VHE gamma-ray observations of Markarian 501

A.C. Breslin[1], I.H. Bond[2], S.M. Bradbury[2], J.H. Buckley[3], A.M. Burdett[4,2], M.J. Carson[1], D.A. Carter-Lewis[5], M. Catanese[5], M.F. Cawley[6], S. Dunlea[1], M. D'Vali[2], D.J. Fegan[1], S.J. Fegan[4], J.P. Finley[7], J.A. Gaidos[7], T.A. Hall[7], A.M. Hillas[2], D. Horan[1], J. Kildea[1], J. Knapp[2], F. Krennrich[5], S. LeBohec[5], R.W. Lessard[7], C. Masterson[1], B. McKernan[1], J. Quinn[1], H.J. Rose[2], F.W. Samuelson[5], G.H. Sembroski[7], V.V. Vassiliev[4] and T.C. Weekes[4]

[1] *Experimental Physics Dept., University College, Belfield, Dublin 4, Ireland*
[2]*Dept. of Physics & Astronomy, University of Leeds, Leeds, LS2 9JT, U.K.*
[3]*Dept. of Physics, Washington University, St Louis, MO 63130, U.S.A.*
[4]*Fred Lawrence Whipple Observatory, Harvard-Smithsonian CfA, Amado, AZ 85645-0097, U.S.A.*
[5]*Dept. of Physics and Astronomy, Iowa State University, Ames, IA 50011, U.S.A.*
[6]*Physics Dept., National University of Ireland, Maynooth, Ireland*
[7]*Dept. of Physics, Purdue University, West Lafayette, IN 47907, U.S.A.*

Abstract

Markarian 501, a nearby (z=0.033) X-ray selected BL Lacertae object, is a well established source of Very High Energy (VHE, E$\gtrsim$300 GeV) gamma rays. Dramatic variability in its gamma-ray emission on time-scales from years to as short as two hours has been detected. Multiwavelength observations have also revealed evidence that the VHE gamma-ray and hard X-ray fluxes may be correlated. Here we present results of observations made with the Whipple Collaboration's 10 m Atmospheric Čerenkov Imaging Telescope during 1999 and discuss them in the context of observations made on Markarian 501 during the period from 1996-1998.

1 Introduction:

In 1995, the Whipple Collaboration discovered Very High Energy (VHE, E$\gtrsim$300 GeV) gamma rays from Markarian 501 (Mkn501) (Quinn et al., 1996) using the 10 m Atmospheric Imaging Čerenkov Telescope (IAČT). This detection has since been confirmed by several other IAČT experiments (e.g. see Protheroe et al., 1997). Markarian 501 is one of four active galactic nuclei (AGN) detected at VHE energies, the others being Markarian 421 (Mkn421) (Punch et al., 1992), 1ES2344+514 (Catanese et al., 1998) and PKS2155-304 (Chadwick et al., 1999). These objects all exhibit optical properties characteristic of the BL Lacertae (BL Lac) class of AGN and, due to the extension of their synchrotron spectra into the X-ray band, are classified as X-ray Selected BL Lacs (XBLs). Markarian 501 has been detected at the 4σ level by the Energetic Gamma-Ray Experiment Telescope (EGRET) on board the Compton Gamma-Ray Observatory (Kataoka et al., 1999).

Since 1995 the Whipple Collaboration has extensively monitored the gamma-ray emission from Markarian 501. The VHE flux level has been observed to vary dramatically on a range of different timescales (Quinn et al., 1999). The mean flux level has varied from $\sim$0.1 to $\sim$5 times that of the Crab Nebula. Significant variability has been observed on a range of timescales from years to hours. Extreme variability has also been observed in Mkn421 (e.g. Gaidos et al., 1996). However, a major difference in the flux characteristics of the two objects is that Mkn501 appears to have a base emission level, whereas any such base level in the case of Mkn421 lies below the minimum sensitivity level of the Whipple 10 m telescope.

