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MULTIWAVELENGTH OBSERVATIONS OF MARKARIAN 421 DURING A TeV/X-RAY FLARE

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ABSTRACT

A TeV flare from the BL Lac object Mrk 421 was detected in May of 1994 by the Whipple Observatory air Cherenkov experiment during which the flux above 250 GeV increased by nearly an order of magnitude over a 2-day period. Contemporaneous observations by *ASCA* showed the X-ray flux to be in a very high state. We present these results, combined with the first ever simultaneous or nearly simultaneous observations at GeV gamma-ray, UV, IR, mm, and radio energies for this nearest BL Lac object. While the GeV gamma-ray flux increased slightly, there is little evidence for variability comparable to that seen at TeV and X-ray energies. Other wavelengths show even less variability. This provides important constraints on the emission mechanisms at work. We present the multiwavelength spectrum of this gamma-ray blazar for both quiescent and flaring states and discuss the data in terms of current models of blazar emission.

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

1. INTRODUCTION

Multiwavelength observations of active galactic nuclei (AGNs) have provided important clues to the nature of the radiation associated with these objects and have been central to the development of the relativistic jet model. The nearby BL Lac object, Mrk 421, provides particularly fertile ground for such studies. Previous campaigns emphasizing radio through X-ray observations have generally found that the multiwavelength spectrum is adequately fit by a standard synchrotron self-Compton (SSC) model of a relativistic jet (Brodie, Bowyer, & Tennant 1987; Makino et al. 1987) or inhomogeneous relativistic jet (George, Warwick & Bromage 1988; Mufson et al. 1990). Gamma-ray observations are proving to be a valuable addition to this field. The EGRET instrument has detected 42 AGNs at energies above 100 MeV (von Montigny et al. 1995), including Mrk 421 (Lin et al. 1992). The subsequent detection of Mrk 421 at energies greater than 500 GeV with a spectrum that apparently connects smoothly with the EGRET spectrum (Punch et al. 1992), making it the only extragalactic object detected at such energies, gives it a unique place in this class of gamma-ray sources. Producing photons with what appears to be an unbroken power-law spectrum over more than four orders of magnitude in gamma-ray energy poses severe constraints on any theoretical models attempting to explain high-energy emission from blazars.

Simultaneous observations provide the best and perhaps the only means to test the hypothesis that a single power-law describes the gamma-ray spectral behavior, and to also search for variability within the the gamma-ray band or between gamma-rays and other wavelengths. Accordingly, Mrk 421 was observed during April/May of 1994 by Whipple, EGRET, ASCA, IUE, UKIRT, JCMT, and UMRAO. Many of these observations nearly coincide with the occurrence of a TeV flare during which the flux above 250 GeV increased by almost an order of magnitude over previous levels (Kerrick et al. 1995). The TeV flare occurred primarily on May 14/15 which overlaps an EGRET observation taken from May 10–17. This

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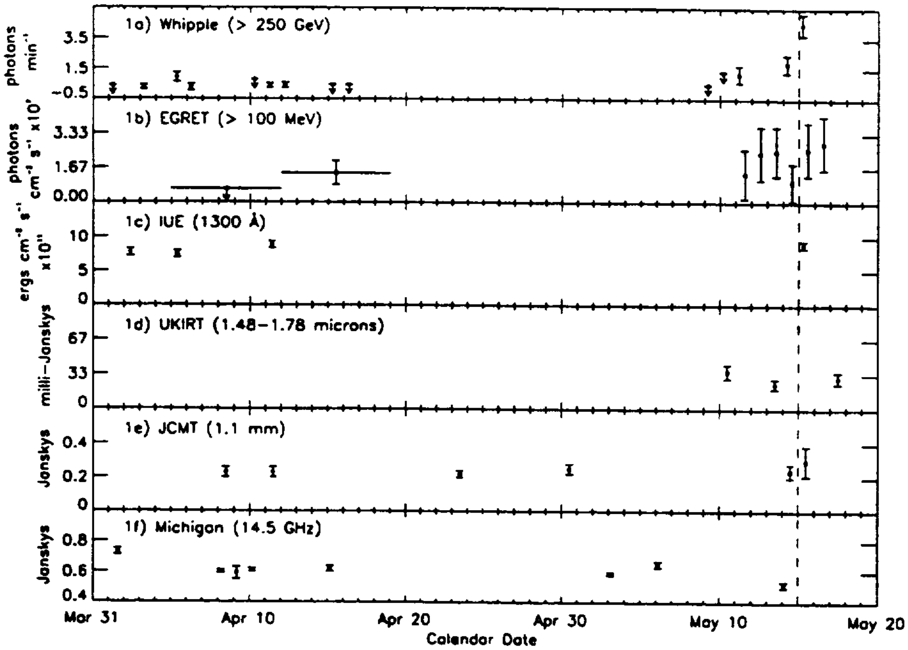

