Blazars: recent developments

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Abstract. Recent observational and theoretical results on blazars are presented and discussed. We are beginning to understand the rich phenomenology of blazars, and we are finding trends which will hopefully lead us to unveil the physics of these extreme sources. Limits and constraints on how jets originate can be derived by their intense and variable $\gamma$-ray emission. We are now starting to study their variability behavior simultaneously at different frequencies, to find delays and lags, to put constraints on emission models and source geometry. We observe trends in the overall spectral energy distribution. Also the problems of the overall energetics of jets and of their matter content are now being tackled.

1. Introduction

EGRET, onboard CGRO, and ground based Cerenkov telescopes detected intense and variable $\gamma$-ray emission from blazars (von Montigny et al. 1995; Thompson et al. 1995, 1996; Weekes et al. 1996; Petry et al. 1996). This discovery has allowed a much deeper understanding of their emission processes and, more generally, of the physics of relativistic jets. We can at last construct the entire spectral energy distribution (SED) of blazars, and know that, during flares, the $\gamma$-ray power output can greatly exceed what is emitted in the rest of the electromagnetic spectrum. This discovery has revived blazar research and further stressed the need for strictly simultaneous observations in different bands, since fluxes emitted at different frequencies may be produced by the same process or within the same emitting region.

2. A few things that $\gamma$-ray tell us

The very fact the we observe a strong and variable $\gamma$-ray flux from blazars bears very important consequences.

The first implication is that the $\gamma$-rays we see are not absorbed by the $\gamma$-$\gamma \rightarrow e^+e^-$ process, the most effective $\gamma$-ray absorption process in the blazar disk/jet environment. This means that the hard X-ray and the $\gamma$-ray radiation must be beamed: in this way the photon density in the comoving frame is reduced, and the source can be transparent to the high energy emission (see Dondi & Ghisellini 1995 for the derivation of the beaming factor for a sample of EGRET sources).
The second implications is that there cannot be, even externally to the \( \gamma \)-ray production site, any strong source of X-rays, which are target photons in the \( \gamma\gamma \rightarrow e^+e^- \) process. Therefore not only the emitting plasma must be in relativistic bulk motion, but it also has to be far away from any strong X-ray source, such as the hot corona sandwiching the accretion disk. This must be true not only for the region emitting the \( \gamma \)-rays reaching us, but throughout the entire jet. Let us consider, in fact, the inner part of the jet (closer to the black hole), and assume that it emits a significant fraction of the total power in \( \gamma \)-rays and that they get absorbed, originating \( e^\pm \) pairs, as in the Blandford & Levinson (1995) model. These pairs are born relativistic, and reprocess, through inverse Compton scattering, the UV radiation produced by the disk. The inverse Compton and the photon–photon pair creation processes have roughly the same cross section: the relative importance of the two processes is determined by the relative energy densities in X-rays vs IR–UV photons. The result is that those pairs reprocess the power originally in \( \gamma \)-rays into X-rays. We should then observe roughly equal X-ray and \( \gamma \)-ray luminosities (the latter coming from more extended, optically thin parts of the jet). This is not observed. Most of the radiative power must therefore be produced far away (hundreds of Schwarzschild radii) from the black hole. There must be some energy transport mechanism which is dissipationless up to these distances (Ghisellini & Madau, 1996). Candidates are Poynting flux and collimated relativistic protons.

