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OUTBURST OF TeV PHOTONS FROM MARKARIAN 421

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ABSTRACT

Markarian 421, an active galactic nucleus (AGN) of the BL Lacertae type, is the closest EGRET-detected AGN. It has been monitored by the Whipple Observatory very high energy gamma-ray telescope since its discovery at TeV energies (Punch et al. 1992), for approximately 90 nights, totaling 130 hours of observation. Observations from 1993 December 23 to 1994 May 10 showed an average source flux only half that of its 1992 discovery level. However, observations on 1994 May 14 and 15 show an increase in flux above this quiescent level by a factor of ~10. The timescale of this increase provides the best geometric constraint on the extent of TeV photon emission regions within AGNs. The observation of the high TeV flux occurred 1 day prior to the observation by *ASCA* of a very high 2–10 keV X-ray flux (Takahashi et al. 1994). This strong TeV outburst is reminiscent of the behavior seen for the stronger 100 MeV–GeV EGRET sources (e.g., 3C 279; Kniffen et al. 1993) but was not anticipated in view of the fact that the six EGRET observations of Mrk 421 from 1991 June to 1993 July (Lin et al. 1994) showed no evidence for variability.

Subject headings: BL Lacertae objects: general — BL Lacertae objects: individual (Markarian 421) — gamma rays: observations

1. INTRODUCTION

The full-sky survey by the EGRET gamma-ray detector (Fichtel et al. 1994) has reported detections of nearly 40 active galactic nuclei (AGNs) at photon energies above 100 MeV. At other wavelengths, these sources are all bright, flat-spectrum radio sources with, in many cases, optical polarization and rapid optical variability, characteristics of the blazar class of AGNs (Dermer & Schlickeiser 1992, and Antonucci 1993 are useful guides to AGN taxonomy. In the simplest, unified picture of the AGN phenomenon, blazars are those AGNs which have associated jets with the jet axis oriented near the observer's line of sight.)

The gamma-ray luminosities inferred from the EGRET observations are in the range of 10^{44} to more than 10^{49} ergs s^{-1} if one assumes isotropy. However, the true luminosities will be several orders of magnitude less if the gamma rays are associated in some way with the relativistic jets of the blazars and are thereby beamed. Most models that have been advanced to account for the gamma rays make this assumption.

The closest EGRET source is Markarian 421 at a redshift $z = 0.031$. Mrk 421 is a BL Lac object extensively observed at radio (Owen et al. 1978; Zhang & Bååth 1990), UV/optical (Maza, Martin, & Angel 1978; Mufson et al. 1990), and X-ray frequencies (Mufson et al. 1990; Mushotzky et al. 1979; George, Warwick, & Bromage 1988). Its parent galaxy has been identified as a giant elliptical (Ulrich et al. 1975; Mufson, Hutter, & Kondo 1989). Variability has been observed in X-rays and at lower photon energies, with a timescale of days (optical; Xie et al. 1988) to hours (X-ray; Giommi et al. 1990). However, Mrk 421 has not been observed to vary at EGRET energies in spite of the fact that it has been observed a total of six times during phase 1 (1991 May 16–1992 October 17) and phase 2 (1992 October 17–1993 September 7) of the *Compton Gamma Ray Observatory* program (Lin et al. 1994). All six observations were consistent with a constant, relatively weak flux above 100 MeV of $(1.7 \pm 0.3) \times 10^{-7}$ photons cm^{-2} s^{-1}. In Michelson et al. (1994) Mrk 421 was considered a notable exception to the variability which has been generally associated with the other EGRET AGN sources.

In 1992 Mrk 421 became the first (and as yet the only) EGRET source to be detected at higher energies. The Whipple Observatory collaboration reported its detection at a significance of 6.3 σ (Punch et al. 1992) for photon energies above 500 GeV. Since its discovery as a TeV source, Mrk 421 has been monitored by the Whipple Observatory very high energy gamma-ray telescope (Cawley et al. 1990) for approximately 90 nights, totaling 130 hours of on-source observation with a comparable amount of time off-source. Observations from 1993 December 23 to 1994 May 10 showed an averaged source flux only approximately half that of its 1992 discovery level (Schubnell et al. 1995). However, subsequent observation showed a strong increase to a level (on 1994 May 15.25 UT) approximately 10 times the "quiescent" 1993–1994 flux, rising to this level within a period of 5 days. At this high level, Mrk 421 was brighter at TeV energies than the Crab Nebula

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(Vacanti et al. 1991). The outburst detected by the Whipple Observatory is strongly reminiscent of the behavior seen at EGRET energies for the bright EGRET source 3C 279 (Kniffen et al. 1993), in which this source varied by a factor of 5 over several days. A possible correlated flare, in the 2–10 keV X-ray band, has been reported by Takahashi et al. (1994) for Mrk 421 from *ASCA* (*Astro D*) observations. The *ASCA* observations began approximately 1 day after the observation of the TeV high state.

