Proceedings of ICRC 2001: 2613 © Copernicus Gesellschaft 2001

ICRC 2001

Observations of extreme flaring activity from Markarian 421 with the Whipple 10m telescope

J. Holder[1] **and the VERITAS Collaboration**[2]

[1]Dept. of Physics and Astronomy, University of Leeds, Leeds, LS2 9JT U.K.
[2]Whipple Observatory, Amado, AZ, 85645, USA

Abstract. Markarian 421 was the first TeV blazar to be detected and has shown extremely variable gamma-ray emission levels over various timescales. During observations by the Whipple $10\ \mathrm{m}$ telescope in the 2000/2001 observing season the source was in an extremely active state. We report here on these observations, including the results of a search for very short timescale variability.

1 Introduction

Markarian 421 was the first extragalactic source to be detected at TeV energies (Punch et al., 1992). The $\nu \mathrm{F}\nu$ spectral energy distributions (SEDs) of blazars such as Mkn 421 are characterized by their "double bump" structure. The lower energy bump (up to $\sim 100\ \mathrm{keV}$) is thought to be due to synchrotron radiation from electrons in a relativistic jet oriented close to the line of sight. The GeV-TeV emission is probably produced by inverse Compton scattering of low energy photons by the electron beam (Jones et al., 1974; Dermer et al., 1992; Sikora et al., 1994) or possibly pion photoproduction from a hadronic component of the relativistic beam (Mannheim, 1993).

Mkn 421 is the closest blazar in the EGRET catalogue (z=0.031), with a relatively low flux but a rather hard spectrum (Hartman et al., 1999). The TeV flux at the time of its original detection was ~ 0.3 times that of the Crab Nebula, but since then it has shown extremely variable emission levels over various timescales, the most dramatic flaring episode occurring on 7th May 1996 (Gaidos et al., 1996), when the source reached a level of $\sim 10\ \mathrm{Crab}$. Eight days later another flare was observed, with half the maximum intensity of the previous flare, but with a remarkably fast doubling timescale of $\sim 15\ \mathrm{mins}$.

Since its TeV detection Mkn 421 has been regularly monitored by various atmospheric Čerenkov experiments (Buckley, 1999; Aharonian et al., 1999b; Piron, 1999). In addition, contemporaneous world-wide multiwavelength campaigns have provided excellent evidence for correlated variability between the emission at X-ray and TeV gamma-ray energies (Buckley et al., 1996; Catanese et al., 1999; Maraschi et al., 1999).

In this paper we report on observations of Mkn 421 with the Whipple $10\ \mathrm{m}$ telescope from the 2000/2001 observing season, concentrating on the time variability of the gamma-ray flux. The results of an intensive multiwavelength campaign during March 2001 (Jordan et al., 2001), detailed spectral measurements (Krennrich et al., 2001) and observations of flaring behaviour in the 1999/2000 observing season (Fegan et al., 2001) appear elsewhere in these proceedings.

2 Observations

The current status of the Whipple Observatory $10\ \mathrm{m}$ imaging Čerenkov telescope is described in detail in Finley et al. (2001). The telescope triggering threshold was fixed in October 2000 and the energy threshold, defined as the peak differential gamma-ray flux for a source with the same spectrum as the Crab Nebula, is now estimated to be $390 \pm 80\ \mathrm{GeV}$. Mkn 421 was regularly monitored from the end of November 2000 until the end of April 2001. The majority of observations were made in a tracking mode in which the source is observed continuously, with the observations divided up in to runs of $28\ \mathrm{mins}$. A subset of 10 minute runs are also included in the analysis.

