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DETECTION OF GAMMA RAYS WITH $E > 300$ GeV FROM MARKARIAN 501

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ABSTRACT

The detection of gamma rays of energy greater than 300 GeV from the BL Lacertae object Mrk 501 demonstrates that extragalactic TeV emission is not unique to Mrk 421. During 66 hr of observations between 1995 March and July we measured an average flux of $8.1 \pm 1.4 \times 10^{-12}$ cm^{-2} s^{-1} above 300 GeV, a flux that is only 20% of the average Mrk 421 flux. The new gamma-ray source has not been reported by the *Compton Gamma Ray Observatory* as an emitter of gamma rays at lower energies. There is evidence for variability on timescales of days.

Subject headings: BL Lacertae objects: individual (Markarian 501) — gamma rays: observations

1. INTRODUCTION

The discovery by EGRET (Thompson et al. 1995) of photons with energies above 100 MeV from more than 50 active galactic nuclei (AGNs) has generated much interest in the study of those extremely luminous objects which in many cases show maximum power at gamma-ray energies. Since 1992 the Whipple Observatory Gamma Ray Collaboration has conducted a systematic search for TeV emission from EGRET-detected AGNs and from AGNs with similar characteristics. Of the 35 sources examined (Kerrick et al. 1995a; Weekes et al. 1995), only Mrk 421 was detected (Punch et al. 1992; Schubnell et al. 1995) prior to this season. Mrk 421 is a relatively nearby BL Lac object at a redshift of $z = 0.031$; it was first detected by EGRET in gamma rays (Lin et al. 1992).

Theoretical speculation on the absence of TeV emission from other AGNs has centered on the possibility of intergalactic absorption of the TeV photons against an infrared background field (Stecker, de Jager, & Salamon 1993; Biller et al. 1995), although intrinsic absorption is also possible.

Recently the Whipple observing program has concentrated on the observation of relatively nearby ($z < 0.1$) BL Lac objects. In this Letter the first success of that program, the detection of Mrk 501 at energies above 300 GeV, is announced.

2. OBSERVATIONS

The observations reported in this paper were made using the atmospheric Cerenkov imaging technique (Cawley & Weekes 1995). They were taken with the 10 m optical reflector located at the Whipple Observatory on Mount Hopkins in Arizona (elevation 2.3 km). The high-resolution camera, consisting of 109 photomultiplier tubes (pmts), is mounted in the focal plane of the reflector and records images of atmospheric Cerenkov radiation produced by gamma rays and cosmic rays (Cawley et al. 1991). The Cerenkov light images are classified according to the angular size and orientation. Gamma-ray images are typically smaller and more elliptical than background hadronic images. The gamma-ray images that originate from a putative source in the center of the camera will be preferentially oriented with their major axis pointing toward that center. The orientation angle α is defined as the angle between the major axis of the ellipse and the line joining the centroid of the ellipse and the center of the camera.

A number of recent innovations have been made which lead to a reduction in energy threshold and minimum detectable flux sensitivity. A reduction in energy to 200 GeV was achieved because of (*a*) higher average mirror reflectivity (anodization of aluminum coating); (*b*) the use of light cones to collect light in front of the pmts (greater collection efficiency and reduction of albedo); and (*c*) a lower discriminator triggering threshold, i.e., operation closer to noise. In practice most of the observations reported here were analyzed at a slightly higher threshold (above 300 GeV), where the background rejection is better using the usual gamma-ray selection routines (Reynolds et al. 1993). At a later stage the results of an analysis on the lower threshold data using new selection routines will be reported.

Improved flux sensitivity has been a direct result of improved methods of gamma-ray event selection (background rejection), which were made possible by optimization of the software selection routines using observations taken on the Crab Nebula and simulations of the properties of air showers. An important practical innovation has been the introduction of immediate off-line data analysis whereby the gamma-ray emission level on any source is available within 10 minutes of the completion of the observation.

