TEV BLAZARS: STATUS OF OBSERVATIONS

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ABSTRACT The close relation between ground-based TeV observations and satellite borne \(\gamma\)-ray measurements has been important for the understanding of blazars. The observations which involve the TeV component in blazar studies are reviewed.

KEYWORDS: AGNS - BLAZARS - BL LACERTAE OBJECTS

1. INTRODUCTION

Six years after the discovery of the first extragalactic \(\gamma\)-ray source at TeV energies (Punch et al. 1992) the efforts to understand the non-thermal emission processes have stimulated the field of ground-based \(\gamma\)-ray astronomy. The experimental techniques have evolved in a variety of aspects: starting from contemporary observations with several instruments covering a substantial part of the multi-wavelength spectrum and by measuring the energy spectra and their temporal behavior.

Extragalactic TeV astronomy has been inspired by the detection of more than 50 AGNs between 30 MeV - 30 GeV by the EGRET detector (Thompson et al. 1995) on-board the Compton Gamma Ray Observatory (CGRO). Nearly all of the EGRET AGNs are radio-loud, flat spectrum radio sources in which the radio emission comes predominantly from a core region rather than from the outer lobes. The relatively high \(\gamma\)-ray luminosity of those sources implies that the emission is relativistically beamed (Blandford \& Rees 1978; Blandford \& Königl 1979; Maraschi, Ghisellini \& Celotti 1992) in the direction of the observer. These \(\gamma\)-ray AGNs with their jets aligned with the line of sight of the observer are collectively called blazars, but they subdivide into two classes, the flat-spectrum radio quasars and BL Lacertae objects (review see Padovani et al. 1997).
The spectral energy distribution (SED) of the γ-ray emission from individual blazars clearly indicates a second component in addition to the synchrotron spectrum at lower energies. The second component could be for example due to the synchrotron-self-Compton (SSC) mechanism as predicted by Königl (1981) and Marscher & Gear (1985). It has also been realized, that Comptonization of external radiation could produce γ-rays in blazars (Dermer & Schlickeiser, & Mastichiadis 1992; Sikora, Begelman & Rees 1994; Blandford & Levinson 1995; Ghisellini & Madau 1996). Also pion photoproduction by a proton component of the jet (Mannheim & Biermann 1992; Mannheim 1993) has been suggested as source of γ-rays in blazars.

The complete coverage of the second component between MeV-multi-TeV energies can only be achieved by using satellite-based and ground-based detectors. Without either one of them the spectral coverage of the second component would be incomplete and the understanding of the emission process at the source significantly less constrained.

Several ground-based γ-ray observatories (Whipple, HEGRA, CAT) have participated in the study of blazar emission. The Whipple observatory γ-ray telescope has started to constrain the high energy end of the second component for one of the EGRET blazars: Mrk 421. The detection of Mrk 421 (Punch et al. 1992; Petry et al. 1996) and subsequent monitoring of this source has shown some unexpected and extreme properties of the emission process.

2. VARIABILITY

Extreme variability on time scales ranging from days (Kerrick et al. 1995) to 1/2 of one hour (Gaidos et al. 1996) (Figure 1) constrains the size of a presumably spherical emission.

The rapid variability implies a compact emission region resulting in high opacities. To escape the dense emission regions the radiation has to be substantially Doppler boosted in order to avoid absorption through γ-γ pair production. Assuming the TeV emission is correlated with optical emission a Doppler factor of δ > 9 has been derived (Gaidos et al. 1996). For the variability of the emission from a spherical blob relativistic causality requires that the size R of the emission region is limited to R < cTδ/(1 + z).

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure1}
\caption{Light curves of two Mrk 421 flare events of 1996 May 7 (left) and 1996 May 15 (right). This figure has been adapted from Gaidos et al. (1996)}
\end{figure}
Gaidos et al. (1996) have shown that $R < 10^{-3} - 10^{-4}$ pc. The variability time scale places severe constraints on the geometry and the location of the gamma-ray emission region. The small emission region might hint that TeV emission comes from close to the base of the jet, but this cannot be firmly concluded.

2. MULTI-WAVELENGTH OBSERVATIONS

Studying a class of astrophysical objects with a single source provides a limited view of the underlying physics and more sources are needed to either derive information about them in a statistical sense and by studying their differences. The discovery of Mrk 501 (Quinn et al. 1996; confirmed by Bradbury et al. 1997) and 1ES 2344+514 (Catanese et al. 1998a) by the Whipple observatory $\gamma$-ray telescope ($E > 250$ GeV) has emphasized the significance of the high energy coverage of blazars: both, Mrk 501 and 1ES 2344+514 are not detected by EGRET.