There is as yet no consensus on the dominant gamma-ray production mechanisms in BL Lacs. The preferred model is that emission is associated with the accretion of matter onto a supermassive black hole, the generation of magnetic fields and the production of jets of electrons, although the precise manner in which the beam is generated and collimated is unclear (Buckley et al., 1997). Jet models are consistent with evidence that the emission is beamed. The observed correlation of the variability of TeV gamma rays and hard X-rays implies that both are produced by non-thermal electrons. Furthermore, if the synchrotron emission at energies

$\gtrsim$ 100 keV detected by OSSE is also attributed to the same source, then there is a test for beaming in XBLs (Catanese at al., 1997). Observations of emission from Mkn501 up to 7.5 TeV (Samuelson et al., 1999) show clear evidence of beaming, with a Doppler boost factor of 1.5-2.0. The short timescales of correlated variability put more restrictive constraints on a proton beam, which is assumed to lose energy mainly by synchrotron radiation. The necessary magnetic field of 30-90 G for a boost factor of the order of 10 are not excluded and would be consistent with the variability of Mkn421 (Mannheim et al., 1998).

2 Observations and Analysis:

Observations were made with the Whipple IAČT, located on Mt. Hopkins in southern Arizona. The 10 m optical reflector focuses Čerenkov light from gamma-ray and cosmic-ray initiated air-showers onto a high resolution camera mounted in the focal plane. Subsequent off-line analysis of images identify candidate gamma-ray events. The camera, which comprises a close-packed array of 331 photomultiplier tubes (PMTs), has a field of view of 4.8°. The telescope is triggered when two out of the 331 PMTs register a signal which exceeds some pre-set threshold. This is typically achieved by summing the outputs of a discriminator on each channel and putting the summed signal through another discriminator. However, a disadvantage of this method is that random two-pixel events, caused by fluctuations in the night sky background, can trigger the system. The rate at which such unwanted triggers occur is a major factor in determining the operating threshold of the telescope.

A pattern selection trigger (PST), which can be pre-programmed with acceptable PMT trigger combinations, has been developed (Bradbury et al., 1999). This permits a decrease in the operational energy threshold of the telescope. During the 1998/1999 observing season the PST was initially tested and subsequently used for routine data taking. As a result, the Markarian 501 dataset consists of two components, one taken at a slightly higher threshold than the other. Based on observations of the Crab Nebula, we estimate that the energy thresholds are 500 GeV and 400 GeV respectively. The same selection criteria have been used for both datasets and the effective energy threshold with the PST is lower than 400 GeV with an optimised analysis.

For the analysis presented here, only data taken under good weather conditions and with elevations greater than 50° have been used. Our data set consists of 4.5 hours taken at an energy threshold of ∼500 GeV and 15.5 hours taken at the ∼400 GeV threshold, spanning a total of 20 nights in the period February 1999 to April 1999. The integral fluxes obtained with the different thresholds have been normalised by expressing them as fractions of the measured Crab Nebula flux (CF) at the same threshold. This assumes that the slopes of the VHE energy spectra of Mkn 501 and the Crab Nebula are similar, which is true only to a first approximation (Samuelson et al., 1998, Hillas et al., 1998).

3 Results:

Figure 1 shows the averaged gamma-ray rate expressed in terms of the Crab Nebula rate over three month's of observation during 1999. The mean rate of gamma rays from Markarian 501 is 0.36±0.025 CF for the season. This rate is comparable to the measured rate in 1998 and significantly higher than that in 1995 or 1996 (Quinn et al., 1999). There is strong evidence for variability (figure 1) with the rate on the first night (MJD 51224) of observation being considerably higher than for the rest of the observations. A test for constant flux level gives a χ^2/DOF of 107/19, with a chance probability $\sim 10^{-14}$. Omitting this first night still suggests variability with a chance probability of 2×10^{-4}. There is also evidence for variability in the monthly averages when the first data point is omitted, with average rates of 0.60 ± 0.065, 0.33 ± 0.045 and 0.26 ± 0.034 CF respectively for February, March and April, giving a probability for constant flux $\sim 2 \times 10^{-5}$. Data from MJD 51228 were excluded because of extremely poor weather conditions, although there was a strong signal of approximately 3 CF on that night.