The telescope is used in two operating modes:

1. *Discovery mode*.—In this mode the source is tracked continuously without taking data off source on a control region. Events whose orientations are such that they are not from the direction of the source are used to determine the background level. This eliminates the need for OFF control observations, which accounted for 50% of the total observing time in the past. In addition, since the background is being simultaneously monitored, observations can be made under

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TABLE 1

OBSERVATION LOG

Dark Period	ON/OFF Mode (minutes)	Tracking Mode (minutes)
March ...	28	540
April.....	649	810
May......	988	162
June	276	81
July......	333	108
Total ..	2274	1701

adverse weather conditions which previously would have prevented ON/OFF observations. On the basis of observations made in 1994–1995 on the Crab Nebula, the systematic error in flux measurements with this technique is such that $\sigma_{\rm experimental} < 1.25\,\sigma_{\rm statistical}$. This is a worst case, since the Crab has a bright star within 1° of the source. To be conservative, the error bars on measurements made in this mode are increased by 25%.

2. *Confirmation mode*.—ON/OFF observations are also made in the conventional manner (Reynolds et al. 1993) when a detection requires careful confirmation. Both the ON and the OFF run are 28 minutes in duration. Previous and contemporaneous observations of the Crab Nebula show no detectable systematic errors in measurements made in this mode. The absolute flux is also derived from these measurements.

Initial indications of the presence of a signal from observations in 1995 March in the discovery mode led to a change to ON/OFF observations on the source in subsequent months. The complete observing log for Mrk 501 is summarized in Table 1.

The images are parameterized off line, and subsequent analysis is based on the image parameters: width, length, distance, and α. The basic data selection (rejection of background to select candidate gamma-ray events) was based on the Supercuts criteria described elsewhere (Reynolds et al. 1993). However, some changes were necessary because the reduced threshold increased the background from (*a*) event triggers caused by fluctuations in night-sky background light and (*b*) events caused by Cerenkov signals from single local muons. The criteria used (Supercuts 95) were optimized using observations on the Crab Nebula earlier in the observing year.

To reduce the new source of background, a minimum-size cut of 400 digital counts (d.c.) was introduced (note: 1 d.c is approximately equal to 1 p.e.). It was also required that each event have at least one channel above 100 d.c. and another above 80 d.c. Further, it was required that there be three adjacent pmts above the triggering threshold. The selections based on width and length were unchanged ($0\overset{\circ}{.}073 <$ width $< 0\overset{\circ}{.}15$ and $0\overset{\circ}{.}16 <$ length $< 0\overset{\circ}{.}30$). The upper bound on the distance selection was reduced to account for the reduced overall diameter of the camera when the outer partial ring was changed from pmts with diameter 5 cm to those with 2.5 cm; thus the distance selection was $0\overset{\circ}{.}51 <$ distance $< 1\overset{\circ}{.}00$. Finally, the maximum value of α was reduced from 15° to 10° as a result of the improved tracking of the telescope.

3. RESULTS

3.1. *Tracking Data*

A total of 31.0 hr of data were taken in the tracking mode, with each run of approximately 28 minutes duration. A small number of runs were eliminated where the atmospheric conditions were clearly very unstable. Using the selection criteria listed above, the α plot shown in Figure 1 is derived for 28.3 selected hours of observation. The gamma-ray domain is defined as 0°–10°, and the control region as 20°–65°. Because of the limited field of view of the camera, the α distribution is not flat; observations of a number of regions of sky in which no known sources were present gave the ratio k = Sum (20°–65°)/Sum (0°–10°) = 4.42. With this value the background expectation in the gamma-ray domain in the Mrk 501 observations is 405 events, whereas 699 events are observed. Using the maximum likelihood method of Li & Ma (Li & Ma 1983) the nominal significance of the observed excess is 11.7 σ. Because of systematics the real statistical significance is lower, probably nearer 9 σ. Thus, just considering this data set there is a strong indication for the emission of gamma rays from Mrk 501.