In the following section, observational details of the TeV outburst and its analysis are given. In a concluding section, a discussion of the implications of these observations and possible constraints that they place on theoretical models of AGNs are presented.

2. OBSERVATIONS, ANALYSIS, AND RESULTS

The very high energy gamma-ray telescope (Cawley et al. 1990) at the Whipple Observatory employs a 10 m diameter reflector to image Cerenkov light from air showers onto a two-dimensional array of 109 fast photomultipliers (PMTs) with a pixel size of 0°.25. Since 1992, the 10 m telescope has been improved in a number of respects, with completely recoated mirror facets and somewhat lower electronic thresholds for its camera elements. The camera itself has been upgraded. Its outer ring of 18 5.08 cm diameter PMTs has been replaced with 18 2.86 cm diameter PMTs. Most recently each PMT was surrounded by a simple light funnel which captured Cerenkov light previously lost to the space between the PMTs. The net result of these improvements is a reduction in effective threshold of the telescope to 250 GeV, with a cosmic-ray shower count rate of 9 showers s^{-1}.

Monte Carlo simulations (Hillas 1985; Macomb & Lamb 1990), repeated observations of the Crab Nebula by the Whipple collaboration (Vacanti et al. 1991), and observations by the CANGAROO group using the imaging technique (Tanimori et al. 1994) demonstrate that the Cerenkov light images of air showers induced by gamma rays can be reliably distinguished from those induced by cosmic rays (i.e., nucleons). The most sensitive technique yet used by the Whipple group for this purpose, "supercuts" (Punch et al. 1991; Reynolds et al. 1993), uses four parameters to characterize the roughly elliptical shape of gamma-ray shower images. Two of the parameters specify the shape of the image, and a third gives its location relative to the center of the field of view. The fourth parameter, α, is the angle between the major axis of the shower image and a line from its centroid to the assumed source location in the image plane. For gamma-ray showers from a pointlike source, α should be small.

In Figure 1 the on- and off-source α distributions for the 1994 May 15.24 observations of Mrk 421 are shown. The distributions are for those events which have satisfied the selection criteria for the other three parameters. In Figure 1*a* no further selection is made. In Figure 1*b* only those showers with a total digital signal greater than 500 digital counts are selected. (This selection corresponds to an increased threshold of $\sim$500 GeV, consistent with the threshold of the original Whipple 1992 detection; Punch et al. 1992.)

A very strong excess near 0° is apparent in both data sets. In the data set in Figure 1*a*, in the region $\alpha < 15°$ (the standard supercut α-cut value), there is a 6.5 σ excess, with 254 on-source showers and 127 off-source showers. (The substitution of smaller pixel PMTs in the camera's outer ring gave better angular resolution but reduced the 1992 field of view from 3°.9 to 3°.0. This field-of-view reduction causes the α distribution for off-source showers to decrease somewhat for angles beyond 75°.) The duration of both the on- and off-source observations

