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Whipple and Crimean Observations of Markarian 501 in 1997 and 1998

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Abstract. The atmospheric Cherenkov imaging telescopes at the Crimean Astrophysical Observatory and the Whipple Observatory, although operating on the same basic principles, have a number of differences. Until now, it has not been possible to cross-calibrate their sensitivities because the most favorable sources are inconveniently located for optimum observing at the two sites. The high luminosity of Markarian 501 (Mrk 501) in 1997 allowed overlapping observations with good correllations; the correllation in 1998, when the source was less luminous, was less clear.

1 Introduction

The first two atmospheric Cherenkov imaging telescopes developed were those at the Crimean Astrophysical Observatory (Vladimirsky et al., 1989) and the Whipple Observatory (Cawley et al., 1990) in 1982-3. They have been in regular operation ever since. Although operating on the same general principles they have several important differences. Both are located in the Northern Hemisphere, but the summer months are optimum for observing in the Crimea and the winter months in Arizona and hence it has not been possible to cross-calibrate the two versions of the technique using the best TeV standard candle, the Crab Nebula. The outburst of Mrk 501 in 1997 provided a bright source that could be seen at both observatories. Here we examine the extent to which the two datasets of quasi-contemporaneous observations are consistent.

2 Crimean Observations

The Crimean Astrophysical Observatory (CrAO) high energy gamma-ray telescope is located at an elevation of 600 m. It is a complex instrument consisting of two sections separated by 20 m. On each section there is a group of six parallel telescopes; three of these are equipped with visible-sensitive imaging cameras, while the other three have non-imaging ultraviolet-sensitive detectors. Each imaging camera consists of 37 photomultiplier tubes. Light concentrators in optical contact with the photomultiplier tubes increase the light collecting efficiency by a factor of two. The mean input diameter of the light concentrators is 34 mm, corresponding to an angular field of view of 0.4° per pixel; the total field of view of each camera is 2.8°.

Mrk 501 was observed by the CrAO group on a number of nights in May and June 1997, and again in May, June and July 1998. All of the observations of Mrk 501 were performed with the two sections in coincidence mode with a time resolution of 100 ns. The source was studied by comparing observations of the gamma-ray source with background observations shifted in time from each other by 30 minutes. The source and background were observed at the same azimuth and zenith angles. A total of 59 pairs of ON/OFF scans were made in 1997 and 39 in 1998; the duration of each ON and OFF scan was 25 min. Scans conducted under bad weather conditions were excluded from the data analysis. This left a total of 53 and 34 acceptable scans in 1997 and 1998, respectively. After the signal amplitudes in individual channels were adjusted using calibration coefficients, the data were subjected to the following further processing: (1) events were excluded in which the total signal from the light detectors of all telescopes was larger than the signal saturating the analog-to-digital converter (about 150 photoelectrons) in at least in one of the 37 channels; (2) events were excluded whose maximum amplitude was in the outer annulus of the detector; (3) events were excluded when failures of the telescope tracking system were recorded, i.e., when the optical axis of one of the telescopes deviated by more than $3'$ from the specified direction.

As a result of this preliminary data processing, the number of observed events retained for subsequent analysis was 30139 source events and 29345 background events in 1997, and 17803 source events and 17393 background events in 1998. For these events, the parameters of the Cherenkov flashes were determined: effective length A and width B;

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DIST, the angular distance from the image centroid to the source position in the focal plane; and *AZWIDTH*, the projected width perpendicular to the line joining the image centroid to the source position. For each flash, the parameters in the two sections of the instrument were averaged. Averaging the parameters over the two sections causes their relative fluctuations to decrease and, consequently, leads to a better separation of the flashes caused by gamma rays from those caused by charged cosmic-ray particles. This method of analysis is used here for the first time.

Analysis of the observations indicates that the optimum parameter-based selection criteria for the 1998 data differ from those for the 1997 data. These differences are attributable to the changes in equipment characteristics resulting from the addition of a fourth imaging telescope to each section. The criteria for selecting gamma-like events are shown in Table 1, and the results are presented in Table 2. Other selection parameters such as the parameter *UV* associated with the detection of ultraviolet emission were not used, as they did not lead to an increase in the statistical significance of the results.

Calculations of the gamma-ray flux were determined using gamma-ray and proton shower simulations. The flux averaged over the observation time in 1997 at energies $E > 1\mathrm{TeV}$ was found to be $(5.0 \pm 0.6) \times 10^{-7}\mathrm{m}^{-2}\mathrm{s}^{-1}$. In 1998, the average flux was $(3.7 \pm 0.6) \times 10^{-7}\mathrm{m}^{-2}\mathrm{s}^{-1}$. The errors quoted are the total statistical observational and modeling errors.

