Blazars - Observational Aspects

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Abstract

Results from blazar observations by space- and ground-based high energy experiments are reviewed. In the past decade, EGRET detected intense and variable γ-ray emission from more than 66 active galaxies belonging to the "blazar" class, establishing these as a class of high energy γ-ray sources. At very high energies ($>$ 500 GeV) ground-based atmospheric Cherenkov telescopes (ACTs) have detected γ-ray emission from a few high-frequency peaked BL Lac objects (HBLs). Most EGRET blazars are, however, not detected above 500 GeV, possibly because of cutoffs in the spectra due to $\gamma\ \gamma$ absorption by the diffuse extragalactic background light (EBL). Recently, solar array experiments, like STACEE and CELESTE, have detected the blazar Mrk 421 for the first time below 200 GeV, and are continuing to observe other blazars at lower energy thresholds. In the future, GeV-TeV studies of blazars will be a rapidly growing area of high energy astrophysics, facilitated by the low energy thresholds of current solar array experiments, and the improved sensitivities of the next generations ACTs.

1. Introduction

The study of high energy emission from blazars made significant progress in the 1990's. The EGRET experiment on the *Compton Gamma-Ray Observatory* detected about 70 blazars at $E > 100$ MeV, and established these as powerful γ-ray sources. In most EGRET-detected blazars the γ-ray emission dominates the bolometric power in the spectral energy distributions (SEDs) of these sources.

Mrk 421 was, in 1992, the first EGRET blazar to be detected at TeV energies by the Whipple experiment [1]. Since then five other blazars, Mrk 501, PKS 2155-304, H 1426+428, 1ES 2344+514, and 1ES 1959+650 have been detected at $>$ 250 GeV by imaging atmospheric Cherenkov telescopes (IACTs) such as Whipple, HEGRA, CAT and CANGAROO [2]. Of these, Mrk 421 [3] [4] [5], Mrk 501 [6] [7] [8], and H 1426+428 [9] [10], have been detected independently by more

pp. 1–10

than one IACT, and have yielded signals strong enough to make spectral studies viable. At TeV energies it is possible to study rapid flux variations in blazars, at much shorter time scales than was possible with EGRET. The 1996 γ-ray flare in Mrk 421 represents the shortest time scale variability in any AGN to date [3], with a flux doubling time of < 15 min. Both the EGRET observations and the TeV studies of blazars have come to play an important role in understanding emission models in high energy blazars.

Despite better sensitivities at higher energies, however, the majority of the EGRET sources have not been detected above 250 GeV, presumably because of spectral cutoffs due to absorption by the extragalactic background light (EBL). This has motivated the study of blazars in the 50-500 GeV energy range by solar arrays, such as STACEE and CELESTE. Blazar observations at these energies will not only allow us to study the EBL, but also help to increase the number of blazar detections above 50 GeV, making it possible to study particle acceleration at these energies for the first time. Solar arrays achieve a low energy threshold by taking advantage of the large collection areas of solar mirrors (heliostats). In the future, new low threshold imaging ACTs, like HESS, VERITAS, CANGAROO and MAGIC, with much better sensitivities, promise to make substantial progress in the high energy study of blazars.

2. EGRET Observations of Blazars

EGRET has detected 271 point sources above 100 MeV, as presented in the Third EGRET (3EG) catalog [11]. Of these, active galactic nuclei (AGN) of the "blazar" class are the predominant extragalactic sources. The detection of optically violent variable quasars, and BL Lac objects out to redshifts of ~ 2.3, whose emission at most wavebands is dominated by non-thermal processes, has been one of the highlights of EGRET.

Blazars detected by EGRET are characterized by emissions that include high radio and optical polarizations, strong variability at all wavelengths, and non-thermal, continuum spectra. Most EGRET blazars are associated with radio sources with 5 GHz fluxes of > 500 mJy. However, it is likely that several of the unidentified 3EG sources are blazars with lower radio fluxes. The γ-ray luminosity of the EGRET blazars (assuming isotropic emission) ranges from 10^{45} to 10^{49} erg s^{-1} and in most cases the spectral energy distributions of these objects are dominated by the γ-ray emission.