FIG. 1.—Time history of Mrk 421 emission in each waveband for the 1994 April/May timeframe. There is little evidence here for variability comparable to that for TeV/X-ray at other wavelengths. Upper limits are 2 σ.

flare also coincides to within 24 hours of an X-ray measurement by the *ASCA* satellite which showed the source to be in a flaring state at hard X-ray energies (Takahashi et al. 1994). As discussed below, there is little evidence that the flare seen at TeV energies continued down to energies of around 100 MeV. Also, an *IUE* measurement on May 15 showed little increase in flux over April levels. Observations in the IR, mm, and radio bands taken nearly simultaneous to the TeV flare revealed little sign of enhanced activity.

The lack of UV variability accompanying an X-ray flare is typical for Mrk 421 (e.g., Brodie et al. 1987) and indeed might be a general feature of BL Lac objects (Giommi et al. 1990). While the EGRET detection of Mrk 421 for the observation during the TeV flare is weakly consistent with an enhancement for the full week, there is no sign of intraweek variability. The apparent hardening of the gamma-ray spectrum during the flare and the positive correlation between the X-ray and TeV emission has important consequences. Details about the observations in each wavelength band are described in § 2. The combined multiwavelength spectrum both during the flare and in quiescence is highlighted in § 3. Section 4 summarizes our findings and further considers the relevance of these observations to theories of gamma-ray emission from blazars.

2. OBSERVATIONS

The basic observational results for April and May of 1994 are summarized in Figure 1. The data shown are those for which at least two flux measurements were obtained. Our observations cover 16 orders of magnitude in energy. The plots in the various individual energy ranges are explained below. The vertical line in each subplot delineates May 15. Figure 1*a* shows the Whipple Observatory measurements at energies above 250 GeV (300 GeV for April data). The April observations are consistent with emission about half that of the original detection (Schubnell et al. 1995). The May flare is seen to evolve over at least a 4 day period. Due to ground-based air-Cherenkov viewing constraints, data after May 15 were not available. Kerrick et al. (1995) describe the air-Cherenkov observations of this flare in more detail, including the calculation of absolute flux levels.

Figure 1*b* presents the time history of EGRET (Energetic Gamma-Ray Experiment Telescope) observations at energies above 100 MeV. Fluxes are calculated using the maximum-likelihood method (Mattox et al. 1995). This approach allows one to estimate the source counts as well as the diffuse extragalactic and galactic backgrounds using the model of Bertsch et al. (1993). The summed April flux is roughly a factor of 2 below the May flux. When divided into two one-week segments, as shown in the figure, there is no sign of emission during the first week of April while emission is clearly detected during week 2. The May flux points represent overlapping 2 day segments for the 1 week observation. For the entire week, the flux is about twice the average April flux and about 50% above the flux averaged over all available EGRET data (1991–1994). Clearly the flare seen on May 14/15 did not extend too far below sub-GeV energies at the magnitude seen at TeV energies. If the flux $\geq$100 MeV increased by a factor of 6–7 (averaged over 2 days) as it did at TeV energies, this would have been detected by EGRET. Despite the slightly higher average flux for the week, no such dramatic increases are apparent.

The UV points, plotted in Figure 1*c*, are discussed in more detail by Bruhweiler et al. (1995). The May 15 flux differs little from that detected in mid April. There is little evidence of spectral variability among the four observations. The X-ray measurements, for which only one observation was taken, are not shown but are discussed further in § 3.

Observations were made at wavelengths of 2.0, 1.3, 1.1, and 0.8 mm with the UKT14 bolometer on the James Clerk Maxwell Telescope (JCMT) on Mauna Kea, Hawaii, on 1994 April 8, 11, 23, and May 14 and 15 (not all wavelengths on all dates), all at 0600 ± 0100 UT. Infrared (IR) *J*, *H*, and *K* band

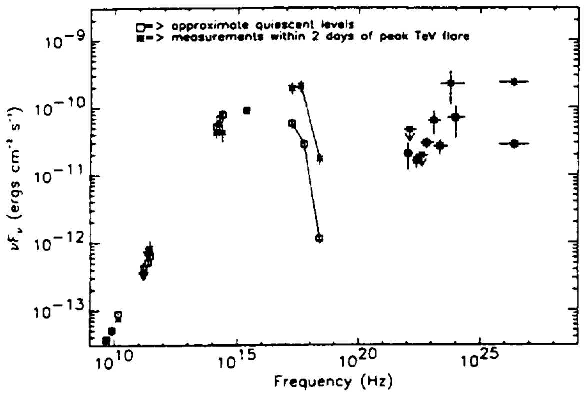

FIG. 2.—Multiwavelength spectrum of Mrk 421 near the time of the flare (*asterisks*) and during "quiescent" periods (*squares*).