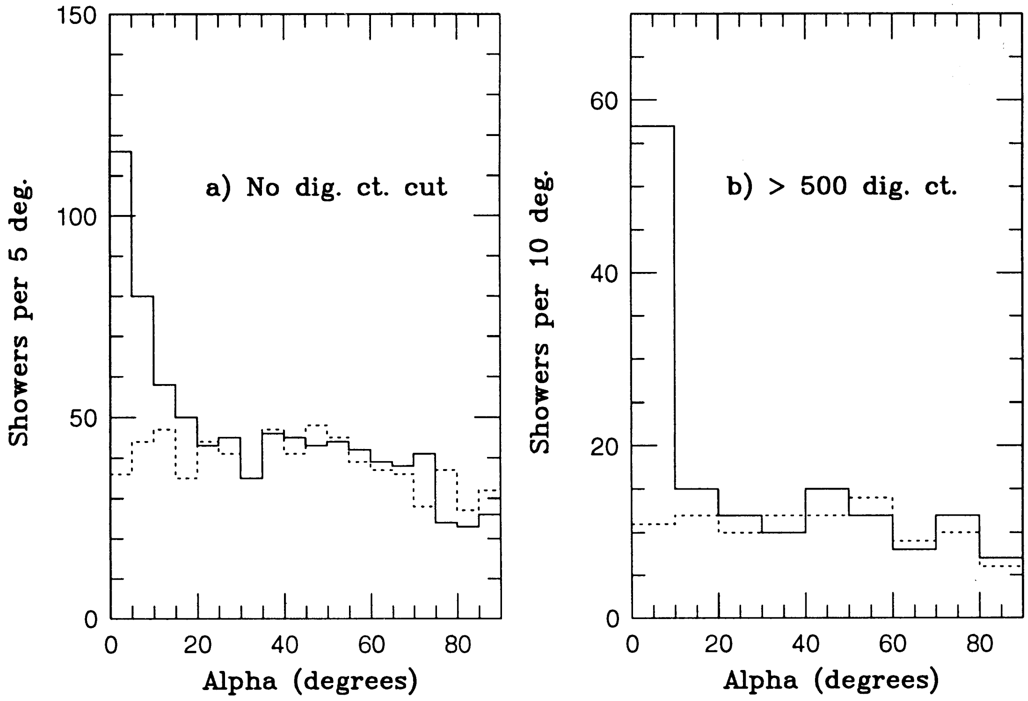

FIG. 1.—On- and off-source α distributions for Mrk 421 for 1994 May 15.25 (UT). The distributions are for those showers for which the other supercuts selection criteria have been satisfied. The duration of each observation is 28.3 minutes. (*a*) No selection has been made on the number of digital counts contained in a shower image. (*b*) Only those showers which have more than 500 digital counts are retained. The latter selection is approximately equivalent to raising the threshold energy from 250 to 500 GeV.

is 28.3 minutes. The difference in the two distributions gives a gamma-ray count rate of 4.5 ± 0.7 photons minute^{-1}. The effective collection area for gamma rays above 250 GeV is 3.5×10^8 cm^2. Thus this excess corresponds to a flux of $(2.1 \pm 0.3) \times 10^{-10}$ photons cm^{-2} s^{-1} above 250 GeV. This flux level is 9 ± 1.5 times greater than the average flux observed from 1993 December to 1994 April (Schubnell et al. 1995), which we take to be representative of a "quiescent" level. Possible systematic errors in the effective collection area give the flux quoted an additional overall ±30% uncertainty; in addition, there is a possible systematic uncertainty in the energy threshold of ±30%.

The photon rates for Mrk 421 derived from observations on 1994 May 10–15 and May 29–June 12 are shown in Figure 2. The errors on the points are purely statistical. Possible systematic errors due to changing sky conditions and zenith-angle variations are small and, to some extent, measurable, with the raw shower count rate in the telescope being the principal diagnostic. Using this diagnostic, we estimate that there is an additional uncertainty of ±10% in the rates shown in Figure 2. The observations were taken in two modes: an on/off mode in which equal time is given to on- and off-source observations, and a tracking mode in which only on-source data are taken. In order to establish an off-source background for the tracking runs, a background template taken from the sum of all-source runs was used.

The observations prior to May 15 (day 135) clearly show a rising rate consistent with an *e*-folding time of ~2 days. This is the first clear-cut case for variability in the TeV region for an extragalactic object on such a short timescale. In addition, a second region of enhanced emission of lesser significance, peaking on June 7 (day 158) 3 σ above the quiescent level and confined to an interval of 4 days, is evident as well.

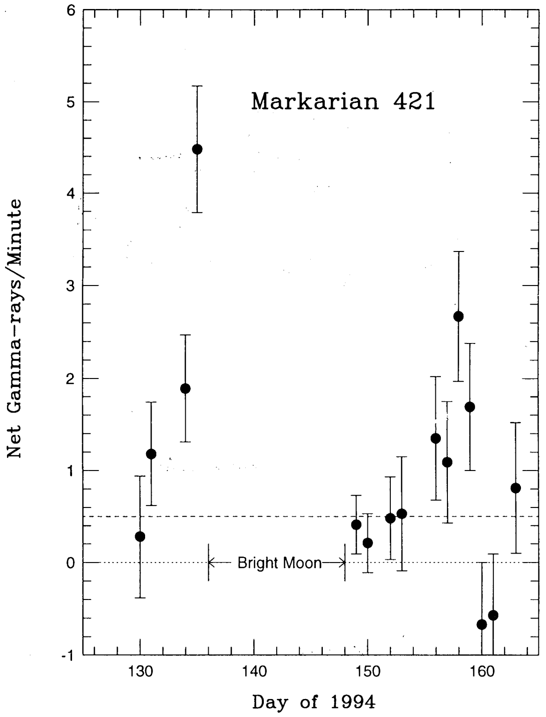

FIG. 2.—Variation in net gamma-rays minute^{-1} for the Mrk 421 observations from 1994 May 10 (day 130) through 1994 June 12 (day 163). The peak intensity of May 15.25 (day 135) occurs 27 hours prior to a reported X-ray high state (Takahashi et al. 1994). Data from May 16–28 (days 136–148) were not obtained, owing to bright Moon conditions. The dashed line shows the 1994 quiescent level (Schubnell et al. 1995).

While there are still large systematic uncertainties in the absolute energy spectra derived from imaging Cerenkov detectors, it is possible to compare the energy spectrum in the high- and low-intensity states. A preliminary analysis shows no change in the previously measured spectral index (Mohanty et al. 1993) by more than ±0.5 at the 90% confidence level.