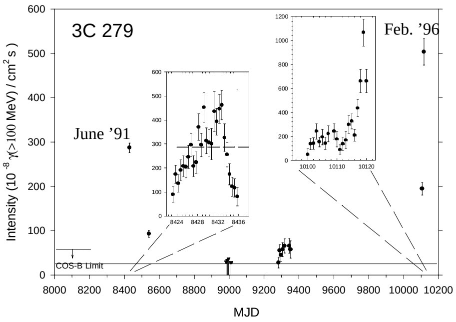

Fig. 1. Flux history of the blazar 3C 279 for the time period 1991 - 1998. The insets show rapid variability on short time scales. Fig. from Hartman et al. (1999).

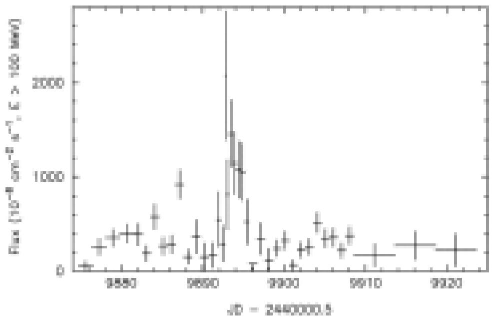

Fig. 2. Day-scale temporal variability seen in the γ-ray light curve of PKS 1622-297 in 1995. Fig. from Mattox et al. (1997).

2.1. Flux Variability

EGRET blazars are characterized by flux variabilities on time scales on the order of days to months [12]. In the few cases that EGRET was able to observe day-scale variability, the blazar emission was seen to change significantly on short time scales. Short term variability in blazars is consistent with small sizes of the emission region, and a bright nucleus.

Figs. 1. and 2. shows two examples of short time scale variability seen in EGRET blazars. The light curve of 3C 279 (Fig. 1.) shows flux variations in the source over a period of 9 years, with the insets showing rapid variability during the June 1991 and February 1998 flares. Another example is that of PKS 1622-297 which exhibited a major flare during the observation in 1995 (Fig. 2.). A flux increase by a factor of at least 3.6 was observed in a period of less than 7 hours [13]. The peak flux observed was $(17 \pm 3) \times 10^{-6}$ cm^{-2} s^{-1} ($E > 100$ MeV), which corresponded to an isotropic luminosity of 2.9×10^{49} ergs s^{-1}. PKS 0528+134, 3C 454.3, PKS 1633+382, 1406-076, and CTA26 are examples of some other blazars that have shown strong variability on day time scales.

2.2. Spectral Studies

Spectra of EGRET blazars are well-represented by power-laws in the energy range 30 MeV to 10 GeV [12] and show no evidence of any spectral cutoff at energies below 10 GeV. At the highest energies the photon flux is severely limited and the high energy study of blazars is only possible with ground-based ACTs.

In order to understand blazar models and interpret the underlying physics of emission mechanisms, it is necessary to study the broad band spectral energy

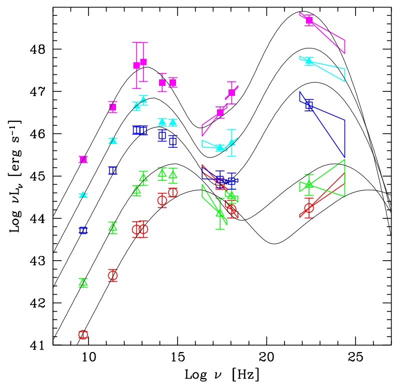

Fig. 3. Blazar Unification: SEDs of different blazar sub-classes. The lines correspond to "analytic" SEDs, which represent families of curves binned according to blazar radio luminosities. The topmost curves are for quasars (low frequency- and high frequency-peaked) and the lower curves are for BL Lacs (LBLs and HBLs). Fig. from Fossati et al. (1998).