(central wavelengths of 1.25, 1.65, and 2.20 μm) observations were carried out with the IRCAM3 array on the United Kingdom Infrared Telescope (UKIRT) on Mauna Kea on 1994 May 10, 13, and 17, all between 2030 and 2130 UT. The JCMT data were analyzed in a standard manner (see, e.g., Stevens et al. 1994). The data collected in the H band and at 1.1 mm are plotted in Figures 1*d* and 1*e*. The analysis of the UKIRT data was difficult due to the superposition of the nonthermal nuclear emission on the thermal emission of the host galaxy. A circle of radius 5" around the nucleus was used to determine the flux of radiation from the nucleus and from the standard star used to calibrated the flux, while an area of sky with no detected sources determined the background sky level. This flux thus contains some "contamination" from thermal emission from the host galaxy. We subtract from our fluxes the galaxy contribution (J, H, and K fluxes of 7.2, 8.2, and 8.2 mJy, respectively) determined by Makino et al. (1987), who observed with UKIRT using a photometer with an aperture similar to our effective aperture. The uncertainties assigned to our IR flux densities reflect the error associated with determining the value for the pointlike nucleus in the presence of the host galaxy.

The radio data in Figure 1*f* is from the University of Michigan 26 m telescope (UMRAO, Aller et al. 1985). The source was monitored at 4.8, 8.0, and 14.5 GHz. Figure 1*f* shows the 14.5 GHz data, including a flux point on May 14. The points in each subplot closest to May 15, when supplemented by an *ASCA* observation on May 16, form the basis for a flaring state spectrum of Mrk 421 Comparing this with a spectrum formed from data taken during more quiescent periods can significantly constrain emission models.

3. THE MULTIWAVELENGTH SPECTRUM

The spectral information from these observations is summarized in Figure 2. The two types of points represent the "quiescent" flux level as well as those measurements taken within a few days of May 15, the peak of the TeV flare. Table 1 repeats much of this information with explicit dates and flux values.

The TeV (10^{27} Hz) points were calculated from the integral flux assuming a spectrum with photon index α = 2.0 using the flux values given by Schubnell et al. (1995) and Kerrick et al. (1995). The 100 MeV quiescent spectrum was calculated using all available Mrk 421 data from 1991 July through 1994 April since the lack of variability indicates little change in spectrum over that time. Again an α = 2.0 power law is assumed within the individual bins. The flare state utilizes all data from the week of May 10–17 since, again, little variability was evident. The binning is slightly different than the quiescent points to accommodate the low number of counts (25 source counts for the entire week). The 30 MeV through 4 TeV quiescent data are consistent with a single power law of index around 2.0. In the flaring state, however, the variability appears much less pronounced as gamma-ray energy decreases, indicating a possible spectral hardening.

The *ASCA* flare spectrum is from the fits detailed in Takahashi et al. (1995). The quiescent spectrum is from an observation taken 1993 May 10/11. Both spectra were calculated using the the XSPEC package (Shafer et al. 1990). The plotted flux values include a 20% systematic error in absolute flux determination.

The general features of the radio-through-UV portion of both the quiescent and flaring states of Mrk 421 follow a shape typical of BL Lac objects (see, e.g., Rudnick 1987). The greater variability at the X-ray energies, which in other BL Lac flaring events has been observed to precede lower-energy variability, has been attributed to shocks propagating along the jet (see, e.g., Marscher & Gear 1985). The most interesting feature of the spectra in Figure 2 comes from comparing the higher energy gamma-ray component with the lower energy synchrotron component. There is clearly less variability below the breaks at UV and 100 MeV gamma-ray energies than there is above the break (at X-ray and TeV energies), suggesting that the variability of the X-ray and TeV components are correlated.