3. Many kinds of variability behaviors

Fast and large amplitude variability is a defining property of blazars (see the review by Ulrich, Maraschi & Urry, 1997). However, not all blazars share the same variability behaviour, and the ‘old’ rule of more extreme variability for larger frequencies is not always true. Even in this research area the discovery of GeV–TeV emission of blazars has been crucial in stimulating many (but not yet enough) observational campaigns aiming to follow single sources from the radio to the TeV band (see the review by Wagner 1997 and references therein). Fig. 1 tries a first naive classification of the variability we see. Variability in different bands is correlated, suggesting that a single populations of electrons is responsible for producing the two broad peaks of emission by the synchrotron and inverse Compton processes. Time lags are starting to be observed, and even if these results are still somewhat puzzling (e.g. the different variability behavior of PKS 2155–304 in two different campaigns, see Ulrich, Maraschi & Urry, 1997 and references therein), this is one of the most powerful way to study the acceleration mechanism, and to put strong constraints on emission models (Kirk, 1997 and references therein; Tavecchio, Maraschi & Ghisellini, 1998). In Fig. 2 some SEDs of specific blazars are shown, to illustrate concrete examples of the tentative variability classification sketched in Fig. 1.

4. The blazar SED

Fig. 2 illustrates the overall SED of some of the best known blazars. As can be seen, the SED is characterized by two broadly peaked components. The first component, produced by synchrotron emission, peaks in the mm–far IR band in
Figure 1. Schematic examples of the observed overall variability behavior of blazars.
Figure 2. Some examples of blazar SEDs, corresponding to multifrequency observational campaigns. PKS 2155–304: Maraschi et al. 1998; 3C 279: Maraschi et al. 1994, Werhle et al. 1998; Mkn 501: Pian et al. 1998; ON 231: Tagliaferri et al. in preparation. The solid lines are homogeneous synchrotron self-Compton plus external photon models (see Ghisellini et al. 1998).
powerful blazars, while it peaks at higher energies as the total power decreases, reaching the EUV–soft X–ray band in HBL (high energy peaked BL Lacs). Correspondingly, also the second more energetic component peaks at higher and higher energies as the total power decreases. The correlated variability strongly suggests that this component is produced by inverse Compton emission by the same population of electrons emitting the synchrotron radiation. Moreover, this Compton component becomes increasingly dominant (with respect to the synchrotron one) as the total observed power increases.

5. Unifying blazars

The trends just mentioned have been discussed in detail by Fossati et al. (1998), who considered three complete samples of blazars, and by Ghisellini et al. (1998), who studied all blazars detected by EGRET for which we have some γ–ray spectral information. In the latter paper we have modeled all sources with a homogeneous synchrotron and inverse Compton model, taking into account, for the scattering process, both the locally produced synchrotron photons and photons produced externally to the jet. The modeling allows to derive the intrinsic parameters of the sources such as the size, the magnetic field, the energy $\gamma_{\text{peak}} m_e c^2$ of the electrons emitting at the peaks, the particle density and so on. The fitted spectra are constructed through a literature search, and are rarely simultaneous. This implies that the fitting parameters found may be not completely correct for individual sources, but are representative on statistical grounds.

One of the most important results of this study is the striking correlation found between $\gamma_{\text{peak}}$ and the total (magnetic plus radiative) energy density of the emitting region, as shown in Fig. 3. Furthermore, $\gamma_{\text{peak}}$ also correlates with the observed power, the amount of external seed photons used for the scattering process and the ratio between the Compton and the synchrotron luminosity. The smaller $\gamma_{\text{peak}}$, the larger the energy densities and the total power, dominated by the Compton luminosity.

Different blazar subclasses then form a well defined sequence:

• powerful quasars, both polarized and not, are characterized by small values of $\gamma_{\text{peak}}$, so that their synchrotron spectrum peaks in the mm–far IR band and their Compton spectrum in the MeV band. The Compton component is stronger than the synchrotron one, and the contribution of photons produced externally to the jet to the scattering process is more important than the synchrotron one.

• At the other extreme, HBL have large values of $\gamma_{\text{peak}}$, and consequently their spectra peak in the soft-X–ray and in the GeV–TeV bands. The Compton emission is roughly as powerful as the synchrotron one. The contribution of externally produced photons is almost negligible (even if photons produced in regions of the jet adjacent to the γ–ray emitting site may be important, as in the case of Mkn 501, Pian et al. 1998).