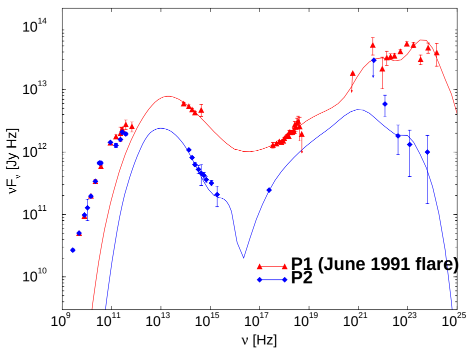

Fig. 4. Spectral energy distribution of 3C 279 from radio to γ-ray energies for two different epochs, 1991 June (top curve) and 1992 Dec (bottom curve). Note the considerable spectral variability, particularly at γ-ray energies, that is often seen in blazars. The lines correspond to a leptonic jet model. See Hartman et al. (2001) for model parameters.

distributions (SEDs) of these sources. Fig. 3. shows the SEDs of different blazar sub-classes as proposed in the blazar unification scenario [14]. The figure shows that the non-thermal emission consists of at least two distinct, broad spectral components and that a sequence of different blazar classes can be defined by relating the peak frequencies and the relative νF_ν peak fluxes of these components. Blazars detected by EGRET are mostly flat-spectrum radio quasars (FSRQs) and low frequency peaked BL Lacs. As described in §3, no FSRQ has been detected by IACTs at > 100 GeV.

Fig. 4. shows an example of a typical SED of a flat-spectrum radio quasar detected by EGRET, namely 3C 279. The SED was measured at two different epochs and demonstrates that blazars exhibit not only temporal, but considerable spectral variability [15] [16]. Current blazar models are roughly divided into leptonic and hadronic jet models, and are based on the assumption that blazars are powered by accretion of matter on to supermassive black holes. The γ-ray emission is believed to originate in strongly beamed jets. The spectral variability in 3C 279 between different epochs is explained by variations in the bulk Lorentz factor of the jet. A review of the theoretical aspects of blazar observations is given in [17].

3. Blazar Studies by Imaging Atmospherics Cherenkov Telescopes

The most significant contribution from IACTs has been the confirmation that there is a γ-ray sky at energies above 250 GeV. A review of the current and future TeV experiments is given elsewhere [2]. Five blazars have been confirmed as TeV sources: Mrk 421, Mrk 501, H 1426+428, 1ES 2344+514, and recently 1ES 1959+650 [18] [19]. Other reports of blazar detections at TeV energies include PKS 2155-304 [20], and 3C 66A [21], but these await confirmation. While the number of sources detected above 300 GeV is small compared to the EGRET catalog, the detection of these sources has shown that the TeV emission is an important component of the spectral energy distribution of these sources. Some recent reviews summarize the current status of TeV astronomy quite well [22] and present the source catalog at TeV energies [2].

3.1. Flux Variability

IACTs have the ability to study very short time scale variability in blazars, as well carry out long term flux monitoring studies. Mrk 421, the first EGRET blazar to be detected by IACTs [1] [23], has exhibited strong flares at TeV energies, much above quiescent levels [3] [24] [4], with variability time scales of 15 min or less in 1996 May [3]. Cross-correlations of various data sets of Mrk 421 indicate a significant correlation of the X-ray and TeV γ-ray flux variability [23] [25]. Recently, Mrk 421 exhibited a specially strong and long-lasting flare between January and March, 2001 [26], making spectral measurements possible with unprecedented precision.