Table 1. CrAO selection criteria for 1997 and 1998 seasons.

parameter	1997	1998
length, A	$< 0.275^\circ$	$< 0.315^\circ$
width, B	$< 0.150^\circ$	$< 0.165^\circ$
$AZWIDTH$	$< 0.15^\circ$	$< 0.225^\circ$
$DIST$	0.55° - 1.00°	0.20° - 0.80°

Table 2. CrAO Data: number of recorded and selected events

Selection criterion	Number of source events	Number of background events	Diff.	Diff. to-error ratio
1997				
No selection	30139	29345	794	3.26
Selection by *A*, *B*	2446	2049	397	5.92
Selection by *AZWIDTH*	819	423	396	11.24
1998				
No selection	17803	17393	410	2.19
Selection by *A*, *B*	3107	2759	348	4.54
Selection by *AZWIDTH*	1410	1054	356	7.17

The flux values for 1997 are plotted in Figure 1 and those for 1998 in Figure 2.

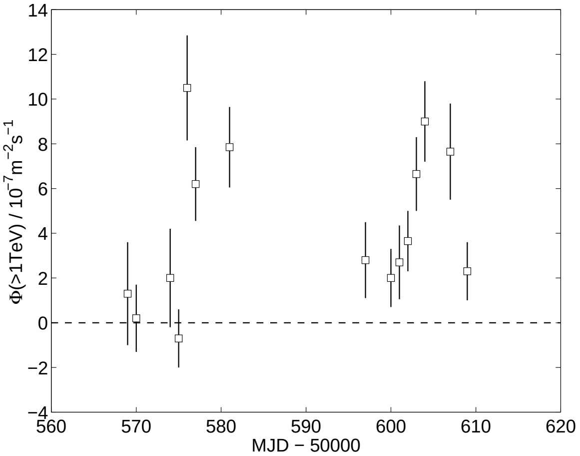

Fig. 1. CrAO observations of Markarian 501 in 1997.

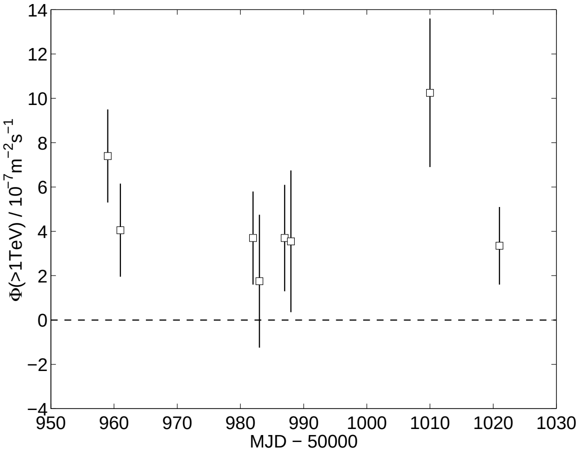

Fig. 2. CrAO observations of Markarian 501 in 1998.

3 Whipple Observations

The Whipple telescope was built in 1968 and consists of a 10 m optical reflector on an alt-azimuth mount. The reflector comprises 250 mirror facets of focal length 7.3 m. It is located on Mount Hopkins in Arizona at an elevation of 2.3 km. The high resolution camera in the focal plane consisted of an array of phototubes (Cawley et al., 1990) which was upgraded before these observations. Initially the camera consisted of a closely packed hexagonal array of 109 photomultipliers (PMTs), each of which viewed a circular field of view (FOV) of 0.26° diameter, giving a total FOV of 3°. The number of PMTs was increased from 109 to 151 in 1997 with consequent increase of total FOV to 4.8°.

Markarian 501 was discovered as a TeV gamma-ray source by the Whipple Observatory Gamma-ray Telescope in 1996 (Quinn et al., 1996). It was monitored in 1997, when it was observed to be in a high state (Breslin et al., 1997), and again in 1998. Whipple observations of Mrk 501 carried out between 970429 and 970615 (MJD 50567 - 50614) and between 980518 and 980727 (MJD 50951 - 51021) have been examined and compiled, for comparison with the CrAO measurements. The overall Whipple Mrk 501 database for April-June 1997 consists of 22 ON/OFF pairs (∼10 hours on-source) and 92 tracking runs (∼42 hours on-source). For the present study, only observations taken in good weather at zenith angle less than 35° were considered - this restricts the database to 17 ON/OFF pairs and 62 tracking runs. For 1998, 17 ON/OFF pairs and 92 tracking runs were recorded in May-July. All ON/OFF runs and 57 of the tracking runs were taken in good weather at zenith angle less than 35°. In the analysis, the OFF runs were ignored, and the ON runs treated as tracking.