A tentative interpretation of these trends is that in all sources there is a competition between the acceleration and the cooling processes, which determines the relevant value of the electron energy, i.e. $\gamma_{\text{peak}}$. The particular form
of the found correlations between $\gamma_{\text{peak}}$ and the (comoving) energy density $U$, $\gamma_{\text{peak}} \propto U^{-0.6}$, implies that the radiative cooling rate ($\dot{\gamma} \propto \gamma^2 U$) at $\gamma_{\text{peak}}$ is almost the same for all sources. This suggests the existence of a ‘universal’ acceleration process (i.e. the same in all sources, and independent of $\gamma$ and $U$) which accelerates the electrons up to the energy where their gains balance their losses.

We could then explain why only in lineless and relatively weak BL Lacs the electrons can attain TeV energies: in these sources the energy densities are relatively small, and correspondingly the balance between heating and cooling rates is achieved at a larger $\gamma_{\text{peak}}$. On the contrary in powerful blazars with significant emission line luminosity the electron energy density is large, and the balance between heating and cooling is achieved at a smaller $\gamma_{\text{peak}}$. In these sources the Compton cooling is enhanced (because of greater radiation energy densities), and this is why the Compton to synchrotron luminosity ratio is larger.

5.1. How to falsify the proposed scenario

In the proposed picture blazars lie along a sequence: from powerful flat spectrum radio sources to less powerful lineless BL Lacs. The electron cooling rate is the key parameter ruling the value of $\gamma_{\text{peak}}$ and therefore their overall SED.

This scenario could then be falsified if there exist powerful blazars with relatively strong emission lines and with synchrotron and Compton peaks located at high energies (in the soft X–rays and in the GeV–TeV band).

Instead low luminosity blazars with a SED peaking at low energies (far IR and MeV–GeV) would not necessarily contradict our picture, since they can be slightly misaligned powerful blazars.
6. The power of blazar jets

Jets must power the extended radio lobes of radiogalaxies and quasars, which contain a huge amount of energy. By estimating it with equipartition arguments, and dividing it by the age of the source, one obtains the average power that lobes needed to be formed and to grow (Rawlings and Saunders 1991). This can amount to $10^{46} - 10^{47}$ erg s$^{-1}$. Jets have to carry this amount of power in the form of bulk kinetic flow ($L_k$) and/or Poynting vector ($L_B$). These powers can be estimated at any location in the jet knowing the corresponding cross sectional jet area ($\pi R^2$), the particle density ($n = n'/\Gamma$, where $n'$ is the density in the comoving frame), the bulk Lorentz factor ($\Gamma = 1/\sqrt{1 - \beta^2}$), the magnetic field ($B$, as measured in the comoving frame), the matter content (electron–positron pairs or electron–protons) and the average internal energy of the leptons ($< \gamma > m_e c^2$, assuming that the protons are cold). We then have (Celotti & Fabian 1993, Ghisellini & Celotti 1998):

$$L_k = \pi R^2 \beta c^3 n'(< \gamma > m_e + m_p)$$

$$L_B = \frac{1}{8} R^2 \Gamma^2 \beta c B^2$$

where we have assumed a proton–electron plasma. The observed synchrotron luminosity of a blob of volume $(4\pi/3)R^3$, observed at an angle $1/\Gamma$ is

$$L_{s,obs} = \frac{4\pi R^3}{3} \Gamma^4 \int n'(\gamma) \gamma m_e c^2 d\gamma = \frac{2R^3}{9} \Gamma^4 \sigma_T c n' B^2 < \gamma^2 >$$

where $< \gamma^2 >$ is averaged over the emitting particle distribution. By substituting the particle density derived by this equation into Eq. (1), we have

$$L_k = \frac{9\pi m_e c^2}{2\sigma_T} \frac{L_{s,obs}}{\Gamma R^2 B^2} \frac{< \gamma > + m_p/m_e}{< \gamma^2 >}$$

