Multi-wavelength Observations of VHE BL Lac Objects

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Abstract.
We present multi-wavelength observations of the very high energy (VHE, $E \gtrsim 250$ GeV) $\gamma$-ray sources Mrk 421 and Mrk 501. The VHE data presented here were taken with the Whipple Observatory 10m $\gamma$-ray telescope. In the Mrk 421 campaign, conducted in 1995 April-May, correlations were observed between VHE $\gamma$-ray, X-ray, extreme ultraviolet (EUV) and possibly R-band emission. The X-rays and $\gamma$-rays vary together with similar flux amplitude while the EUV photons lag the X-rays and $\gamma$-rays by $\sim 1$ day and have a lower variability amplitude. In the Mrk 501 campaign, conducted in 1997 April, a correlation was also observed between the VHE $\gamma$-rays and X-rays with no delays apparent. Here, the VHE $\gamma$-ray variability is larger than the X-rays. The observations also indicate that the synchrotron spectrum extends to 100 keV before cutting off. For Mrk 421, the X-ray/VHE $\gamma$-ray correlation indicates that $\delta > 38$ and $B > 0.03$G. For Mrk 501, the correlation indicates a more modest $\delta > 2$ and $B > 0.09$G.

1. Introduction
At this time, three BL Lacertae objects (BL Lacs) have been detected at very high energies (VHE, $E \gtrsim 250$ GeV): Markarian 421 (Mrk 421) (Punch et al. 1992), Mrk 501 (Quinn et al. 1996), and 1ES 2344+514 (Catanese et al. 1998). The VHE detections of Mrk 421 and Mrk 501 have been confirmed (e.g., Bradbury et al. 1997, Petry et al. 1996) while the 1ES 2344+514 detection is still unconfirmed. All three objects are high frequency-peaked BL Lacs (HBLs) (Padovani & Giommi 1995a), that is, the peak in the spectral energy distribution (SED), plotted as $\nu F_\nu$, is in the X-ray region. The VHE sources are also the BL Lacs with the lowest known redshifts (Padovani & Giommi 1995b): $z=0.031$ for Mrk 421, $z=0.034$ for Mrk 501, and $z=0.044$ for 1ES 2344+514.

Because of their variability at all wavelengths, BL Lacs can best be understood through multi-wavelength observations. The sensitivity of VHE telescopes to sub-hour scale variability (cf., Gaidos et al. 1996), their ability to detect low source fluxes, and the measurement of spectra up to 10 TeV or more make the VHE observations an important addition to multi-wavelength campaigns. In particular, if the $\gamma$-ray emission arises from inverse Compton scattering of the same electron population which produces the low energy synchrotron emission
(e.g., Maraschi, Ghisellini, & Celotti 1992, Dermer, Schlickeiser, & Mastichiadis 1992, Sikora, Begelman, & Rees 1994, Bloom & Marscher 1996), the combination of VHE $\gamma$-ray and synchrotron observations permit the estimation of the magnetic field strength and Doppler factor in the jet where the $\gamma$-ray emission is produced.

In this paper we describe a campaign on Mrk 421 conducted in 1995 (§2) and one on Mrk 501 completed in 1997 (§3). Both campaigns gave the first strong indication of correlated variability between VHE $\gamma$-rays and lower energy emission in these objects. Finally, we compare the results of these observations and discuss their implications (§4).

2. 1995 Markarian 421 campaign

Between 1995 April 20 and May 5, Mrk 421 was monitored with the Whipple Observatory $\gamma$-ray telescope (E~250 GeV – 10 TeV), the Energetic Gamma-Ray Experiment Telescope (EGRET) on the Compton Gamma-ray Observatory (E = 30 MeV – 10 GeV), the Advanced Satellite for Cosmology and Astrophysics (ASCA) (E = 0.7 – 7.5 keV), the Extreme Ultraviolet Explorer (EUVE) ($\lambda = 58$ – 174 Å), and in the optical R band. Less dense monitoring of radio flux and optical polarization was also done. The results of these observations were first reported by Buckley et al. (1996). The light-curves for the contemporaneous observations are shown in Figure 1. EGRET observations resulted in an upper limit on the flux above 100 MeV of $1.2 \times 10^{-7}$ cm$^{-2}$ s$^{-1}$.

