti in prep).

6. Large scale X–ray jets

*Chandra* is finding that jets of both blazars and radiogalaxies show X–ray emission at large scales (Chartas et al. 2000; Schwartz et al. 2000; Wilson et al., 2000). In the case of the blazar PKS 0637–752 [a superluminal source (Lovell 2000), hence observed under a very small viewing angle], the X–ray flux comes from a (deprojected) distance of $\sim 1$ Mpc from the center. These observations imply the presence of a large number of relativistic electrons, and the relatively faint optical emission implies that the X–rays cannot be produced by the synchrotron process (see Fig. 5).

We (Celotti, Ghisellini & Chiaberge 2000) have proposed that the X–ray flux in PKS 0637–752 is inverse Compton scattering with the cosmic background radiation, which in the comoving frame of the source is seen enhanced by blueshift and time contraction. We then require that, at the Mpc scale, the jet is still relativistic ($\Gamma = 10–15$) and therefore that the produced X–ray rays are beamed.

Although it may seem odd to have relativistic motion at such large distances, consider that it is the most economic way to account for the observed X–ray power. In fact for lower values of $\Gamma$ more emitting electrons are needed, and the total bulk kinetic power carried by them increases despite the smaller $\Gamma$–factor. We also pointed out that the large scale jet could have some velocity structure (Celotti et al., 2000; Chiaberge et al., 2000), consisting in fast “spines” and slowly moving “layers”. The layers could consist of dissipation zones of the jet where the jet material collides with obstacles in the jet or its walls: particles can be accelerated there and produce quasi–isotropic synchrotron emission. If these regions are not misaligned with respect to the inner (sub–pc) jet, they can be illuminated by the intense and beamed radiation coming from the sub–pc core of the jet, and hence receive an extra contribution of seed photons to be Compton scattered at high energies, enhancing the X–ray emission.

Fig. 5 (left, top panel) shows one example of enhanced Compton emission with respect to a pure SSC spectrum. Being slow, and possibly only mildly relativistic, the layers produce radiation which is much more isotropic than the
Figure 5. Examples of spectra expected from large scale jets. **Left:** At 10 kpc from the center a region of 1 kpc of size embedded in a magnetic field of $10^{-5}$ G radiates an intrinsic power of $3 \times 10^{41}$ erg s$^{-1}$. The nuclear (blazar) component emits an intrinsic power of $10^{43}$ erg s$^{-1}$. The upper panel shows the emission from a layer with $\Gamma_{\text{layer}} = 1.1$ and viewing angle $\theta = 60^\circ$. The dashed line corresponds to the SED assuming SSC radiation only. The solid line accounts for radiation coming from the core of the jet and illuminating the region. The bottom panel shows the emission from a spine moving with $\Gamma = 10$ at a viewing angle $\theta = 5^\circ$. **Right:** The SED of the core and the large scale knot of PKS 0637–752, together with the models for both components (solid lines). From Celotti, Ghisellini & Chiaberge, (2000).

spine: at small viewing angles (blazar case) this component is outshined by the spine component, but it can become visible as the viewing angle increases (i.e. in radio–galaxies).

7. Jet power

Due to beaming, it is not trivial to estimate the amount of luminosity intrinsically emitted by blazars and radio–galaxies, and then to use it to estimate the power carried by jets. Powerful FR II radiogalaxies and quasars, on the other hand, have extended radio structures and lobes containing huge quantity of energy, which we can estimate resorting to equipartition arguments and simplifying assumptions. These structures can be thought of as calorimeters, since there the radiative cooling time of the emitting particles is long: by knowing the lifetimes of these structures we can then estimate the average incoming power that jets must provide. This has been done, among others, by Rawlings & Saunders (1991) who also found a correlation between the average power required by radio lobes and the luminosity of the narrow lines. These power estimates are appropriate for the largest scales, i.e. 100–1000 kpc.

