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Observations of gamma-ray sources at energies > 300 GeV

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Abstract. Results from recent observations with the Whipple Observatory gamma-ray telescope are reported; after the successful detection of Markarian (Mkn) 421 particular emphasis was put on the observation of nearby Bl Lacs. The Bl Lac, Mkn 501, which is similar to Mkn 421 in many ways, was detected for the first time as a gamma-ray source. Extensive coverage of Mkn 421 this season revealed unusual variability; one episode of intensity change in April, 1995 was measured with high statistical significance. Upper limits were found for a number of Bl Lacs with $z < 0.1$.

Key words: galaxies: Mkn 421, Mkn 501 — BL Lacertae objects — gamma-rays: observations

1. Introduction

The sensitivity of the Compton Gamma Ray Observatory appears to be an extraordinarily good match to most of what is interesting in observational gamma-ray astrophysics. Only at very high energies (>30 GeV) does its sensitivity effectively disappear. Its design reflects the general expectation that source emission spectra would steepen with energy. It was anticipated that at higher energies (>100 GeV) if any phenomenon was detected it would, at best, be a mere extension of lower energy phenomena. Surprisingly it has been found that many of the sources in the 2nd EGRET Catalog (Thompson et al. 1995) have hard spectra out to the maximum EGRET energy and there are some phenomena that are only (or best) seen in the 100 GeV−10 TeV energy range. These include: the inverse Compton-synchrotron component of the Crab Nebula (Weekes et al. 1989), the detection of an unpulsed component from PSR 1706−44 (Kifune et al. 1994), the first detection of short term gamma-ray variability in Mkn 421 (Kerrick et al. 1995a), the possible emission from X-ray binaries such as Vela X-1 and AE Aqi (Meintjies et al. 1994; Chadwick et al. 1995). In this paper we provide evidence for time variations of Mkn 421 on shorter times-scales and report the first detection of a gamma-ray emitting blazar (Mkn 501) which is not detected by EGRET.

The only viable method of gamma-ray astronomy at very high energies is the ground-based atmospheric Cherenkov technique. Although significant advances have been made in the sensitivity of this technique it is still not possible to completely remove the background of cosmic hadrons and electrons. The Whipple 10m imaging telescope is currently the most sensitive in operation (Cawley et al. 1991; Reynolds et al. 1993). Since the launch of the Compton GRO the Whipple observing program has concentrated on the observation of sources detected by EGRET. One of the advantages of ground-based detectors over space telescopes is that the detector can be upgraded in incremental steps.

2. Technique

Since 1991, improvements have been implemented in the Whipple imaging telescope which, although individually of small consequence, have together significantly improved its sensitivity. These improvements come under three headings: 1) Energy threshold: this has been reduced to 200 GeV. In practice most of the observations reported here were analyzed at a slightly higher threshold (>300 GeV) where the gamma-ray selection (i.e. background rejection) routines at this time are better. At a later stage we hope to report on the lower threshold data. The reduced energy threshold was achieved because of a) higher average mirror reflectivity (anodization of Aluminum coating); (b) use of light cones to collect light in front of the pmt's (greater collection efficiency and reduction of albedo); (c) reduction of the discriminator triggering threshold i.e. operation closer to noise.

2) Improved flux sensitivity: it is now possible to detect a source at the 5σ level when it has a gamma-ray flux that is 5% of that of the Crab Nebula in 50 hours of observation. This 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 of the Crab Nebula and simulations of the properties of air showers. In addition the telescope tracking has been refined so that the source is more accurately positioned in the center of the field of view. An important practical innovation has been the introduction of on-line data analysis whereby the gamma-ray emission level on any source is available within ten minutes of the completion of the observation.