A prominent VHE flare is evident with peak flux on MJD 49833. The VHE flux is $\approx 0.75$ times the VHE flux of the Crab Nebula. Cross-correlation analysis of the VHE $\gamma$-rays and the X-rays indicates a significant correlation with no time lag on day scales. The amplitude of the flux variations of the VHE $\gamma$-rays and X-rays are both $\approx 400\%$. A flare is also apparent in the EUVE observations, and cross-correlation analysis indicates a maximum correlation with a 1 day lag relative to the VHE $\gamma$-ray/X-ray flare. The amplitude of the EUVE flare was $\approx 200\%$. The R-band and optical polarization observations also appear to correlate with the VHE $\gamma$-ray/X-ray flare with a 1 day lag, but the statistics of those observations do not permit a firm identification of this variation with the X-ray/VHE $\gamma$-ray flare. Indeed, results reported by Wagner (1998) at this conference indicate that optical observations conducted after the VHE $\gamma$-ray observations had stopped show a flux increase while the X-ray flux continues to decrease. The amplitude of the R-band variation is only about 20% (after the galaxy light contribution is removed). The U-band polarization measurements show an $\approx 200\%$ variation in amplitude.

3. 1997 Markarian 501 campaign

Between 1997 April 2 and 20, Mrk 501 was observed with the Whipple Observatory $\gamma$-ray telescope, EGRET, the Oriented Scintillation Spectrometer Experiment (OSSE) (50 keV - 10 MeV), the Rossi X-ray Timing Experiment (RXTE) (2 keV - 250 keV), and the Whipple Observatory 1.2m optical telescope (UVBRI). The results of the Whipple Observatory, OSSE, and quicklook RXTE All-Sky Monitor (ASM) observations were first reported by Catanese et al. (1997). Here
we add preliminary results from the Proportional Counter Array (PCA) and High Energy X-ray Timing Experiment (HEXTE) on RXTE. These latter observations consisted of two $\sim$1 ksec exposures per night between April 2 and 15. The light-curves of the contemporaneous observations are shown in Figure 1. For comparison, the count rate from the Crab Nebula for the Whipple Observatory telescope during this period was 2.7 $\gamma$/min.

During these observations, Mrk 501 exhibited two large amplitude, day-scale VHE $\gamma$-ray flares (see Figure 1). The VHE data are best fit by a spectrum which is parabolic when plotted as $\log_{10}(dN/dE)$ versus $\log_{10} E$: $dN/dE \propto E^{-2.20\pm0.04\pm0.05-(0.45\pm0.07)\log_{10}E}$ (Samuelson et al. 1998). The spectrum extends to at least 8 TeV with no evidence of a cut-off and no spectral variability is detected. EGRET observations resulted in an upper limit above 100 MeV of $3.7\times10^{-7}$ cm$^{-2}$ s$^{-1}$ even though the VHE flux was much higher during this period than it was when EGRET detected Mrk 421. In contrast, OSSE detected the highest 50 keV - 150 keV flux it had observed from any blazar (McNaron-Brown et al. 1995) while it has never detected Mrk 421 in several observations. The spectrum measured by OSSE is fit well by a simple power law with photon spectral index $-2.08\pm0.15$. OSSE observations show no evidence of spectral variability. The PCA spectra are best fit by broken power laws with a break consistently in the range 5-6 keV. The photon spectral indices vary from -1.9 to
-1.6 below the break energy and from -2.1 to -1.8 above the break energy. The average 2-10 keV flux during this period is $\approx 4.5 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$.

The correlation between the VHE $\gamma$-rays and the soft and hard X-rays observed with RXTE and OSSE is clearly evident in Figure 1. In the overlapping period of observations, April 9-15, a peak in the flux is detected by all three instruments on April 13 (MJD 50551), indicating time lags, if any, of <1 day. The flux amplitude variation between April 9 and April 13 is a factor of 4 for the VHE $\gamma$-rays, 2.6 for 50-150 keV X-rays, 2.3 for 15-25 keV X-rays, and 2.1 for 2-10 keV X-rays. Optical measurements in the U-band (without galaxy light subtraction) exhibit no simple correlation, but the emission is significantly higher than in the previous month (indicated by the dashed line in Figure 1).