3 Analysis

The events were parameterized using a standard moment analysis and candidate gamma-ray events were selected by applying a version of the Supercuts technique (Reynolds et al., 1993), Supercuts 2001 (Finley et al., 2001), optimized on data from the Crab Nebula obtained over the same observing season. Observations of off-source regions were combined to calculate the tracking ratio: a factor which converts the

Correspondence to: J. Holder (jh@ast.leeds.ac.uk)

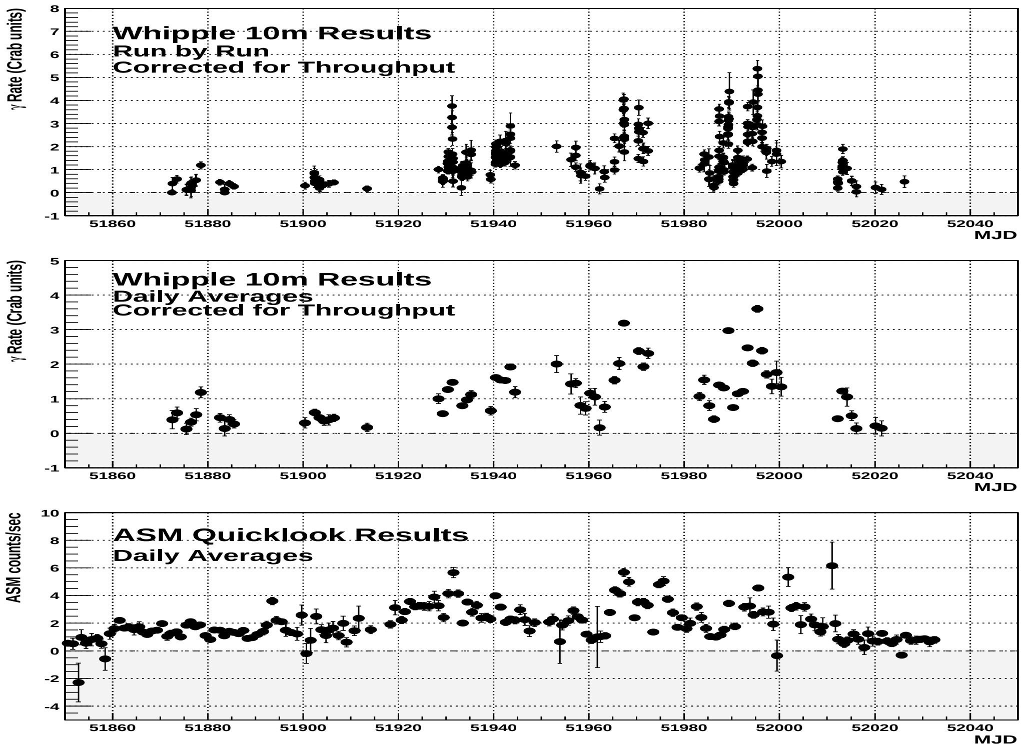

Fig. 1. Light curves for Mkn 421 in 2000/2001. *Top*: Whipple results for each run, with the measured gamma-ray rate shown as a fraction of that from the Crab Nebula. *Middle*: Whipple daily averages. *Bottom*: ASM/RXTE quicklook daily averages.

number of events not orientated towards the source position ($20^\circ < \alpha < 65^\circ$) into an estimate of the background rate.

In order to provide the most complete coverage possible of the source light curve, data have been taken under all weather conditions and over a wide range of zenith angles. To the first order, the effect of these different conditions on the measured gamma-ray rate can be corrected by the use of a "throughput" factor derived from the spectrum of the total amount of light (*size*) produced by background cosmic ray images. The *size* spectrum is first measured for a reference run and the throughput factor for each run which produces the same *size* spectrum as the reference run is then calculated by a χ^2 minimization. The gamma-ray rate can then be found by

$$\text{true rate} = \frac{\text{measured rate}}{\text{throughput}^{\alpha}}$$

where $\alpha = 1.5$ is the assumed integral spectral index for the source. Tests using data from observations of the Crab Nebula indicate that this parameter provides a reasonably accurate correction for changes in both weather and zenith angle conditions (S. Le Bohec, private communication).

4 Results

4.1 Light Curves and Correlation with the X-ray flux

The Mkn 421 light curve for 2000/2001 up until April 27^{th} 2001 is shown in Fig. 1. The throughput correction described above has been applied to correct for the different elevations and weather conditions at the time of observation.