Fig. 5. shows the light curve of Mrk 501 observed by HEGRA in 1997 [27], demonstrating the ability of IACTs to carry out long term flux monitoring of blazars. The 1997 TeV (HEGRA) and X-ray (RXTE) light curves also showed flux correlations on short time scales [28], with the TeV flux lagging the X-ray

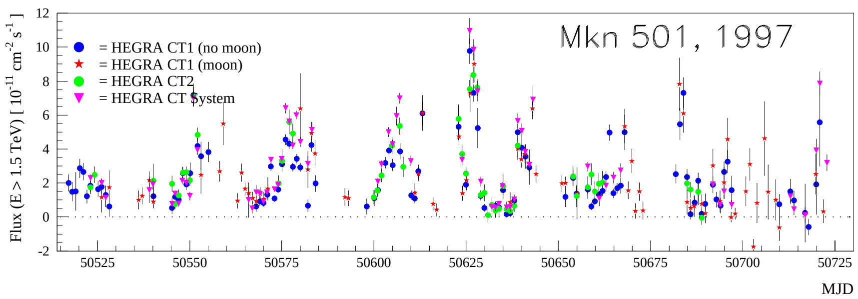

Fig. 5. Light curve of Mrk 501 at TeV energies measured by HEGRA in 1997. Fig. from Krannich et al. (1999).

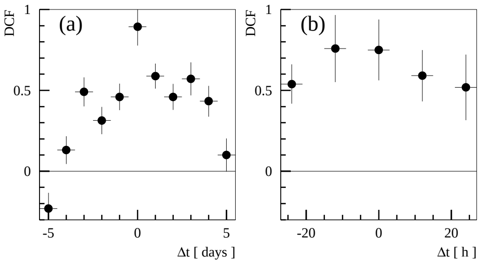

Fig. 6. Short time scale correlation of the TeV (HEGRA) and X-ray (RXTE) light curves measured during the 1997 flare in Mrk 501. Fig. from Krawczynski et al. (1999).

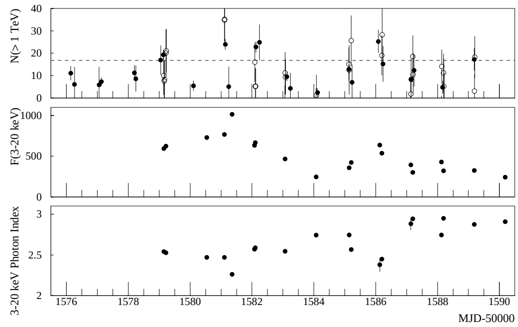

Fig. 7. TeV (HEGRA) and X-ray (RXTE) light curves of Mrk 421 in 2000. Fig. from Krawczynski et al. (2001).

flux as shown in Fig. 6. Similarly, a comparison of TeV and RXTE light curves for Mrk 421 in 2000 (Fig. 7.) showed e-folding times of ~ 1 hour at TeV energies and ~ 5 hours at X-ray energies [5]. The different variability time scales seen at X-ray and TeV energies indicates the need for inhomogeneous blazar models, perhaps with several emission regions.

3.2. Spectra

Broadband study of the SEDs of TeV blazars has been carried out most extensively for Mrk 421 and Mrk 501. Fig. 8. shows the SED of Mrk 501 measured in 1996 and during the flare in 1997 [29]. All blazars detected at TeV energies are high-frequency-peaked BL Lacs (HBLs) and the SED of Mrk 501 shown is typical of these objects. Unlike in FSRQs, the synchrotron peak of Mrk 501 is located in the X-ray band, while the Compton peak is in the GeV-TeV regime. In spite of extending to very high photon energies, the peak flux of the γ-ray component in the SEDs of HBLs tends to be, at most, comparable to the spectral output in the low-frequency component. This is also seen in the recently measured spectrum of the relatively "new" TeV blazar, H 1426+428 [30] [10] [9] [31], as shown in Fig. 9. Interestingly, H 1426+428 was not an EGRET source, but was predicted to be a TeV source [30] and an "extreme BL Lac," based on its synchrotron peak location at ~ 100 keV. This source has the highest redshift of all blazars detected at TeV energies, and is therefore interesting for spectral studies, as the TeV radiation is expected to be strongly absorbed by the diffuse extragalactic background radiation.