Celotti & Fabian (1993) and Celotti, Padovani & Ghisellini (1997) have instead directly estimated the power carried by jets by estimating the number of electrons required to account for the radio flux seen in VLBI components, hence at the 1–10 pc scale.
Figure 6. Histograms of the distribution of kinetic power (in erg s$^{-1}$) of the blazars considered in Celotti & Ghisellini 2001. $L_p$ is the power carried by protons assuming one proton per emitting electron; $L'_r \Gamma^2$ is the power radiated by the jet and $L'_\text{syn} \Gamma^2$ the power in synchrotron radiation only; $L_B$ is the Poynting flux; $L_e$ is the power carried by the emitting electrons. The gray thin histograms and the shaded areas correspond to FSRQs and BL Lacs respectively, detected by EGRET and with measured $\gamma$-ray spectrum. The bold line histograms correspond to extreme BL Lacs not detected by EGRET, for which we have assumed that the SSC emission has about the same power as the synchrotron one.
Finally, Celotti & Ghisellini (2001, in prep) estimate the jet power by computing the number of particles required to account for the bulk of the observed luminosity (often coinciding with the $\gamma$--ray luminosity) by applying a simple one--zone homogeneous synchrotron inverse Compton model to the SED of blazars. These estimates refer to the inner part of the jets, i.e. to the 0.01-0.1 pc scale. The distributions of the bulk kinetic power carried by jets in the form of protons ($L_p$, assuming one proton for each emitting electron); emitted total radiation ($\Gamma^2 L'_r$, where $L'_r$ is the emitted power as measured in the comoving frame); emitted synchrotron radiation ($\Gamma^2 L'_\text{syn}$); Poynting flux ($L_B$) and electrons ($L_e$) are shown in Fig. 6. As can be seen, the dissipated power ($\Gamma^2 L'_r$) is greater, on average, than the power carried by electrons and magnetic field only, (in this case the jet would dissipate more than what it can), implying an energetically important proton component. In the absence of electron–positron pairs we would have the $L_p$ distribution shown in Fig. 6, whose average value is a factor 10 larger then the average dissipated power. Considering that most of the jet power must be transported out to reach the extended radio structures, there is little room for a large amount of electron–positron pairs (if present, they would decrease $L_p$ because there would be less than one proton for each emitting lepton).

The histograms in Fig. 6 assumed that the particle distribution of emitting electrons had no low energy cutoff, i.e. $\gamma_{\text{min}} = 1$. This parameter is important because the particle number depends on its value, which in turn is very poorly constrained by observations. On the other hand the plotted $\Gamma^2 L'_r$ distribution does not depend on it. We therefore conclude that, in order for the bulk kinetic jet power to be larger than the dissipated power, $\gamma_{\text{min}}$ cannot be larger than a few (in other words: many particles are needed to transport a power larger than what is wasted).

8. Internal shocks

In gamma–ray burst science, the most accepted scenario for explaining the origin of the prompt emission is the so called internal shock scenario, in which the central engine works intermittently, producing shells of slightly different velocities, mass and energy (e.g. Rees & Mészáros 1994). Faster and later shells can then catch up slower earlier ones, dissipating part of their bulk kinetic energy into radiation. This model could work even better in blazars: for them we require a moderate efficiency for the bulk to random energy conversion, as is the case in this scenario. Indeed, this idea was born in the blazar field (Rees 1978), and only later became the leading idea to explain the gamma–ray burst emission (but see Sikora, Begelman & Rees 1994). This model is very promising, since it can explain some basic properties of blazars:

- The efficiency is of the right order: most of the jet power has not to be dissipated, in order to power the radio lobes.
- If the initial separation is comparable to a few Schwarzschild radii, i.e. $R_0 \sim 10^{15}$ cm, the collision takes place at $R_i \sim 10^{17}$ cm (for $\Gamma_1 \sim 10$), just at the distance where the inverse Compton scattering off the photons of the Broad Line Region is efficient, where the $\gamma-\gamma\to e^\pm$ process is not important,
Figure 7. **Left:** SED of 3C 279 with, superimposed, different spectra resulting from our simulations of internal shocks. These correspond to different shell–shell collisions in different parts of the jet. **Right:** Cross correlation between the simulated $\gamma$–ray light curve and the X–ray, the optical and the mm light curves. Only for the latter there is a clear delay of about 40 days, due to the average distance of the regions producing $\gamma$–rays and mm radiation, once Doppler time contraction is accounted for. From Spada et al., 2001.

and yet the emitting region is still sufficiently compact to account for the rapid variability.

- There can be a hierarchical structure in shell–shell collisions: pairs of shells can collide once more, at greater distances, where the dominant channel for radiation is synchrotron emission with a smaller value of the magnetic field. Hence there can be a link between the flares at optical and $\gamma$–ray energies and the flares in the radio–mm band (see Fig. 7, right panel).

These qualitative properties have been verified by numerical simulations by Spada et al. (2001), assuming a jet of average bulk kinetic power of $10^{48}$ erg s$^{-1}$, carried by shells or blobs injected in the jet, on average, every few hours, with a bulk Lorentz factor chosen at random in the range [10–30]. The first collisions happen at a few$\times 10^{16}$ cm, well within the Broad Line Region (BLR), assumed to be located at $5 \times 10^{17}$ cm and to reprocess 10% of a disk luminosity, of the order of $10^{46}$ erg s$^{-1}$. Particles emit by synchrotron, synchrotron self–Compton and Compton scattering off the external radiation (EC) produced by the BLR. In Fig. 7 (left panel) we show some spectra, each corresponding to one single shell–shell collision at a different distance, and the entire time dependent evolution can be seen in the form of a movie at the URL: [http://www.merate.mi.astro.it/~lazzati/3C279/index.html](http://www.merate.mi.astro.it/~lazzati/3C279/index.html).

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