Also shown is the corresponding light curve in the $2 - 12$ keV range as measured by the All Sky Monitor (ASM) on board the Rossi X-Ray Timing Explorer satellite. Mkn 421 showed a clear increase in X-ray activity during this period. In Fig. 2 we plot the daily averaged TeV gamma-ray flux versus the daily averaged X-ray flux. There is evidence for a correlation between the two wave bands, with a straight line fit giving $\Phi_X(\text{counts sec}^{-1}) = 0.90+1.16\Phi_{TeV}(\text{Crab units})$. The TeV data have again been corrected for throughput; a similar fit using uncorrected Whipple data taken under good weather conditions only yields a χ^2 value of 470 for 54 degrees of freedom, with a linear correlation coefficient, $r = 0.67$.

4.2 Short Term Variability

The timescale of flaring emission in AGN is an important parameter to measure as it can be used to constrain the size of the emission region. During the 2000/2001 season the TeV emission from Mkn 421 was clearly variable over the course of a night; some examples of this are shown in Fig. 3. The throughput correction method is still rather preliminary and so has not been used in the searches for short term variability described in this section. We have instead used only data taken under good weather conditions and above an elevation of 45°.

The scale of the variability of a source can be quantified by

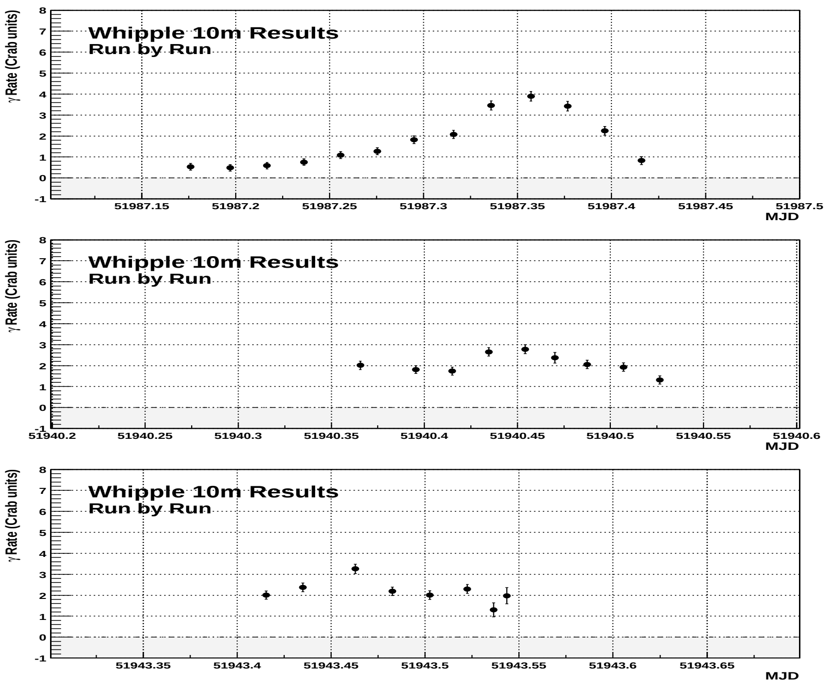

Fig. 3. Observation of flux variability within a night for three nights. The plots show the measured rates, without any throughput correction, for: *Top*: MJD 51987. *Middle*: MJD 51940. *Bottom*: MJD 51943. The data on all three of these nights was taken under good weather conditions and with the source at an elevation of less than $45°$.

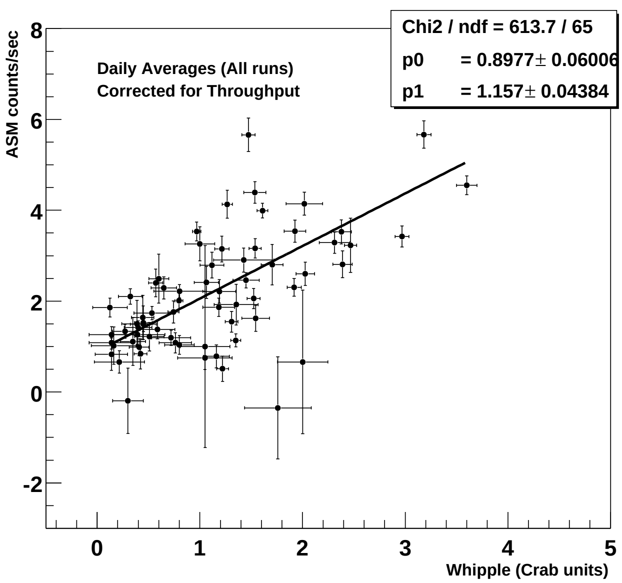

Fig. 2. The correlation of the TeV gamma-ray rates with one-day ASM quicklook count rates. The linear correlation coefficient, $r = 0.63$.