An important feature of TeV blazars is the considerable spectral variability that is observed in different epochs. Fig. 10. shows the spectral variability

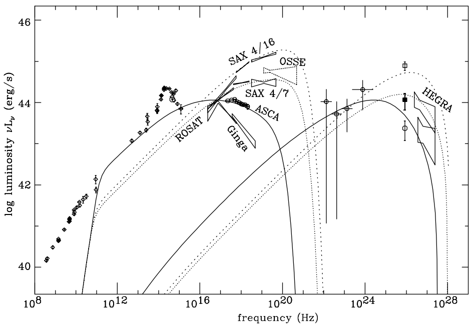

Fig. 8. SED of Mrk 501 at two different epochs. Note the peak shift to higher energies during the 1997 flare. Fig. from Kataoka et al. (1999).

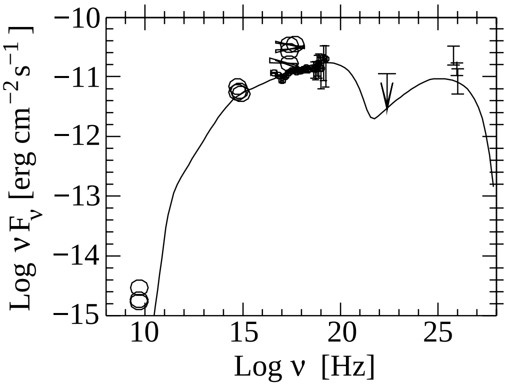

Fig. 9. SED of the "extreme BL Lac" H 1426+428. Note its synchrotron peak at $\sim$ 100 keV. Fig. from Horan et al. (2002).

observed in Mrk 421 averaged over a 4.5 month period [32] in 2001. During this time the source was flaring, at levels of 0.4-13 times the Crab flux. The spectral index in the 380 GeV - 8.2 TeV range was found to vary between 1.89 (high state) and 2.72 (low state). Spectral hardening was also observed for Mrk 421 at X-ray energies by BeppoSAX [33], as demonstrated in Fig. 11. The changes in the γ-ray spectrum could arise either from changes in the charged particle spectrum or the soft photon distribution. It is therefore important to further study spectral variability over short time scales, measure the lag between X-ray and TeV γ-ray flux variability, and carry out time dependent modelling of blazar spectra. Recently a time-dependent modelling analysis using a soft steady X-ray component plus a variable SSC component has been carried out for the blazar Mrk 501 [34]. Simultaneous X-ray and γ-ray observations are powerful probes of particle acceleration and emission mechanisms in TeV blazars.

TeV blazars are seen to exhibit exponential-like cutoffs in their spectra. This has been observed in Mrk 501 by Whipple [35], HEGRA [8], and CAT [7]. Similarly, the spectrum of Mrk 421 measured in the 260 GeV to 17 TeV band in 2000 shows an absorption-like feature at 3-6 TeV [26]. The cutoff in the spectra of these blazars could be due either to absorption in the source [36] or absorption by the extragalactic IR background [37], and is discussed further by Krennrich et al. [26].

4. Blazar Studies at 50-250 GeV

The energy range from 50 to 250 GeV is important for studying blazars, particularly because so few of the closest blazars have been detected by ground-based experiments above 250 GeV. Low-threshold ACTs may be able to study

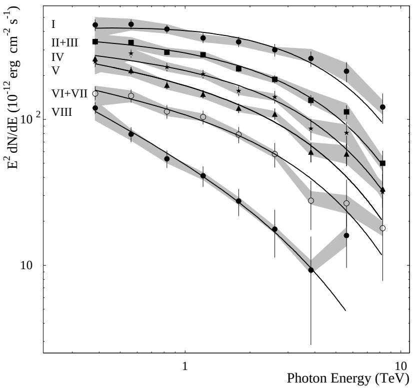

Fig. 10. Spectral variability measured in Mrk 421 during Dec 2000 - Apr 2001. Fig. from Krennrich et al. (2002).