We see that $L_k \propto (BT)^{-2}$, while $L_B \propto (BT)^2$: therefore $L_{jet} = L_k + L_B$ is minimized for some value of $BT$, which corresponds to equipartition between particle and magnetic energy densities (Ghisellini & Celotti, 1998; see also Celotti & Ghisellini, this volume). In this case the observed (at a viewing angle $\sim 1/\Gamma$) synchrotron emission is maximized. In other words, the most economic way for a blazar to emit the observed synchrotron power is to be in equipartition. Fig. 4 shows that blazars can really be in equipartition: for this figure we have used the parameters ($B$ field, particle distribution, dimension) derived by fitting the spectra of the EGRET blazars (Ghisellini et al. 1998). One can see that for $\Gamma \sim 10-15$ (which is the value used for the fits) we have the minimum energetic requirement. In this figure we also plot the radiative total luminosity $L_r$, which is the power emitted in the rest frame multiplied by $\Gamma^2$, i.e. it is the power received over the entire solid angle (it is not the power inferred from the flux multiplied by $4\pi d^2$, where $d$ is the luminosity distance). If the radiative power originates from the conversion of bulk into random kinetic energy, and in steady state conditions, $L_r$ cannot exceed $L_k$. However, $L_r$ approaches $L_k$ in the case of Mkn 501, suggesting that extreme flaring states (the power of Mkn 501 during
the 1997 flare was 20-fold the power in the quiescent state) may correspond to more efficient bulk to random energy conversion.

Another interesting consequence is that there is a limit to $\gamma_{\text{peak}}$, at least in steady state sources: the higher $\gamma_{\text{peak}}$, the faster the cooling rate, and the greater the radiated luminosity. But the latter cannot exceed the power in bulk motion, and thus sets an upper limit to $\gamma_{\text{peak}}$ (which might have been almost reached by Mkn 501 during its flare).

7. Jet content

We know the power required by the extended radio lobes to exist. We can equate this power to the power in bulk kinetic motion of the jet plasma, and infer if the jet is composed by electron–positron pairs or by an electron–proton plasma. The crucial quantity we need to know is the particle density in the jet. We can estimate it through the synchrotron emission of the relativistic particles, integrating over the particle distribution $n(\gamma)$. Unfortunately, this integral depends on the low energy end of the distribution, $\gamma_{\text{min}}$: at these energies the electrons emit self-absorbed synchrotron radiation and are therefore unobservable. The other quantity required is the dimension of the region emitting this radiation, which can be directly obtained through VLBI observations. In this way Celotti & Fabian (1993) derived two possible solutions:

i) $\gamma_{\text{min}} \sim 1$, and the jet is $e^{\pm}$ dominated;

ii) $\gamma_{\text{min}} \sim 30–100$, and the jet is made by electrons and protons.
Note that pairs could not be formed at the base of the jet, since they would not survive the strong annihilation implied by their large density. Furthermore, for what discussed in §2, it is problematic to use the $\gamma$–ray radiation to create them along the jet, since an inevitable by–product of this would be an excessive X–ray radiation. For these reasons I prefer solution ii) (preferred also by Celotti and Fabian). For reviews on the problem of the matter content of jet, see Celotti (1997 and 1998).

8. Conclusions

- Strong and variable $\gamma$–ray emission implies that the high energy radiation is beamed, and is produced far away from the black hole and the accretion disk. This points to an energy transport mechanism which is dissipationless up to the $\gamma$–ray production site.

- Electron–positron pairs cannot be created by absorbing a significant amount of $\gamma$–rays. This would produce too many X–rays.

- Variability is complex, but the correlations observed in different bands suggest a single population of electrons, emitting by the synchrotron and the inverse Compton processes.

- Blazars form a sequence. Their relevant electron energy correlates with the comoving energy density, the observed power, the Compton to synchrotron power ratio and the amount of external seed photons scattered at high energies, which can be identified with photons from the broad emission line region. Low luminosity BL Lacs are the best candidates to be TeV emitters, powerful blazars are strong MeV sources.

- Blazars are close to equipartition between the power in bulk kinetic motion and the Poynting flux. This is the most economic way to produce the synchrotron emission we observe.

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