3) Increased observing time: by using the off-axis oriented events within the field of view of the ON source observations to determine the background level it has become possible to reduce the need for "OFF" control observations which accounted for 50% of the total observing time. In addition, when the background is being simultaneously monitored observations can be made under adverse weather conditions which previously would have prevented chopping ON/OFF observations. In practice to guard against systematic effects ON/OFF observations are also made when a detection requires careful confirmation. By using a liquid filter (developed for use in the ARTEMIS project (Urban et al. 1996)), it has been possible to extend observations into bright moon time; although the energy threshold is thus increased it has been demonstrated that both the Crab Nebula and Mkn 421 can be detected with this system (Chantell et al. 1995).

3. Sources in the 1st EGRET catalog

The First EGRET Catalog of Gamma-ray Sources (Fichtel et al. 1994) is a comprehensive list of candidate TeV sources for observation with the Whipple telescope. Since 1991, as source positions became available, the Whipple Collaboration has given priority to the observation of these sources. The classification of these sources is shown in Table 1 which also shows the status of the Whipple observation program. The first results of this survey have been published elsewhere (Kerrick et al. 1995; Quinn et al. 1995a).

4. Nearby Bl Lacs

Bl Lacs constitute a substantial fraction of the AGNs seen by EGRET. Because of potential intergalactic absorption of TeV photons by the unknown infrared background the nearby Bl Lacs are of particular interest (Stecker et al. 1992; Biller et al. 1995). A list of nearby Bl Lacs has been compiled from the Hewitt & Burbidge (1993) and Perlman et al. (1995) catalogs (Table 2). These have been the object of a special study by the Whipple group in the past year; a similar study has been made in the EGRET database (Lin et al., 3rd Compton Symposium).

Only Mkn 421 and 501 yield a signal that is statistically significant. Upper limits have been reported on a number of these objects (Kerrick et al. 1995a; Quinn et al. 1995a). New and more sensitive limits are listed in Table 2; the method of observation and analysis is identical to that described already (Kerrick et al. 1995a).

5. Markarian 421

This source was detected by EGRET as a weak GeV source with a flat spectrum (Lin et al. 1993); it was the first AGN seen as a TeV gamma-ray source (Punch et al. 1992). It has continued to be monitored with the Whipple telescope and a strong outburst was detected in May, 1994 (Kerrick et al. 1995b); the results seen over three years have been reported elsewhere (Schubnell et al. 1995). Here we report the preliminary analysis of observations made since December, 1994 when the source has been in a period of unusual activity. The daily rates are shown in Fig. 1. The peak flux was recorded in February and July, 1995. The best observed activity was in the period April 20 through May 01, 1995 which coincided with our EGRET Guest Investigator observation (Buckley et al. 1995). The overall detection significance in this period alone was 15 σ (Fig. 2). Although the results of the EGRET observation are not yet available the X-ray emission levels reported by ASCA (Takahashi, this symposium) show a clear correlation with the > 300 GeV emission. There is also a possible correlation with emission in the R band (S. Wagner, this symposium).

A more complete analysis is now in progress; this will include the lower energy data (<300 GeV) and the spectral information in the TeV energy range.

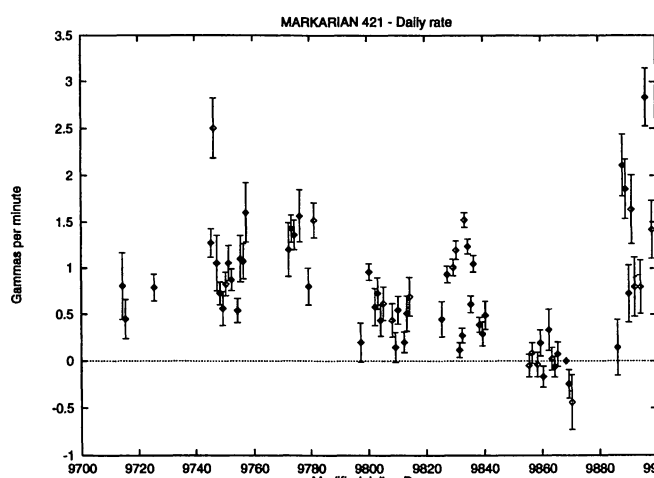

Fig. 1. Detected rate of > 300 GeV gamma-rays from Mkn 421 December 94 - July 1995