The standard image cleaning used at Whipple (Reynolds et al., 1993) was applied to events which triggered the system. Cleaned images were subjected to moment analysis to yield image parameters *length, width, distance, alpha* and *asymmetry*; other parameters used in the selection criteria are *size, max1* and *max2*. Selection of gamma-ray candidates is based on the application of appropriate cuts to the image parameters. The camera configuration was different for the two observing seasons, and accordingly different selection cuts are appropriate: these cuts were optimised in each case on a large sample of observations of emission from the Crab Nebula. The cuts used for each season are shown in Table 3 (Quinn et al., 1999).

Table 3. Whipple Supercuts for 1997 and 1998 seasons.

parameter	1997	1998
$width$	0.073° - 0.16°	0.073° - 0.16°
$length$	0.16° - 0.33°	0.16° - 0.44°
$distance$	0.51° - 1.17°	0.51° - 1.25°
$alpha$	$< 15°$	$< 10°$
$size$	> 0 d.c.[1]	> 0 d.c.
$max1$	> 95 d.c.	> 75 d.c.
$max2$	> 45 d.c.	> 65 d.c.
$asymmetry$	> 0	> 0

[1] 1 digital count (d.c.) $\simeq$ 1photoelectron (p.e.).

In tracking analysis, the *alpha* range defined by the cut on *alpha* shown in Table 3 is considered the “signal” region. The background in the signal region is estimated from events which pass all cuts except the *alpha*-cut, and which have *alpha* between 20° and 65° (the “background” region). If the number of events in the signal region is N_{on} and the number in the background region N_{off}, the gamma-ray signal is estimated as the excess $N_{ex} = N_{on} - \beta N_{off}$, where β is the ON/OFF *tracking ratio* (nominally 15/45 for the 1997 camera and 10/45 for the 1998 camera).

For the cuts in Table 3, the energy threshold of the Whipple system was E_t = 350 GeV, and the effective area was A_{eff} = 3.5×10^4 m^2 (Quinn et al., 1999). The flux above 350 GeV, $\Phi(> 350\,\mathrm{GeV})$, during an interval Δt is found from the number of excess events in that interval N_{ex} as

$$\Phi(> 350\,\mathrm{GeV}) = \frac{N_{ex}}{A_{eff}\Delta t} \qquad (1)$$

The energy threshold for the CrAO system is 1 TeV. In order to compare the two sets of observations, Whipple fluxes above 1 TeV have been determined using results on the spectrum of Mrk 501 (Krennrich et al., 1999; Samuelson et al., 1998). The differential spectrum deviates from a simple power law, being best represented by

$$J(E) \propto \left(\frac{E}{\mathrm{TeV}}\right)^{-2.22-0.47\log_{10}E} \qquad (2)$$

Assuming an upper energy limit of 10 TeV, integration of the expression for $J(E)$ indicates that the flux above 1 TeV, $\Phi(> 1$ TeV), can be estimated as $0.26\ \Phi(> 350$ GeV).

The results for $\Phi(> 1$ TeV) determined from the Whipple observations are plotted in Figures 3 and 4.

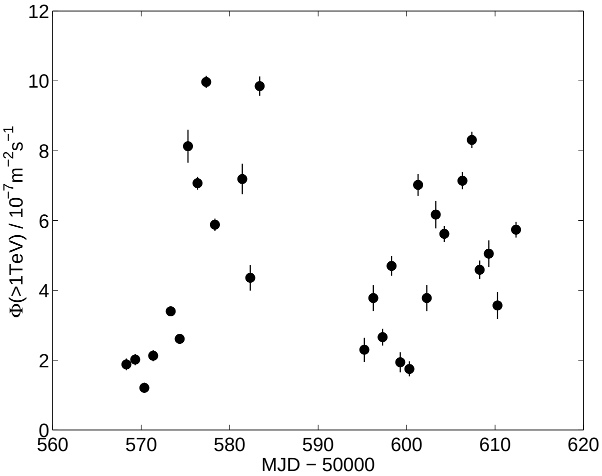

Fig. 3. Whipple observations of Markarian 501 in 1997. The vertical bars are the statistical uncertainties.

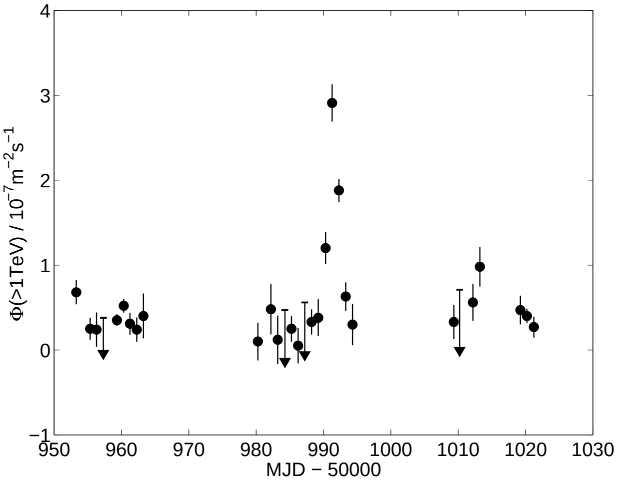

Fig. 4. Whipple observations of Markarian 501 in 1998. Note the difference in vertical scale compared to Figure 3. For four nights, upper limits at the 99.9% confidence level are shown (arrows).