Previous multiwavelength observations indicated that the VHE gamma-ray and X-ray data may be correlated (e.g. Catanese at al., 1997). We have plotted the average weekly rates for data obtained with the Whipple 10 m IAČT in figure 2 (top) and the available X-ray data from the RXTE All Sky Monitor (ASM) in figure 2

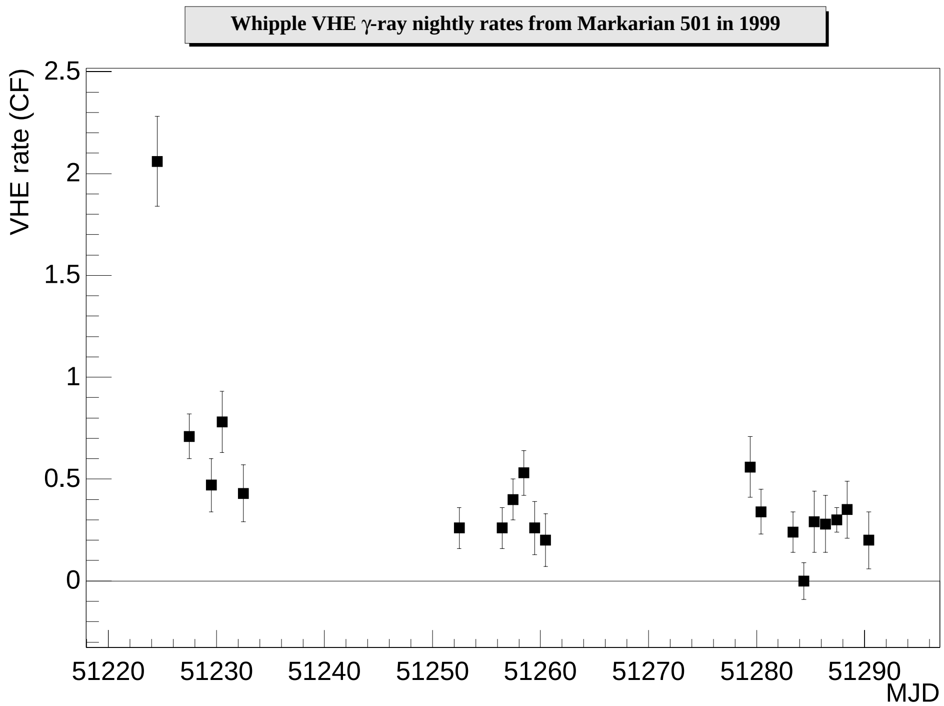

Figure 1: Average nightly rates expressed in terms of the Crab Nebula flux (CF) measured with the Whipple 10 m IAČT in 1999

(bottom) for the period from 1996 to 1999. There is evidence for some correlation in long-term trends in both wavebands. It is difficult to determine correlations on shorter time-scales due to poor sampling in the VHE band and low statistics in the ASM data. The large flare detected at the Whipple Observatory on MJD 51224 seems to have preceded a slightly elevated state in the X-ray emission, which lasted for a few weeks.

4 Conclusions:

The results provide clear evidence for continued variability in Mkn501 in 1999. There is strong evidence for day-scale variability, with the emission on the first night of observation (MJD 51224) considerably higher than on any other night during the rest of the observation period. Even omitting this night from the dataset there is still some evidence for variability on timescales of days and months. The average emission level is significantly below that of 1997, but comparable to the level of 1998. Once again, there is evidence for a baseline emission level which possibly varies on time-scales of several months or longer.

Comparison of the ASM X-ray and Whipple VHE data from 1996 to 1999 show similarities in the long term trends but not in individual flaring episodes. More detailed studies of correlations between the multiwavelength light-curves are under way and will be reported at this conference. Also to be reported are the results of more intensive multiwavelength campaigns undertaken during Spring 1999.

5 Acknowledgements:

We acknowledge the technical assistance of K. Harris and E. Roache. This research is supported by the U.S. Department of Energy, by PPARC (U.K.) and Enterprise Ireland. The X-ray data in this work are quicklook results presented by the ASM/RXTE team.