Table 1. First EGRET catalog: Status of observations

First EGRET Catalog Type	EGRET All	Whipple Visible	Whipple Observed	Whipple Detected
Detected Pulsars	5	2	2	1
b<10° High Confidence	10	6	8	0
b<10° Marginal	27	17	2	0
Normal Galaxies	1	0	0	0
AGN's High Confidence	25	20	11	1
AGN's Marginal	13	7	4	0
b>10° High Confidence	8	7	4	0
b>10° Marginal	36	26	2	0
Totals	124	85	33	2

Table 2. Gamma-ray observations of nearby Bl Lac objects

Object	Alias	z	EGRET 100 MeV (10^{-7}cm^{-2}s^{-1})	Whipple 300 GeV (10^{-12}cm^{-2}s^{-1})	Alpha optical-X-ray	Alpha radio-X-ray
1722+119	4U	0.018	<1.0	Pending	1.02	0.29
1101+384	Mrk421	0.031	1.4+0.4	Detected	1.14	0.42
1652+398	Mrk501	0.034	<1.5	Detected	1.15	0.48
1E S2344+514		0.044	?	Not observed	1.18	0.41
1113+704	Mrk 180	0.046	<0.4	<13	1.27	0.35
1E S1959+650		0.048	?	Pending	1.19	0.32
1514-241	Ap Lib	0.049	<1.0	Too low		
1807+698	3C371	0.050	<0.9	Pending	1.72	0.50
0521-365	PKS	0.055	1.8+0.5	Too low		
1727+502	I Zw 187	0.055	<0.8	< 21	1.01	0.47
1E S2321+419		0.059	?	Not observed	1.19	0.32
0548-322	PKS	0.069	<1.0	Too low	1.02	0.39
2200+420	Bl Lac	0.069	<1.0	< 14	1.31	0.61
2005-489	PKS	0.071	1.8+0.5	Too low	1.11	0.53
1E S1741+196		0.083	?	Not observed	1.18	0.41