4. DISCUSSION

The distinctive multiwaveband variations of the 1994 May high-energy flare of Mrk 421 lead directly to a theoretical interpretation. As emphasized by Makino et al. (1987), the multiwaveband spectrum appears continuous from radio to X-ray frequencies. Since the radio emission has been clearly identified as incoherent synchrotron radiation, it appears that the X-rays are as well. This requires that the electron energy distribution extends to Lorentz factors $\gamma_{max} \sim 3 \times 10^6[E(\mathrm{keV})/(B\delta)]^{1/2}$, where B is the magnetic field strength in gauss and δ is the Doppler factor caused by a combination of relativistic bulk motion of the emitting plasma and the redshift of the host galaxy. Since one expects magnetic fields near the base of a jet to be within an order of magnitude of 1 G (see, e.g., Marscher & Gear 1985), electrons with energies ~1 TeV are required to produce the synchrotron X-rays. These same electrons are capable of producing the observed TeV γ-rays via inverse Compton scattering either of the synchrotron photons (synchrotron self-Compton, or SSC, emission; see, e.g., Bloom & Marscher 1993) or of an external soft photon field (see, e.g., Dermer, Schlickeiser, & Mastichiadis 1992; Sikora, Begelman, & Rees 1994).

If a change occurs only in the upper energy cutoff to the relativistic electron distribution, without affecting either the magnetic field or the normalization of the electron energy distribution, only emission at the highest frequencies will be affected significantly. For example, an increase in the upper cutoff energy would cause a synchrotron flare to occur at X-ray frequencies, and a (first-order) self-Compton flare at very high

TABLE 1

LOG OF OBSERVATIONAL DATA PLOTTED IN FIGURE 2

Observatory	log Frequency	νF_ν (ergs cm^{-2} s^{-1})	Observation Date	Comment
Michigan	9.68	$3.70 \pm 0.34 \times 10^{-14}$	1994 Apr 12	
	9.90	$5.04 \pm 0.80 \times 10^{-14}$	1994 Apr 11	
	10.16	$8.85 \pm 0.15 \times 10^{-14}$	1994 Apr 10	
	9.68	$3.55 \pm 0.05 \times 10^{-14}$	1994 May 10	
	9.90	$5.04 \pm 0.48 \times 10^{-14}$	1994 May 19	
	10.16	$7.54 \pm 0.29 \times 10^{-14}$	1994 May 14	
JCMT	11.18	$4.20 \pm 0.90 \times 10^{-13}$	1994 Apr 11	
	11.36	$5.08 \pm 0.69 \times 10^{-13}$	1994 Apr 11	
	11.44	$6.28 \pm 0.82 \times 10^{-13}$	1994 Apr 11	
	11.18	$<3.75 \times 10^{-13}$	1994 May 15	3 σ upper limit
	11.36	$<7.62 \times 10^{-13}$	1994 May 15	3 σ upper limit
	11.44	$8.19 \pm 2.46 \times 10^{-13}$	1994 May 15	
UKIRT	14.14	$5.13 \pm 0.92 \times 10^{-11}$	1994 May 10	no earlier data
	14.26	$6.73 \pm 0.92 \times 10^{-11}$	1994 May 10	no earlier data
	14.39	$7.78 \pm 1.42 \times 10^{-11}$	1994 May 10	no earlier data
	14.14	$4.22 \pm 0.80 \times 10^{-11}$	1994 May 17	
	14.26	$5.54 \pm 1.05 \times 10^{-11}$	1994 May 17	
	14.39	$4.27 \pm 1.24 \times 10^{-11}$	1994 May 17	
IUE	15.36	$8.97 \pm 0.52 \times 10^{-11}$	1994 Apr 11	
	15.36	$8.84 \pm 0.52 \times 10^{-11}$	1994 May 15	
ASCA	17.23	$5.74 \pm 1.00 \times 10^{-11}$	1993 May 10	20% systematic error
	17.73	$2.84 \pm 0.49 \times 10^{-11}$	1993 May 10	20% systematic error
	18.38	$1.15 \pm 0.20 \times 10^{-12}$	1993 May 10	20% systematic error
	17.23	$1.93 \pm 0.39 \times 10^{-10}$	1994 May 16	20% systematic error
	17.60	$2.09 \pm 0.43 \times 10^{-10}$	1994 May 16	20% systematic error
	18.38	$1.75 \pm 0.54 \times 10^{-11}$	1994 May 16	20% systematic error
EGRET	22.08	$2.07 \pm 0.89 \times 10^{-11}$	1991 Jun–1994 Apr	
	22.42	$1.64 \pm 0.41 \times 10^{-11}$	1991 Jun–1994 Apr	
	22.90	$2.97 \pm 0.52 \times 10^{-11}$	1991 Jun–1994 Apr	
	23.48	$2.64 \pm 0.69 \times 10^{-11}$	1991 Jun–1994 Apr	
	24.16	$7.06 \pm 3.63 \times 10^{-11}$	1991 Jun–1994 Apr	
	22.20	$<4.75 \times 10^{-11}$	1994 May 10–17	2 σ upper limit
	22.68	$<3.27 \times 10^{-11}$	1994 May 10–17	2 σ upper limit
	23.20	$6.36 \pm 2.48 \times 10^{-11}$	1994 May 10–17	
	24.12	$2.24 \pm 1.37 \times 10^{-10}$	1994 May 10–17	
Whipple	26.71	$2.86 \pm 0.57 \times 10^{-11}$	1993 Dec–1994 Apr	30% systematic error
	26.71	$2.37 \pm 0.36 \times 10^{-10}$	1994 May 15	