measuring the time gradient between two points. Assuming an exponential increase or decay in the flaring behaviour, we calculate the time constant

$$\tau = \frac{\Delta t}{\Delta \ln \Phi_{TeV}}$$

where Δt is the time difference between each run and $\Delta \ln \Phi_{TeV}$ is the difference between the logarithms of the measured flux (Aharonian et al., 1999a). Fig. 4 shows the distribution of τ for each consecutive pair of runs where Mkn 421 was detected with a significance $> 2\sigma$. The distribution is symmetrical, implying that the rising and falling behaviour of the emission levels are not systematically different. The shortest τ values are of ~ 30 mins, that is, the duration of a typical run. It therefore seems worthwhile to search for variability within each run.

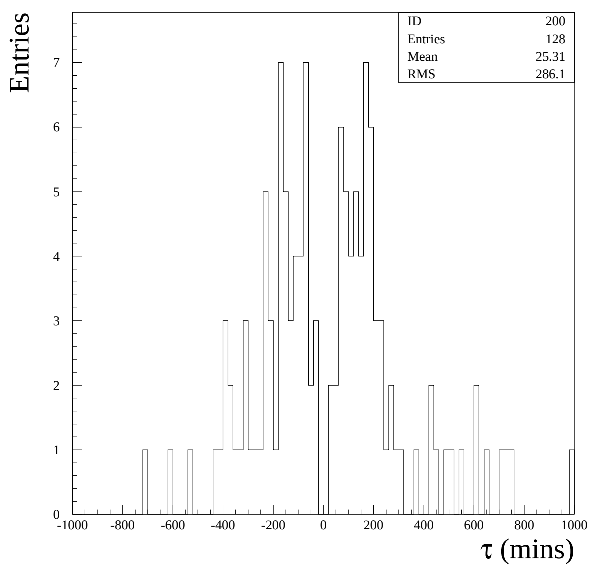

Fig. 4. The distribution of the exponential rise/decay constant for adjacent runs. Only τ values of less than ± 1000 mins are shown.

We have searched for variability by applying a χ^2 test for a constant rate with bin sizes of three and nine minutes. The distributions of the raw probabilities, P_{χ^2}, that the emission is constant about the mean are shown in Fig. 5. Searching for variablility over many runs imposes a large statistical penalty and we correct for the number of trials, N, using $P_{corr} = 1-(1-P_{\chi^2})^N$. After applying this correction there is no evidence for significant variability within any single run on either timescale. The rates for the runs with the lowest probability of constant emission at both timescales tested are shown in Fig.6.

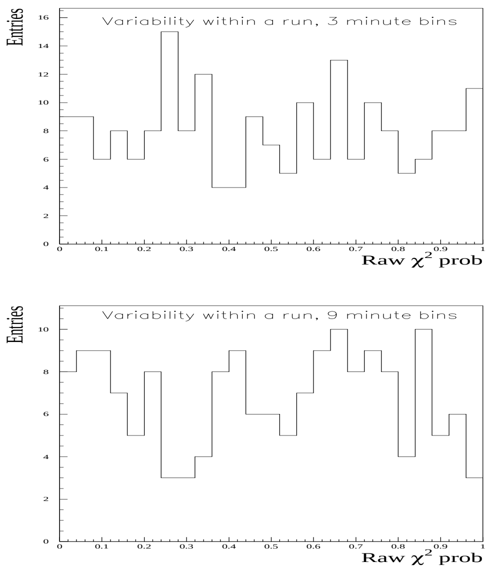

Fig. 5. The raw χ^2 probabilities for constant emission. *Top*: for 3 minute bins. *Bottom*: for 9 minute bins.