4. Discussion

The multi-wavelength observations presented here show that Mrk 421 and Mrk 501 exhibit a combination of similarities and differences. First, as indicated by their SEDs (see Figure 2), the high energy emission does not dominate the power output of Mrk 421 and Mrk 501 as in many of the EGRET blazars. This is consistent with the expectations of recent unification models for blazars because the HBLs have relatively low luminosity (Fossati et al. 1998, Georganopoulos & Marscher 1998). But, while the power output for Mrk 421 in VHE $\gamma$-rays $\approx$ the power output in X-rays in several campaigns, for Mrk 501, the power output in VHE $\gamma$-rays is only comparable to that in X-rays during its highest emission states. In the lower emission states, the VHE $\gamma$-ray power output is somewhat lower. In addition, though the SED of Mrk 421 is typical of an HBL (peak synchrotron power output at UV/soft X-ray energies with a trough in the power output in hard X-rays where OSSE operates), Mrk 501 appears to be an extreme version of an HBL - the synchrotron spectrum observed in 1997 peaks at $\approx 100$ keV before dropping off. This is the highest extent of the synchrotron spectrum ever seen in a blazar. Also, the high energy spectrum in Mrk 501 appears to be shifted to higher energies than in Mrk 421, with a trough in the MeV-GeV range where EGRET operates.

Second, for both Mrk 421 and Mrk 501, the relative variability amplitude in the synchrotron band decreases with decreasing energy and the VHE $\gamma$-rays and X-rays appear to be correlated with no delays evident on day-scales. This is consistent with flares produced by impulsive increases in the efficiency for accelerating the highest energy electrons (Marscher 1995, Mastichiadis & Kirk 1997). However, the relative variability amplitude between the synchrotron and high energy bands is quite different. Mrk 421 exhibits similar variability amplitude between VHE $\gamma$-rays and X-rays but in Mrk 501, the VHE $\gamma$-ray variability amplitude exceeds that of the synchrotron emission. From this data, it is not clear whether this difference indicates a dramatic shift in the high energy peak for Mrk 501 or that its entire high energy emission spectrum varies more than its low energy emission spectrum.

Correlations between the high and low energy emissions constrain the jets of Mrk 421 and Mrk 501 through $\gamma\gamma$ transparency estimates or the assumption that the inverse Compton (IC) mechanism produces the high energy emission (Catanese et al. 1997). In the transparency arguments, a limit on the Doppler
factor, $\delta$, is derived from the requirement that the opacity due to pair production between the $\gamma$-rays and lower energy photons be $<1$ (e.g., Dermer & Gehrels 1995). Assuming that the apparent correlation between the VHE $\gamma$-rays and optical/UV photons observed in Mrk 421 indicates that these photons are produced in the same location, Buckley et al. (1996) derive $\delta \gtrsim 5$. For Mrk 501, the correlation between VHE $\gamma$-rays and X-rays does not lead to a requirement for beaming through transparency arguments (Catanese et al. 1997).

The justification for using the IC method derives from the expectation of IC models that the X-rays and VHE $\gamma$-rays should be correlated because they are produced by the same electrons. Then, an upper limit can be placed on the magnetic field, $B$, from the maximum energy of the VHE $\gamma$-rays and the peak of the synchrotron spectrum (cf., Buckley et al. 1998). A lower limit on $B$ can be derived from the assumption that synchrotron cooling dominates the electron energy losses. This assumption is consistent with the nearly equal power output of the synchrotron and IC emission in these objects and with observations of energy dependent time lags in the X-ray emission of Mrk 421 (Takahashi et al. 1996). By requiring that the lower limit on $B$ is not higher than the upper limit, limits on $\delta$ and $B$ can be derived. For Mrk 421, assuming the VHE spectrum extends to 5 TeV (Zweerink et al. 1997), a synchrotron cut-off at 1 keV, a time variability scale of 1 day, and correlated variability at 700 eV, we derive $\delta \gtrsim 38$ and $B \gtrsim 0.03$G. For Mrk 501, the extent of the VHE spectrum is at least 8 TeV (Samuelson et al. 1998), the synchrotron peak is at 100 keV, the variability time scale is 1 day and correlated variability is observed at 2 keV. These inputs lead to $\delta \gtrsim 2$ and $B \gtrsim 0.09$G. The $\delta$ for Mrk 421 is quite high but it is not considerably different than what is derived from more accurate modeling of the emission as synchrotron self-Compton emission (Tavecchio, Maraschi & Ghisellini 1998). This may indicate that Mrk 421 is beamed atypically high or that more complicated emission mechanisms are at work in this object.
In summary, we have evidence of differences in the multi-wavelength emissions of Mrk 421 and Mrk 501. Given the small sample of good multi-wavelength campaigns on these two objects, it is not clear whether these are genuine differences in the jets of Mrk 421 and Mrk 501, or whether they just indicate different flaring characteristics in specific episodes. Planned and recently completed multi-wavelength campaigns may help resolve these issues.

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