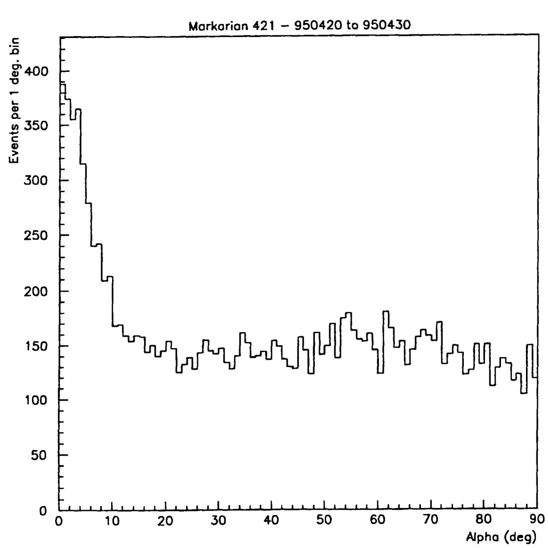

Fig. 2. Alpha plot of signal from Mkn 421 in April, 1995

6. Markarian 501

As part of the program to observe nearby Bl Lacs a series of observations were made on Mkn 501. [In fact both Mrk 421 and Mkn 501 were included in a survey of a small number of AGNs with a less sensitive version of the Whipple imaging camera in 1984-5 (Cawley et al. 1985)]. In the observing campaign reported here the source showed a positive excess in early tracking (discovery) observations and this source was given priority in the observing program in the April, May and June dark runs. As a result a large data-base of Tracking and ON/OFF runs were accumulated and there is clear evidence in both for a weak and apparently steady source (Quinn et al. 1995b). The significance of the signal in 31 hours of Tracking is 11.7 σ (Fig. 3); the source was confirmed in ON/OFF (38 hours of each) which will be reported elsewhere (Quinn et al. 1996). The flux of gamma-rays > 300 GeV is 8.1$\pm$1.4 10 $^{-12}$ photons-cm^{-2}-s^{-1}, about 7% of the flux level from the Crab Nebula at this energy. It is about one fifth the average recorded intensity of Mkn 421. The upper limit in the >100 MeV emission from the EGRET experiment (Fichtel et al. 1995) is $< 1.5\ 10^{-7}$ photons $cm^{-2}s^{-1}$. This limit is, in fact, above the average flux level seen from Mrk 421 by the same experiment. Hence this VHE observation is not incompatible with an energy spectrum of E^{-2} in the MeV-GeV-TeV range as observed in other AGN's.

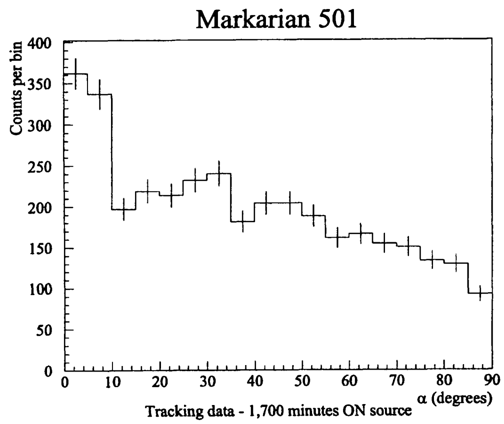

Fig. 3. Alpha plot of signal from Mkn 501 in April-June, 1995

It is striking that Mkn 501 is similar to Mkn 421 is so many ways (Table 3); it may not be coincidental that these are the only nearby Bl Lacs detected in this survey and that they are amongst the closest. In fact they may be the closest: the red-shift of U1722+119 rests on the detection of a single absorption line (Griffiths et al. 1989) which was not confirmed in later observations; based on the relative optical brightness a more reasonable redshift might be 0.1 (Lin, private communication). Hence Mkn 421 and Mkn 501 are the nearest confirmed Bl Lacs; the fact that they are the only ones observed at TeV energies (Table 2) may not be coincidental. It could arise from a number of causes associated with distance: (i) the intergalactic infrared absorption could be higher than expected (or the energy threshold of the TeV telescope underestimated); (ii) the two sources are relatively weak Bl Lacs in absolute luminosity terms so that there would be less gamma-ray absorption at the source; (iii) there could be evolutionary effects so that only later AGNs are gamma-ray emitters (unlikely at this small z).

7. Conclusion

The case for variability in the gamma-ray emission from Mkn 421 is clearly established and the apparent correlation with X-ray emission confirmed. The times-scale of this emission is < 2 days but longer trends are also apparent. The detection of Mkn 501, a Bl Lac with many properties similar to Mkn 421, is reported; this is the first gamma-ray emitting blazar to be discovered at TeV energies. At a signal level of 70 milliCrabs it is probably at the effective threshold sensitivity of atmospheric Cherenkov telescopes at this time.

Table 3. The Bl Lac twins

	Mkn 421	Mkn 501
Redshift, z	0.031	0.034
Optical, m	+14.4	+14.4
X-ray, s (2 keV)	3.92	3.70
Radio, s (5 GHz)	722	1371
Index (optical-X-ray)	1.14	1.15
Index (radio-optical)	0.42	0.48
Time variability	hours-days	months-years?
Gamma Rays		
EGRET > 100 MeV	Flux	Upper limit
$10^{-7}cm^{-2}s^{-1}$	1.4±0.4	< 1.5
Variability	no	
Whipple >300 GeV		
$10^{-12}cm^{-2}s^{-1}$	40	8.1
Gamma rays/minute	0.9	0.17
Crab units	0.3	0.07
Variability	yes	possible

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