Abstract

TeV emission can be a common characteristic of low power blazars. This is in line with the sequence of blazars relating the observed bolometric luminosity with their overall spectral energy distribution. Detecting new TeV blazars, possibly at different redshifts, is important for studying the particle acceleration process operating in the jet, and it is even more important for studying the far infrared–optical background. Recent studies of low power BL Lacs suggest that the particle acceleration mechanism may be a two-step process, analogous to what is invoked to explain the spectra of gamma–ray bursts. I will briefly discuss these findings, together with a simple scheme for selecting good TeV candidates and I will briefly comment on the very fast TeV and X–ray variability observed in BL Lacs.

Key words: Relativistic Jets – BL Lac objects

1 Introduction

TeV astronomy is now leaving its infancy and becoming adult. The few BL Lacs (see Fig. 1) detected by the existing Cherenkov telescopes will become hundreds when the promised tenfold increased sensitivity (and lower energy thresholds) of the new generation of telescopes will be reached. It is a new electromagnetic window which has been opened to scrutiny: the fact that it can be done on ground means that it is one order of magnitude (at least) less expensive than satellites, and this in turn means fast progress. There are at least two science pillars involving TeV astronomy: the first is of course the study of TeV emitting objects, and the violent physics involved, while the second is the cosmological issue of estimating the intergalactic infrared, optical (and in future UV, when the detecting threshold will reach the 10 GeV range) backgrounds, through the study of the absorption imprinted in the intrinsic spectrum of the TeV emitting sources through the photon–photon collision process (e.g. Stecker & De Jager 1997). For these issues it is now important to find good candidates for TeV emission within a range of redshifts. As discussed
Fig. 1. The SED of the 6 BL Lacs detected so far at TeV energies. The dashed and solid lines are model fits of different states of the sources. See Costamante & Ghisellini (2002) for the relevant sources of data and discussion of the models.

below, we think that the best candidates are among low power BL Lacs, characterized by a spectral energy distribution (SED) with the first peak (in a $\nu F_\nu$ plot) at X-ray frequencies. We call them extreme blazars. We argue that the best TeV emitters are extreme BL Lacs with relatively strong radio emission, which measures the amount of seed photons required for the inverse Compton scattering process.

2 Extreme blazars

Besides the phenomenological approach leading to the blazar sequence discussed in Fossati et al. (1998) and in Donato et al. (2001), to understand why blazars have their SED controlled by their bolometric luminosity we need to
Fig. 2. The random Lorentz factor of the electrons emitting at the peaks of the SED, $\gamma_{\text{peak}}$, as a function of the comoving energy density (radiative plus magnetic). The points connected by a line correspond to the quiescent and flaring state of the same source, as labeled. The dashed lines correspond to $\gamma_{\text{peak}} \propto U^{-1/2}$ and $\propto U^{-1}$ (they are not best fits). From Ghisellini, Celotti & Costamante (2002).

model their spectra, in order to derive the physical parameters of the emitting region such as the size, the value of the magnetic field, the particle density and the beaming factor. Ghisellini et al. (1998) considered the sample of blazars detected by EGRET with some spectral information in the EGRET band. We applied a one–zone (leptonic) model, including (besides SSC) the inverse Compton scattering process with photons produced externally to the jet. We found a clear correlation between the energy of the electrons emitting at the peaks of the SED, $\gamma_{\text{peak}}$, and the value of the magnetic plus radiation energy density measured in the comoving frame, $U$. The correlation was of the kind $\gamma_{\text{peak}} \propto U^{-1/2}$, i.e. the radiative cooling rate at $\gamma_{\text{peak}}$, $\dot{\gamma} \propto \gamma_{\text{peak}}^2 U$, is constant and the same for all sources. Since the more extreme BL Lacs were under–represented in this work, Ghisellini, Celotti & Costamante (2002) later extended the range of parameters by including sources with more extreme values of $\gamma_{\text{peak}}$, corresponding to low power BL Lacs. This was possible through the BeppoSAX observations of extreme blazars, covering the range 0.1–100 keV (i.e. all these BL Lacs were detected in the hard X–ray band).