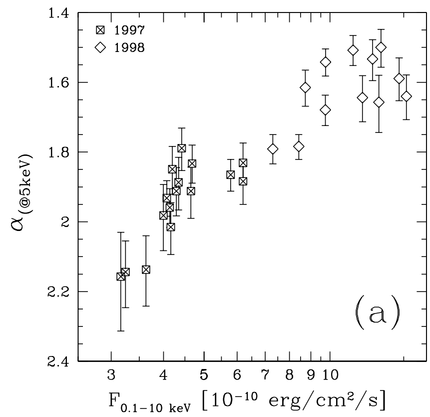

Fig. 11. BeppoSAX observations of spectral hardening in Mrk 421 at X-ray energies. Fig. from Fossati et al. (2000).

the extragalactic background light by measuring spectral cutoffs in distant blazars (reviewed in [38]). Fig. 12. shows the γ-ray horizon as a function of redshift [39], demonstrating the advantage of studying blazars at lower energies.

Blazar studies below 200 GeV are currently carried out by ACTs taking advantage of the large mirror areas of solar arrays to achieve a low energy threshold. STACEE in New Mexico, USA [40] and CELESTE [41] in France are already operational and have reported detections of γ-rays from the Crab and Mrk 421 [42] [43] [44].

Fig. 13. shows the light curve of Mrk 421 measured by STACEE during the 2001 flare, along with that measured by RXTE and Whipple [44]. The integral flux measured by STACEE from March to May of 2001 was $(8.0 \pm 0.7_{stat} \pm 1.5_{sys}) \times 10^{-10}$ cm^{-2} s^{-1} at energies above 140 ± 20 GeV. In addition, STACEE has also observed H 1426+428 and W Comae [45], an interesting source recently investigated from the point of view of γ-ray models [46]. Blazar studies by STACEE and CELESTE with spectral information are currently in progress.

5. Summary & Future Prospects

The future of high energy γ-ray astronomy looks very promising with several new experiments planned, both ground-based as well as satellite-borne. A significant improvement over EGRET will be possible with the next generation space mission, GLAST, projected to be a state-of-the art detector. This will be complemented by new ACTs such as HESS in Namibia, VERITAS in Arizona, MAGIC in Spain, and CANGAROO-III in Australia. Results are eagerly awaited from HESS, which is already operational. Significant advances are expected in

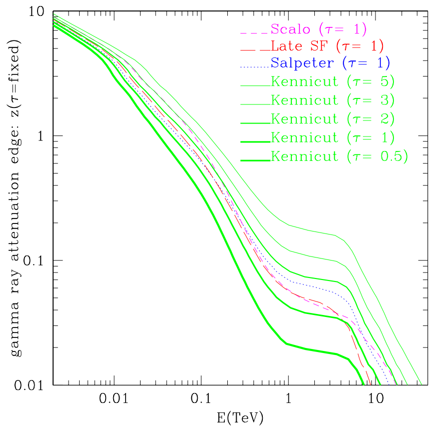

Fig. 12. Visibility of γ-ray sources. Fig. from Primack et al. (2002).

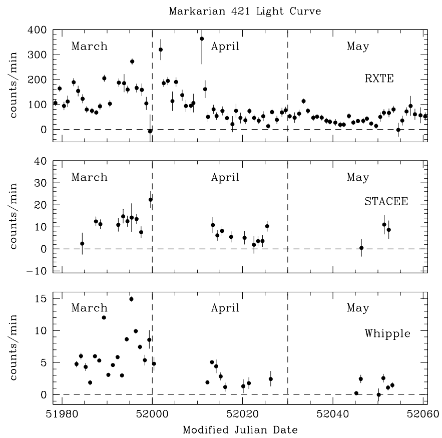

Fig. 13. Light curve of Mrk 421 measured by STACEE and other experiments. Fig. from Boone et al. (2002).

the next decade in the γ-ray study of blazars.

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