3. DISCUSSION

No variability in the gamma-ray emission from Mrk 421 has been reported previously by EGRET at MeV–GeV energies (Lin et al. 1994). This is uncharacteristic of such emission from blazars and has led to the suggestion by the EGRET group (Michelson et al. 1994) that Mrk 421 is qualitatively different from the bulk of the EGRET-detected AGNs. However, the strong TeV outburst with a timescale of a few days reported here is reminiscent of the behavior seen for the stronger EGRET sources (e.g., 3C 279; Kniffen et al. 1993). This suggests that, at least at TeV energies, Mrk 421 exhibits approximately the same degree of variability that the other EGRET AGN sources do.

The time of the peak flux of Figure 2, 1994 May 15.25, precedes by 27 hours the beginning of an *ASCA* X-ray observation from May 16.4 to 17.3. The X-ray flux observed (Takahashi et al. 1994) was approximately 20 times the normal quiescent level of the 2–10 keV flux (George et al. 1988). The near-simultaneity of the two high states confirms the appropriateness of the TeV source's identification with Mrk 421. The previous identification (Punch et al. 1992) was based on the location of the TeV source within $0^{\circ}\!.1$ of the known location of Mrk 421; the *ASCA* X-ray detector pinpoints the source to less than an arcminute.

Variability for active galactic nuclei may be a useful diagnostic in constraining the physical environment of the massive black holes which are thought to be their ultimate power source. For the BL Lac subclass of AGNs, the usual light-travel time argument must be used with care, inasmuch as these objects are thought to have their relativistic jets oriented near the line of sight to the Earth (Antonucci 1993), and, as discussed in § 1, the gamma rays are generally thought to be associated with the jets.

The limits to the spatial extent over which the TeV radiation occurs depend very much on the model for production. We consider two limiting cases representing two mutually exclusive extremes. In one extreme case we take the radiation to be emitted from a highly localized wave front moving directly toward the observer with velocity, βc. Under this assumption, the duration of emission in the wave-front comoving frame is (Zdziarski, Svensson, & Paczyński 1991)

$$\Delta t_{\rm com} = \frac{1}{\gamma(1-\beta)} \Delta t_{\rm obs} \simeq 2\gamma \, \Delta t_{\rm obs} \,,$$

where $\Delta t_{\rm obs}$ is the characteristic duration of the observed emission outburst, 2 days. In the observer rest frame, the wave front travels a distance $2\gamma^2 c \, \Delta t_{\rm obs}$. For a jet bulk velocity with $\gamma \sim 10$, a value suggested from VLBI observations of superluminal jets (e.g., Padovani & Urry 1992), the maximum distance the wave front travels along the jet axis would be stretched to ~1 light-year. This is an extreme upper limit, which may be physically unreasonable if the radiation is due to the inverse Compton process from a population of relativistic electrons. If the magnetic field close to the AGN center is appreciably higher than in the outer lobes, electrons of appropriate energy could not survive for such a long time, and then the 2 day observed duration would represent the actual duration (in our frame) of the injection of high-energy particles.

The other limiting case that we consider is that of a causally linked volume emitting radiation at its boundary. If the volume is at rest with respect to the observer, its characteristic size, Δr, is simply $c\,\Delta t_{\rm obs} \approx 2$ light-days. If the volume is a sphere moving with velocity βc toward the observer, the combined effects of Lorentz contraction and Doppler shift yield

$$\Delta r_{\rm com} = \frac{1}{\gamma(1-\beta)}\, c\,\Delta t_{\rm obs} \simeq 2\gamma c\,\Delta t_{\rm obs} \simeq 0.03 \text{ pc} \quad (\gamma = 10)\ .$$

This last expression may be of interest for models of gamma-ray production which generate photons from shock acceleration of particles in the body of the AGN jet.

The degree to which the X-ray and TeV high states coincide is uncertain because of the limited duration of the X-ray observation, 1994 May 16.4–17.3 UT, and the limited sampling of the TeV observations. A maximum duration of the first TeV high-intensity state is ~10 days. The duration of the X-ray high state is unknown. Previous monitoring of Mrk 421 at X-ray energies (George et al. 1988; Makino et al. 1987; Giommi et al. 1990) has shown that such X-ray high states are relatively rare, consistent with the observation that BL Lac objects spend less than 10% of the time in flares that involve luminosity variation of factors of 2 or more (Giommi et al. 1990). Thus, if typical, the May X-ray flare may be relatively short-lived with a duration comparable to or less than our limit on the duration of the TeV high state. If this is true, then the X-ray and TeV high states may be taken to be coincident to within ~10 days. Future simultaneous X-ray and TeV observations will determine the extent to which these phenomena are correlated.

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