4 Comparison of Results

The results from the Whipple and CrAO observations for 1997 are shown together in Figure 5, and the results for 1998 are shown together in Figure 6.

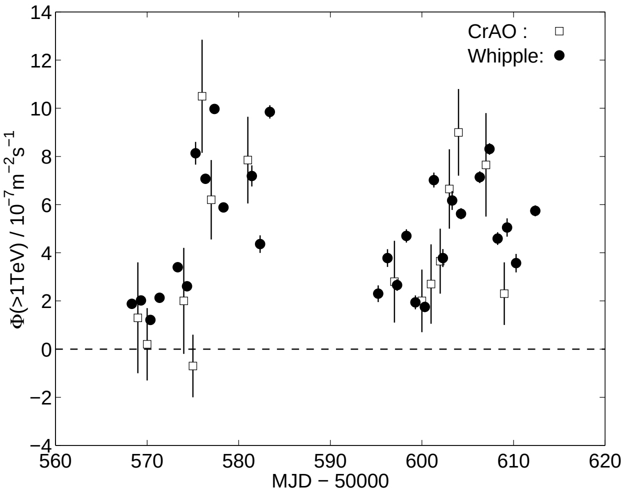

Fig. 5. Combined observations of Markarian 501 in 1997.

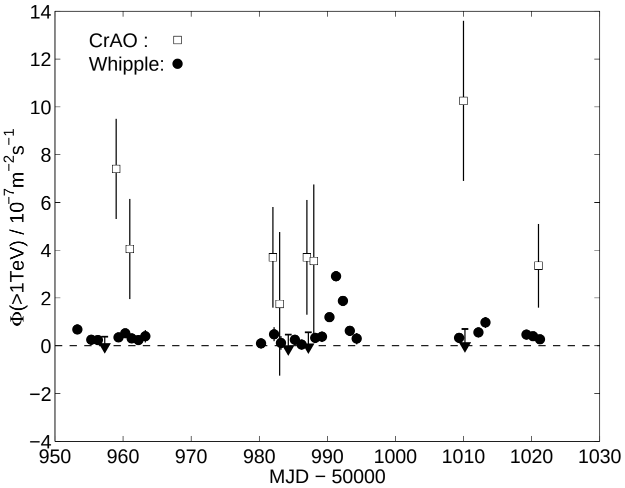

Fig. 6. Combined observations of Markarian 501 in 1998.

For the 1997 data, where the high level of emission over a six-month interval was confirmed by a number of observatories (Protheroe et al., 1997), the CrAO results in general show very good agreement with the trend of the Whipple observations, bearing in mind the differences in observation time arising from the longitude difference of 145° and the fact that the TeV emission from Markarian 501 shows considerable variability on time scales of the order of a few hours.

The good correlation between the two sets of observations is illustrated by Figure 7, which shows Whipple flux plotted against CrAO flux for dates on which the source was observed at both locations, though it must be remembered that the observations were not made simultaneously.

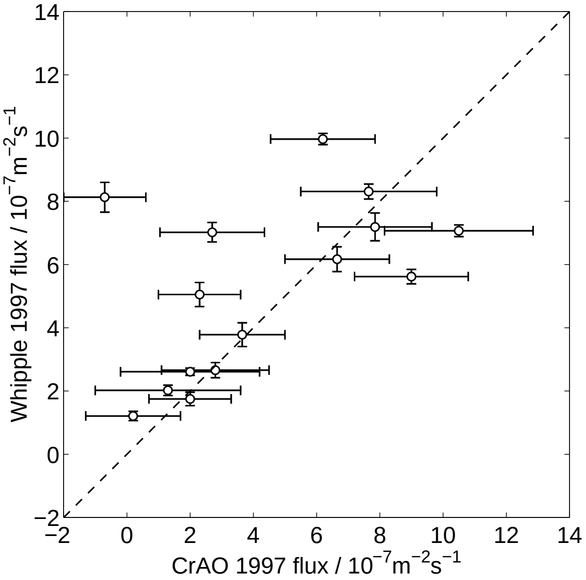

Fig. 7. Comparison of CrAO and Whipple observations of Markarian 501 in 1997.

In the case of the 1998 results, the Whipple observations show a much lower level of activity for Markarian 501, although significant flaring is still seen on occasion (for example, at the end of June 1998). At the same time, the CrAO observations show higher fluxes. Given the extreme variability of the source and the non-contemporaneity of the observations, the possibility that these observations reflect real changes in the flux cannot be excluded.

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