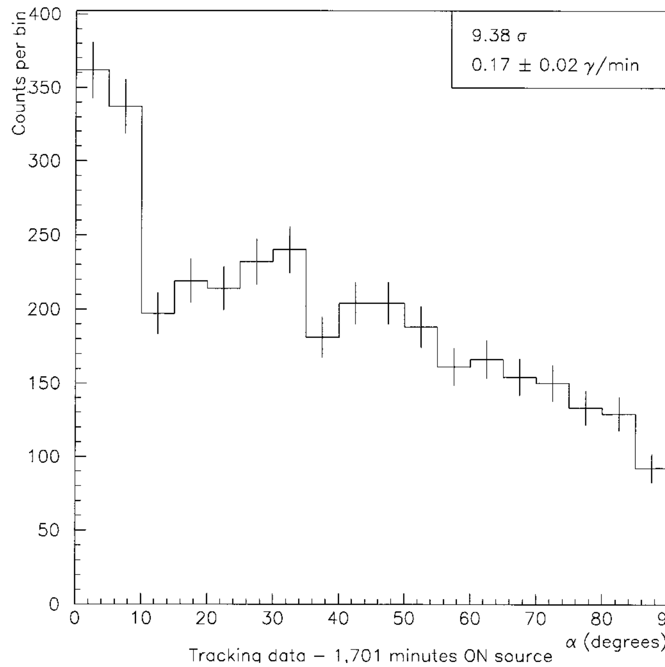

FIG. 1.—α plot of 28.3 hr of tracking data on Mrk 501

3.2. ON/OFF *Data*

The identification of Mrk 501 as a very high energy gamma-ray source was confirmed by ON/OFF observations taken under good sky conditions between 1995 April 23 and July 30. A total of 90 ON/OFF pairs, each of approximately 28 minutes duration, were taken in the conventional manner under excellent observing conditions; the OFF regions were chosen to be either 30 minutes before or after the right ascension of Mrk 501, so that the same range of elevation was tracked for the OFF observations. Although all the observations were judged to be taken under clear skies, subsequent analysis of the variations in the raw data rates led to the rejection of seven ON/OFF pairs. For the remaining 83 pairs, Supercuts 95 is used to give the results shown in Table 2; the α plot for the ON and OFF data are shown in Figure 2. Hence the emission of gamma rays from Mrk 501 is confirmed by the +8.4 σ detection.

The excess corresponds to 334 events in 2274 minutes of ON observations; this is a rate of 0.15 ± 0.02 minute^{-1} compared with 1.88 minute^{-1} for the Crab Nebula and 0.9 minute^{-1} (time averaged) for Mrk 421 using a similar analysis on data taken this

TABLE 2

ON/OFF OBSERVATION SUMMARY

	Raw	Trigger	Shape	Orientation	Supercuts 95
ON	2045813	850866	5408	35875	966
OFF	2049201	850078	5161	35672	632
Difference	−3388	788	247	203	334
Significance (σ)	−1.67	0.60	2.40	0.76	8.36

year. This corresponds to an integral flux of $(8.1 \pm 1.4) \times 10^{-12}$ cm^{-2} s^{-1} at an energy threshold of 300 GeV. Taking the upper limit of the integral flux at 100 MeV to be less than 1.5×10^{-7} cm^{-2} s^{-1} (Lin 1995), the exponent of the integral spectrum between 100 MeV and 300 GeV must be harder than −1.2, which is quite consistent with the value of −1.0 observed for Mrk 421.

3.3. *Variability*

The high-energy gamma-ray emission from AGNs has been characterized by strong variability at all wavelengths; this has been seen also at energies above 300 GeV for Mrk 421 (Kerrick et al. 1995b; Buckley et al. 1995b). No variability has been detected in the gamma-ray signal seen by the Whipple Observatory from the Crab Nebula. At shorter wavelengths Mrk 501 has shown less variability than most AGNs detected by EGRET. To search for possible variability in the signal from Mrk 501, all of the ON and tracking data have been combined and analyzed as tracking data; hence in each run the background has been estimated from the 20°–65° bins in the α distribution. The experimental errors have been increased accordingly. Only runs where the elevation angle was above 55° have been used in the analysis.