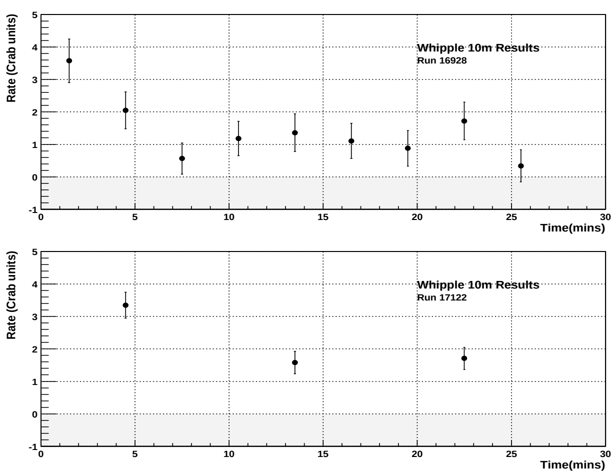

Fig. 6. Rate vs time for the runs with the lowest probability of constant emission at both timescales. *Top*: MJD 51930.3334, $P_{corr} = 0.5$. *Bottom*: MJD 51943.4825, $P_{corr} = 0.1$

5 Conclusions

The extreme flaring behaviour exhibited by Mkn 421 in 2000/2001 constitutes the most sustained high state we have seen from this source; the average gamma-ray rate over the period of the observations was 1.5 times the steady gamma-ray rate from the Crab Nebula. We have shown that the variability of the TeV and X-ray emission is correlated, and found that the shortest timescale for variability at TeV wavelengths is ≤ 30 mins, confirming the behaviour previously observed from this source. There have been various reports of a periodic or quasi-periodic component to the gamma-ray and X-ray emission from Mkn 501 during its 1997 high state (Nishikawa et al., 1999; Kranich et al., 1999; Hayashi et al., 1999; Fegan et al., 1999), although the results appear inconclusive. A search for similar periodicities in the Mkn 421 data from the 2000/2001 season is underway.

Acknowledgements. The VERITAS Collaboration is supported by the U.S. Dept. of Energy, N.S.F., the Smithsonian Institution, P.P.A.R.C. (U.K.) and Enterprise-Ireland. Quicklook results were provided by the ASM/RXTE team. We would also like to thank Kevin Harris and Emmett Roache for their invaluable technical support.

References

Aharonian, F.A. et al., A&A, 342, 69, 1999.
Aharonian, F.A. et al., A&A, 350, 757, 1999.
Buckley, J.H., Astropart. Phys., 11, 119, 1999.
Buckley, J.H. et al., ApJ, 472, L9, 1996.
Catanese, M. et al., in: Proc. of the 26th ICRC, D. Kieda, M. Salomon, B. Dingus, eds. (Salt Lake City) 3, 305, 1999.
Dermer, C.D., et al., A&A, 256, L27, 1992.
Fegan, D.J. et al., These proceedings.
Fegan S.J. et al., in: AIP Conf. Proc., B. Dingus, D. Kieda, M. Salomon, eds. (Snowbird) 515, 129, 1999.
Finley, J.P. et al., These proceedings.
Gaidos, J.A. et al., Nature, 383, 319, 1996.
Hartman, R.C. et al., ApJS, 123, 79, 1999.
Hayashi S. et al., in: AIP Conf. Proc., B. Dingus, D. Kieda, M. Salomon, eds. (Snowbird) 515, 134, 1999.
Jones, T.W., O'Dell, S.L. & Stein, W.A., ApJ, 188, 353, 1974.
Jordan, M. et al., These proceedings.
Kranich, D. et al., in: Proc. of the 26th ICRC, D. Kieda, M. Salomon, B. Dingus, eds. (Salt Lake City) 3, 358, 1999.
Krennrich, F. et al., These proceedings.
Mannheim, K., A&A, 269, 67, 1993.
Maraschi, L. et al., Astropart.Phys., 11, 189, 1999.
Nishikawa, D. et al., in: Proc. of the 26th ICRC, D. Kieda, M. Salomon, B. Dingus, eds. (Salt Lake City) 3, 354, 1999.
Piron, F. in: Proc. of the 26th ICRC, D. Kieda, M. Salomon, B.
Punch, M. et al., Nature, 358, 477, 1992. Dingus, eds. (Salt Lake City) 3, 326, 1999
Reynolds, P.T., et al., ApJ, 404, 206, 1993
Sikora, M., Begelman, M.C. & Rees, M.J., ApJ, 421, 153, 1994