Therefore, it is tempting to speculate that some $\gamma$-ray blazars emit their maximum power at TeV energies rather than in the EGRET regime. However, simultaneous multi-wavelength observations are necessary to study possible correlated spectral variability, because those sources are highly variable. Multi-wavelength campaigns on Mrk 421 (Buckley et al. 1996) showed some evidence for correlations between X-ray and TeV emission. Unusual flaring activity of Mrk 501 starting in 1997 February (Breslin et al. 1997) lasting until 1997 August has inspired numerous observations including optical, X-ray, hard X-ray, MeV-GeV and TeV telescopes, some of them were contemporaneous and can be used for searching for multi-wavelength correlations. Figure 2 shows the result of one of the multi-wavelength campaigns (Catanese et al. 1997; Pian et al. 1997) revealing possible multi-wavelength correlations:
Figure 2 shows the fluxes detected at different wavelengths during an episode of flaring activity in April 1997. The analysis of RXTE PCA detectors (Catanese et al. 1998b) has been included in this plot. These new data strengthen the claim that TeV emission and X-ray emission in the 2 keV - 25 keV band are correlated. Several further conclusion can be derived from the multi-wavelength campaign in April 1997:

1. The TeV flaring activity coincides with a strong detection of Mrk 501 by the OSSE detector aboard the CGRO between 50 - 470 keV. OSSE has detected only a few blazars (McNaron-Brown et al. 1995) whereas Mrk 501 shows the strongest flux ever detected from a blazar except a high state from 3C 273 (McNaron-Brown et al. 1996). X-ray observations of Mrk 501 by BeppoSAX taken in April 1997 support that the synchrotron power in blazars can peak at hard X-ray energies of 100 keV (Pian et al. 1997).

2. The EGRET detector provides only an upper limit and this seems to be consistent with the interpretation that the maximum energy output of Mrk 501 peaks at TeV energies and not in the GeV regime, already suggestive from the fact that the source was discovered at TeV energies and not by EGRET.

3. If the hard X-ray flux and the TeV flux are in fact correlated and this were true from the optical through the γ-ray regime, one can derive a lower limit on the beaming (Doppler) factor of δ > 1.5 (Samuelson et al. 1998).

Summarizing the results from the multi-wavelength campaigns it becomes evident that there are correlations between the X-ray regime from 0.5 keV up to hard X-rays 100 keV and the TeV emission. Furthermore, it shows that the synchrotron emission of Mrk 501 extends up to at least 100 keV which is in contrast to Mrk 421 which shows a break in the spectrum at 1.6 - 2.2 keV (Takahashi et al. 1996). Also the data shows that the amplitude of the flux variations in the X-ray regime are smaller than at TeV energies.

Mrk 501 has also been detected by the HEGRA experiment, the CAT collaboration and the telescope array (Aharonian et al. 1997; Djannati-Atai et al. 1997; Protheroe et al. 1997). Figure 3 shows the daily rates of the CAT experiment located in the Pyrenees, the HEGRA experiment on La Palma and the Whipple observatory in Arizona. It can be seen that the fluxes measured by the different telescopes are correlated. Observations by several instruments at different longitudes could contribute significantly to study hourly to daily flux variations. To study longterm variations over weeks and months avoiding gaps of several days Raubenheimer et al. (1997) have demonstrated that atmospheric Cherenkov detectors can also be operated during the bright moon period.

2. ENERGY SPECTRA

The TeV energy spectra of γ-ray blazars reflect both the physics of the γ-ray production mechanism and possibly differential absorption effects at the source or in the intergalactic medium. The flaring activity of Mrk 501 has provided excellent statistics to calculate energy spectra. Spectra have been published by several groups.
Aharonian et al. (1997) show a spectrum between 1 TeV up to 10 TeV which can be fit by a simple power law with a differential spectral index of $2.49 \pm 0.11 \pm 0.25$ (including the statistical and systematic uncertainties).

A spectrum derived over a larger energy range by Samuelson et al. (1998) (Figure 4) extends from 260 GeV - 12 TeV which is not well described by a simple power-law - a simple power law fit yields $\chi^2$ test probability of $2.8 \times 10^{-7}$. Instead the spectrum exhibits significant curvature and can be well fit by a parabolic spectrum:

$$J(E) = \left( 8.6 \pm 0.3 \pm 0.7 \right) \times 10^{-7} E^{-2.22 \pm 0.04 \pm 0.05 - (0.47 \pm 0.07) \log_{10}(E)} m^{-2} s^{-1} TeV^{-1}.$$

Note, that there is not necessarily a contradiction between the two different spectra derived since Aharonian et al. (1997) cover a smaller energy range and give larger uncertainties in the spectral index.