When the results are plotted as daily averages (Fig. 3), it is apparent that the flux is constant with the exception of one day in mid-July. On MJD 49,921 the observed gamma-ray rate is 5 standard deviations above the average rate of 0.15 minute^{-1}; the observations on that night were the first of the dark run and were taken, under excellent conditions, in the tracking mode. Within 2 days the flux was again consistent with the average rate over the previous months. The factor of 5 transition in rate over 2 days is very similar to that seen in Mrk 421 (Buckley et al. 1995a, b). Lesser variations would not be apparent because of the smaller signal-to-noise ratio in this new source; hence we cannot eliminate the possibility that Mrk 501 is just as variable as Mrk 421 in very high energy gamma rays.

4. DISCUSSION

Gamma rays at energies above 300 GeV have been detected from the two closest BL Lac objects, which, in addition to being at comparable distances, have very similar characteristics across the wave bands (Weekes et al. 1995). Although Mrk 421 has been seen by EGRET, Mrk 501 is below the level of detectability; the power of the ground-based observing technique is thus demonstrated. A deep search for very high energy gamma rays from AGNs at intermediate distances can shed light on this question. To date, observations of other nearby BL Lac objects have only yielded upper limits (Quinn et al. 1995), but observations are continuing.

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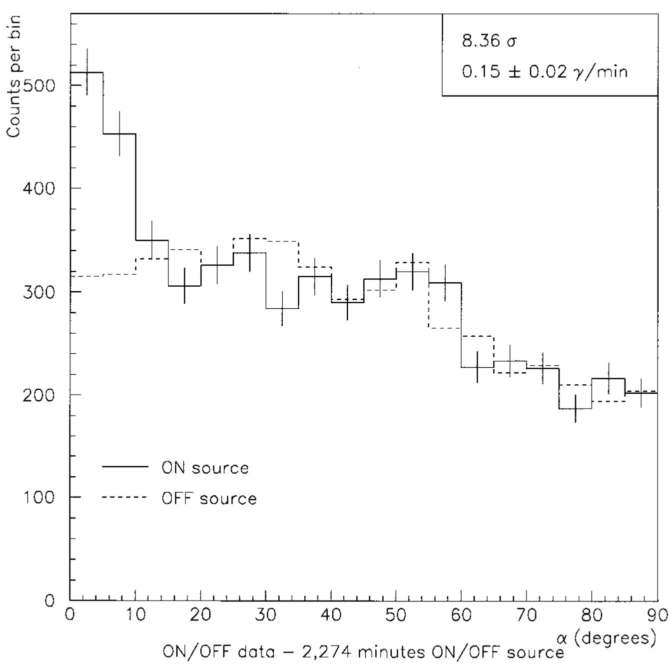

FIG. 2.—α plot of 37.9 hr of ON and OFF data on Mrk 501

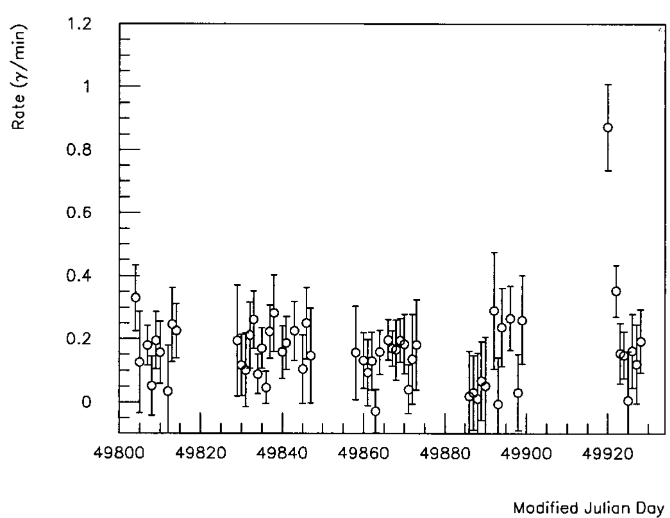

FIG. 3.—Daily gamma-ray rates from Mrk 501; all rates are based on the ON or tracking observations only, and the error bars are increased accordingly.

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