NOTES.—All quiescent points with the exception of the IR data are well separated in time from the flare data. Much of the quiescent data is nearly simultaneous.

γ-ray energies. The optical-ultraviolet and lower energy γ-ray emission would be increased only slightly. This is precisely what is observed. We therefore conclude that the observed X-ray/TeV γ-ray flare in Mrk 421 was caused by variations in the maximum energy of the electron distribution, i.e., it represents a sudden, short-lived increase in the efficiency of acceleration of the highest energy electrons. This qualitative model, while consistent with an interpretation of the multiwaveband spectrum in terms of SSC emission, does not rule out other sources for the seed photons which are scattered to TeV energies.

The timescale of variability of the TeV flare places an additional constraint on this interpretation. The rising portion of the flare varies on a 2 day timescale, and the decaying portion on a time scale $(\Delta t)_{\rm decay} \lesssim 12$ days (Kerrick et al. 1995), where $(\Delta t)_{\rm decay}$ is the timescale for the flux to decrease by at least a factor of 2. In order for this to be consistent with emission from electrons, the comoving-frame electron energy-loss timescale $(\Delta t)_{\rm closs} \equiv |\dot{\gamma}/\gamma|^{-1} \lesssim \delta(\Delta t)_{\rm decay}$. Because the electron energy-loss timescale is at least as short as the synchrotron energy-loss timescale, we find that only electrons with $\gamma \gtrsim 750/\{B^2\delta[\Delta t_{\rm decay}/12 \text{ days}]\}$ will lose a large fraction of their energy during a time scale of $\Delta t_{\rm decay}$. This is certainly consistent with the observations, and could also account for the absence of gamma-ray variability in the EGRET energy range, because the electrons making the 100 MeV–GeV emission cool on longer time scales. If such an interpretation is correct, then the variability time scales will increase with decreasing photon energies.

The time variability strongly constrains hadronic models, which require either large radiation field energy densities (Mannheim 1993) or dense thermal background particle densities (Bednarek 1993) to initiate high-energy flares through photo-hadron processes or secondary production, respectively. A large photon density will increase the optical depth to photon-photon pair attenuation, so the requirement of short-term variability and gamma-ray transparency limits the allowed parameters of a photo-hadron model. Similarly, the requirement that the medium is optically thin to Compton scattering limits the allowed density in a model based on secondary production. The fact that the TeV emission varies strongly, whereas the 100 MeV–GeV emission is consistent with a steady flux, contrasts with the behavior predicted in the homogeneous pair cascade model of Blandford & Levinson (1995). They argue that in order for TeV radiation to avoid attenuation, its γ-ray photosphere has to be at greater distances from the central supermassive black hole. Consequently, higher energy gamma-ray flux varies more slowly than the flux at lower energies.

Zdziarski & Krolik (1993) show that the photon spectrum produced by cooling electrons which scatter photons in the Thomson and Klein-Nishina regimes is unbroken if the injection electron spectral index $\Gamma_i = 2$, which yields a photon flux with spectral index $s = 2$. If the density of the medium is sufficiently dilute that a pair cascade in the Klein-Nishina regime does not occur, this could explain the quiescent spectrum of Mrk 421 in Figure 2, which shows $s \cong 2$. The photon spectral index produced by a cooling electron distribution which scatters photons in the Thomson regime is given by $s_T = 1 + \Gamma_i/2$, whereas $s_{KN} = \Gamma$ in the Klein-Nishina regime (provided no cascade occurs). This would imply a spectral hardening between the Thomson and Klein-Nishina regime when $\Gamma_i < 2$, and a spectral softening when $\Gamma_i > 2$. Because of the large statistical uncertainties in the EGRET data alone, precise tests for the predicted spectral hardening of the flaring data is inconclusive. Additional correlated observations could potentially determine if the spectrum softens or hardens in the high-energy regime, and test whether the TeV flare represents an independent component or a smoothly varying continuum.

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