We found a new branch of the correlation at high $\gamma_{\text{peak}}$, with $\gamma_{\text{peak}} \propto U^{-1}$. We interpreted it as the effect of a finite timescale of injection, $t_{\text{inj}}$: in powerful blazars all particles cool in $t_{\text{inj}}$ (fast cooling regime), while in low power BL
Lacs the radiative cooling is less severe (slow cooling regime), and only the high energy particles can cool in this timescales. If we take a snapshot of the spectrum at the end of the injection, i.e. at the maximum of the flare, we then have two behaviors: in the fast cooling regime $\gamma_{\text{peak}}$ is determined by the low energy cutoff of the injected distribution, since it is at this energy that a break in the final distribution occurs. In the slow cooling regime, instead, $\gamma_{\text{peak}}$ corresponds to particles whose cooling time equals the injection time, and we obtain $\gamma_{\text{peak}} \propto U^{-1}$.

These results suggest a two–step acceleration process: first a phase of “pre–heating” determining the low energy cut–off of the injected distribution, and then a rapid acceleration leading to a non–thermal energy distribution. This two–step process can operate in all blazars: their different SED simply reflects the different degree of radiative cooling. The typical energies produced by the pre–heating (in the range $\gamma_{\min} \sim 10–10^3$) correspond to the balance of the heating and cooling rates: this gives $\gamma_{\min} \propto U^{-0.5}$. We have $\gamma_{\text{peak}} = \gamma_{\min}$ in powerful blazars, where electrons of all energies cool in a time $t_{\text{inj}}$. Instead, when the cooling is less severe, the particle distribution (after $t_{\text{inj}}$) will have a break at $\gamma_{\text{peak}} > \gamma_{\min}$, determined by $t_{\text{cool}}(\gamma_{\text{peak}}) = t_{\text{inj}}$, leading to $\gamma_{\text{peak}} \propto U^{-1}$.

Fig. 2 also shows that the parameters corresponding to different states of specific TeV sources obey the general trend (see the “tracks” connecting different points belonging to the same source). This is true even when the observed synchrotron peak frequency increases with the observed luminosity (as during the 1997 flare of Mkn 501; Pian et al. 1998), contrary to the general sequence discussed by Fossati et al. (1998).

### 2.1 Jet power of TeV sources

The fact that the emission region producing most of the observed luminosity is well localized allows us to estimate the total power carried by the jet. In fact, through modeling, we derive the size, the magnetic field, the particle density and the bulk Lorentz factor of the emission region, and these are the quantities needed to derive the power carried in the form of bulk kinetic energy and in Poynting flux. Fig. 3 shows our results, and we can compare TeV sources with the other blazars. As can be seen, TeV sources have the same kinetic powers of other BL Lacs, but significantly less Poynting flux. Contrary to more powerful blazars, we do not find strong constraints, on energetic grounds, to limit the number of electron–positron pairs of their jets. This is due to the fact that the mean electron random Lorentz factor is very high in TeV sources, making the relativistic mass of electrons to be roughly equal to the proton mass: it makes a little difference then to have an electron–proton or a pure pair plasma (compare $L_e$ with $L_p$ in Fig. 3).
Fig. 3. Histograms of the distribution of kinetic power (in erg s\(^{-1}\)) of the blazars considered in Celotti & Ghisellini 2003 (in prep.). \(L_p\) is the power carried by protons assuming one proton per emitting electron; \(L_e\) is the power carried by the emitting electrons; \(L_B\) is the Poynting flux; \(L'_r\Gamma^2\) is the power radiated by the jet and \(L_{e,cold}\) is the power carried in the form of electron rest mass (i.e. the difference with \(L_e\) is that the latter includes the relativistic random energy of the particles). The shaded and dotted histograms corresponds to TeV and other BL Lac sources, as labeled.