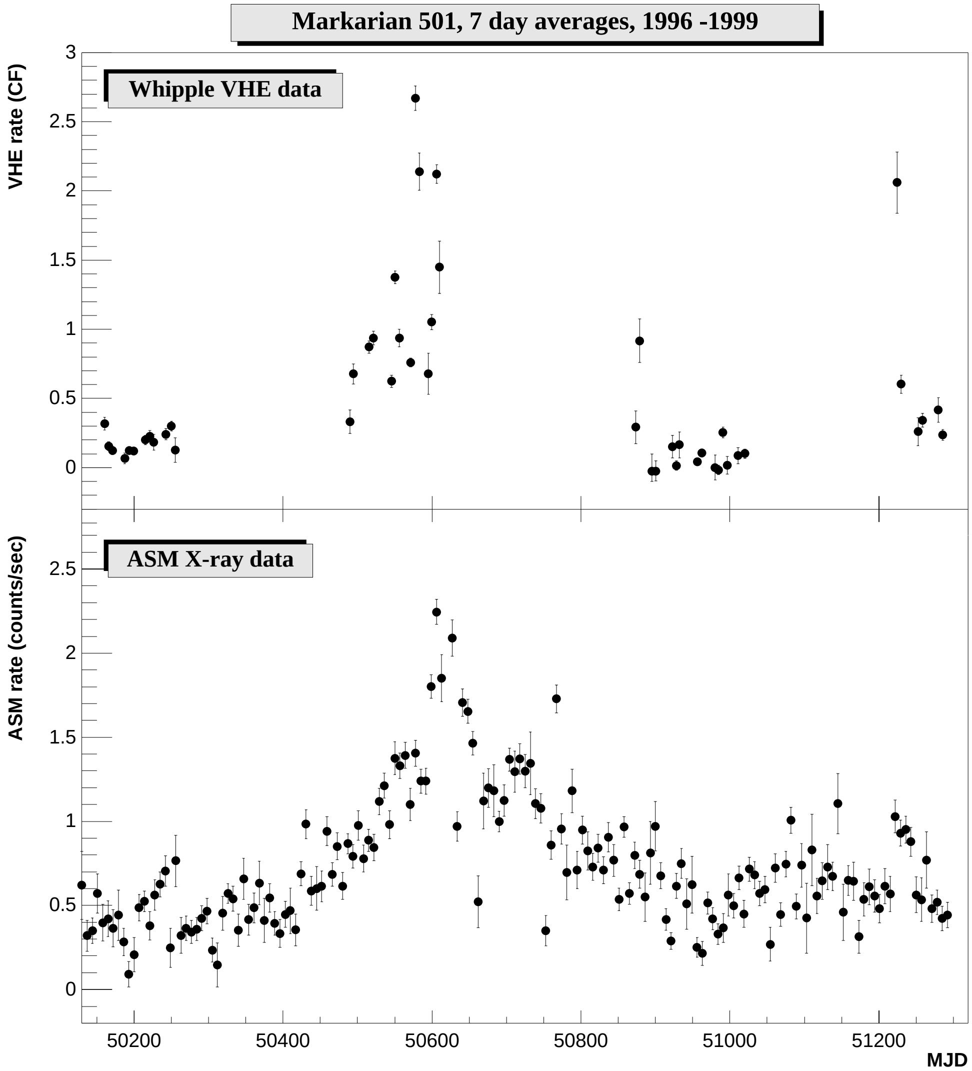

Figure 2: Average weekly rates for Markarian 501 from the Whipple IAČT (top) and the RXTE ASM (bottom) for the period 1996-1999

References

Bradbury, S.M. et al. 1999, Proc. 26th ICRC (Salt Lake City, 1999), OG 4.3.21

Catanese, M. et al., 1997, ApJ, 487, 143

Catanese, M. et al., 1998, ApJ, 501, 616

Chadwick, P.M. et al., 1999, ApJ, 515,161

Gaidos, J.A. et al., 1996, Nature, 383, 319

Hillas, A.M. et al., 1998, ApJ, 503, 744

Kataoka, J. et al., 1999, ApJ, 514, 138

Mannheim, K. et al., 1998, Science, 279, 684

Punch, M. et al., 1992, Nature, 358, 477

Protheroe, R.J. et al., 1998, Proc. 25th ICRC (Durban, 1997), 8, 317

Quinn, J. et al., 1996, ApJ, 456, L83

Quinn, J. et al., 1999, ApJ, in press

Samuelson, F.W. et al., 1998 ApJ, 501, L17