Possible causes of curvature at the lower energies could be related to the intrinsic spectrum of the source requiring that the spectrum has to be consistent with the EGRET upper limits. A small subset of (Samuelson et al. 1998) nearly contemporaneous TeV/GeV observations show that a curved spectrum is consistent with the EGRET upper limits whereas a simple power law is not. Causes of curvature at higher energies include partial absorption of $\gamma$ rays in the intergalactic medium, absorption in the jet by pair production on low energy photons, absorption by photons near the source, or an end in the primary particle beam energy. Intergalactic absorption by infrared photons has been advocated by a number of authors (Gould, R. J. & Schrd'er G. 1967; Stecker & De Jager 1992; Dwek & Slavin 1994; Biller et al. 1995) as a potential cause of such absorption. Therefore, the observed spectrum might be a convolution of the blazar spectrum with an external absorption term. By considering the extent of this potential modification of the blazar spectrum, upper limits to the density of the intergalactic IR field may be determined. Such limits have been recently derived by Biller et al. (1998) in a robust manner using data from Mrk 421 and Mrk 501. The curved spectrum of Mrk 501 (Samuelson et al. 1998) can still accommodate the limits from Biller et al. (1998).
The energy spectrum of Mrk 421 (Krennrich et al. 1999) based on short flares has been derived with a similar statistical precision as the spectrum of Mrk 501 in Samuelson et al. (1998). The resulting spectrum of Mrk 421 is fit reasonably well by a simple power law: \( J(E) = E^{-2.54 \pm 0.03 \pm 0.10} \) photons m\(^{-2}\) s\(^{-1}\) TeV\(^{-1}\).

This is in contrast to the spectrum of Mrk 501. In figure 5 the spectra of Mrk 501 and Mrk 421 are shown in comparison. The spectra are different in shape and since Mrk 421 and Mrk 501 have almost the same redshift (0.031 and 0.033 respectively), the difference in their spectra must be intrinsic to the sources and not due to intergalactic absorption, assuming the intergalactic infrared background is uniform.

At GeV energies, Mrk 421 is seen by EGRET (Lin et al. 1992), albeit weakly, whereas Mrk 501 is not (Catanese et al. 1997). For the latter it could be argued that in a synchrotron-inverse Compton picture it would appear that both the synchrotron and the inverse-Compton peak are shifted to higher energies leaving the EGRET GeV energy sensitivity range in the gap between the peaks. As shown in Fig. 5, in the energy range 260 GeV - 10 TeV, the spectrum of Mrk 501 is harder at lower energies and shows more curvature than Mrk 421. In fact the latter can be fit by a straight line (i.e., pure power-law). This is also consistent with the peak inverse-Compton power occurring at higher energies for Mrk 501. Therefore, also the detailed energy spectra of Mrk 421 and Mrk 501 concur well with the conclusion drawn from the multi-wavelength spectrum: in case of Mrk 501 the TeV emission is closer to the maximum power peak of the second component than in case of Mrk 421. Blazar emission can also reveal important information about the underlying
source mechanism through spectral variability. Short term flare spectra of Mrk 421 have been derived in Krennrich et al. (1999). Figure 6 shows the spectra of Mrk 421 during several flares: a big flare (2 hours: 7.4 Crab) on May 7 1996 (flare I), a flare (30 minutes: 2.8 Crab) on May 15 1996 (flare II) and flares from 3 different nights (1.5 hours total: 3.3 Crab) in June 1995 (flare III).

FIGURE 5. The energy spectral distribution of Mrk 501 between 260 GeV-12 TeV (filled circles) compared to the spectrum of Mrk 421 (open stars) (Krennrich et al. 1999)

FIGURE 6. The energy spectra of Mrk 421 during different flaring states (Krennrich et al. 1999): “Big Flare” (7.4 Crab) on May 7 1996, flare (3.3 Crab) from May 15 1996 and a flare (2.8 Crab) at large zenith angles from June 20, 29 and 30 1995

The average fluxes (Crab units) differ by a factor of 2.6 and the signature of the flares are different: flare I shows a clear rise, whereas flare II includes the rise and the fall and flare III show a constant emission. The energy spectra show the same shape and spectral index for all three flares (Krennrich et al. 1999). There is no significant change. Changes in the spectral index with the flux have also been studied in great detail by (Aharonian et al. 1998) using Mrk 501 observations from the HEGRA array of telescopes. Also, no significant variations of the spectral index are apparent in the data.

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