3 Candidates for strong TeV emission

To emit TeV photons we need TeV electrons, which emit, by the synchrotron process, in the X–ray band (for typical magnetic fields of 0.1–1 Gauss and beaming factors \(\delta \sim 10\)). Therefore sources with a strong synchrotron X–ray flux are obviously good TeV candidates. On the other hand, to have a large TeV luminosity through synchrotron self Compton (SSC), we need also synchrotron IR–optical seed photons, and this leads to a trade-off, since sources with a prominent synchrotron peak at hard X–ray energies have relatively little IR–optical emission. Fig. 4 shows how BL Lac objects (belonging to several samples) are located in the X–ray – radio flux plane. Filled diamonds corresponds to the already TeV detected BL Lacs: all of them are contained in the
Fig. 4. BL Lac objects in the radio (5 GHz) and X–ray (1 keV) $\nu F_\nu$ plane. Sources belonging to different samples have different symbols, as labeled. The objects marked with their name are good TeV candidates, besides the objects already detected (filled circles).

rectangle limited by the solid lines. We can see that all the TeV BL Lac objects are HBL (high frequency peak BL Lac, Giommi & Padovani 1994) characterized by a broad band radio to X–ray spectral index $\alpha_{RX} < 0.75$ (lower dashed line), but all of them are relatively bright radio sources. We believe that this occurs because the radio flux is a measure of the amount of IR–optical emission, providing the seed photons for the scattering. It can also be seen that there are several other sources in the vicinity of the already detected TeV ones. We considered them as the best TeV candidates, and we plot in Fig. 5 the expected flux at three different energy thresholds according to two models: a simple SSC model and the phenomenological model discussed in Fossati et al. (1998) with the modifications introduced in Costamante & Ghisellini (2002).
4 Extreme variability

Besides the famous example of very rapid variability in the TeV band shown by Mkn 421 in 1996 (Gaidos et al. 1996) there have been other examples of nearly factor 2 flux variations in a timescale of $\sim$5–20 minutes: in Mkn 501 in X–rays (Catanese & Sambruna 2000), BL Lac in X–rays (Ravasio et al. 2002) and Mkn 421 again in the TeV band (Aharonian et al. 2002). This very rapid variability is however not common, as indicated by the power spectra and structure functions (e.g. Fossati et al. 2000; Tanihata et al. 2003) calculated for the same sources, which suggests a more relaxed typical timescale of order of a few hours. The ultra–fast variations must be produced by very compact regions of size $\sim 10^{14}$ cm, several times smaller than the “normal” emission regions, and one interesting possibility is that they may correspond to “explosive” events occurring within larger and relatively steadier emission regions. Just for illustration, consider two colliding shells (as in the internal shock scenario), dissipating energy throughout their volumes, but also triggering reconnection of the magnetic field lines in small sub–volumes, dissipating large amounts of energy in the form of relativistic particles. Besides their own synchrotron flux, these particles will also scatter the “ambient” photons produced by the larger...
region, enhancing the inverse Compton contribution. If this idea is true, then we expect that these fast variations of the inverse Compton flux occur on top of flares (produced by the shell–shell collision event), and not during quiescent states (Ghisellini & Tavecchio, in prep.).

5 Internal shock scenario

The complex phenomenology of blazars and of blazar jets can be framed in a coherent picture, in which the central engine does not work continuously, but is injecting power in the jet intermittently, through shells of matter moving at slightly different velocities. These shells catch up at some distance from the black hole, and collide dissipating part of their kinetic energy. This “internal shock” scenario is one of the leading ideas for the generation of the prompt emission of gamma–ray bursts, and can work even better for blazar jets. As in gamma–ray bursts, the typical variability timescales in this scenario is linked with the initial distance $\Delta R$ between two consecutive blobs, which should be of order of the Schwarzschild radius (they collide at a distance $\sim \Gamma^2 \Delta R$, but the observed time variability is shortened by a factor $\Gamma^2$ by the Doppler effect). This scenario is easy to visualize, it explains the main characteristics of blazar jets and it allows numerical estimates (e.g. Ghisellini 1999; Spada et al. 2001; Tanihata et al. 2003).

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