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DETECTION OF GAMMA RAYS WITH $E > 100$ MeV FROM BL LACERTAE

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ABSTRACT

We present evidence for the first detection of gamma rays from the extragalactic object BL Lacertae. Observations taken with EGRET on the *Compton Gamma Ray Observatory* between 1995 January 24 and 1995 February 14 indicate a 4.4 σ excess from the direction of BL Lacertae. The corresponding flux is $(40 \pm 12) \times 10^{-8}$ photons cm^{-2} s^{-1} above 100 MeV. The combination of all previous observations where BL Lacertae was in EGRET's field of view result in a 2.4 σ excess and a corresponding 95% confidence upper limit of 14×10^{-8} photons cm^{-2} s^{-1}, indicating that its gamma-ray emission is variable, at least on timescales of several months. Observations of BL Lacertae between 22 and 375 GHz were also taken between 1995 January 24 and 1995 February 14, and the flux levels for those measurements are similar to the historical average values for this object. A deep exposure on BL Lacertae with the Whipple Observatory 10 m gamma-ray telescope shows no evidence of emission above 350 GeV during a period 9 months after the EGRET observations. The 99.9% confidence flux upper limit derived from these observations is 0.53×10^{-11} photons cm^{-2} s^{-1}, which implies a large reduction in the gamma-ray emission of BL Lacertae between EGRET and Whipple Observatory energies. This reduction should result from processes intrinsic to BL Lacertae because it is near enough to Earth that intergalactic background IR fields should not significantly reduce the flux of gamma rays to which the Whipple Observatory telescope is sensitive.

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

1. INTRODUCTION

Since the launch of the *Compton Gamma Ray Observatory* (*CGRO*), EGRET has detected more than 50 active galactic nuclei (AGNs) (e.g., Thompson et al. 1995; von Montigny et al. 1995) in the energy range from 30 MeV–30 GeV. Of these, nearly all are characterized by one or more of the following emission features: flat spectrum, core-dominated, superluminal radio emission, rapid optical variability, and high optical polarization. The AGNs that exhibit these features are often lumped together into a class called "blazars." BL Lacertae (BL Lac) objects, for which BL Lacertae (2200+420) is the prototype, fall into the blazar class, and they make up a significant fraction of the AGNs detected by EGRET (von Montigny et al. 1995). In addition, the only two extragalactic objects that have been detected as emitters of gamma rays above 300 GeV, Markarian 421 (Punch et al. 1992) and Markarian 501 (Quinn et al. 1996), are both BL Lac objects.

The dominant radiation from blazars is widely believed to arise from relativistic jets that are viewed at small angles to their axes (e.g., Blandford & Königl 1979). This view is supported by EGRET and Whipple Observatory observations of high fluxes above 1 and 300 GeV, respectively, coupled with the short-term variability of the gamma-ray emission (e.g., Kniffen et al. 1993; Mattox et al. 1993; Quinn et al. 1996; Buckley et al. 1996). The gamma-ray emission must be beamed in order to reduce the optical depth from photon-photon pair production that results if the emission is isotropic (Mattox et al. 1993). The broadband radiation spectrum appears to consist of two parts: a synchrotron spectrum that spans radio to optical-ultraviolet wavelengths (and even to X-rays in some objects), and a high-energy part that can extend from X-rays to gamma rays. Plots of the power spectra (i.e., νF_ν) for blazars clearly demonstrate the separation of the two spectral regimes. Cutoffs observed at optical to X-ray wavelengths (e.g., Impey & Neugebauer 1988) mark the end of the synchro-

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tron spectrum, and the relatively flat spectrum of the high-energy component does not connect smoothly with the synchrotron region (von Montigny et al. 1995; Worrall & Wilkes 1990), indicating a separate production mechanism. The majority of the models that attempt to explain the high-energy emission posit that the high-energy photons are produced from inverse-Compton scattering of lower energy photons by beamed relativistic electrons. The low-energy photon fields could arise from synchrotron continuum photons within the jet (e.g., Königl 1981; Ghisellini, Maraschi, & Treves 1985), from ambient photons from the accretion disk that enter the jet directly (e.g., Dermer, Schlickeiser, & Mastichiadis 1992), or after scattering or reprocessing (e.g., Blandford 1993; Sikora, Begelman, & Rees 1994). In addition to the inverse-Compton models, models in which the high-energy photons are produced by proton-initiated cascades have been proposed (e.g., Mannheim 1993). No consensus has been reached regarding which among these models is correct.

BL Lacertae exhibits all of the features listed above that characterize the EGRET AGNs (e.g., Stickel et al. 1991; Vermeulen & Cohen 1994; Pearson & Readhead 1988; Moore et al. 1982), so it would seem to be a strong candidate for gamma-ray emission in EGRET's energy range. Unfortunately, its position ($l = 92\fdg6$, $b = -10\fdg4$) is rather near the Galactic plane, which makes its detection more difficult for EGRET because of the diffuse Galactic emission. BL Lacertae also would seem to be a good candidate for very high energy (VHE, $E > 300$ GeV) emission because both Markarian 421 and Markarian 501 are BL Lac objects that are radio-loud ($S \gtrsim 1$ Jy) and have flat radio spectra. Also, BL Lacertae is relatively nearby ($z = 0.069$), so intergalactic absorption by pair-production on infrared background fields (Gould & Schréder 1967; Stecker, de Jager, & Salamon 1993) should not significantly affect gamma rays detectable by the Whipple Observatory telescope. Consequently, if gamma rays are not seen at VHE energies, that should result from processes intrinsic to BL Lacertae.

2. OBSERVATIONS AND ANALYSIS

2.1. *EGRET Results*

The EGRET instrument uses an anticoincidence system to discriminate against charged particles, a particle-track detector consisting of spark chambers with interspersed high-Z material to convert gamma rays into electron-positron pairs, a triggering telescope that detects the presence of charged particles with the correct direction of motion, and an energy-measuring NaI(Tl) calorimeter. EGRET is sensitive to gamma rays in the energy range from about 30 MeV to 30 GeV. Its effective area is approximately 1500 cm^2 from 0.2 to 1.0 GeV and lower outside this range. The relative sensitivity of the system decreases in directions away from the instrument axis, falling to about 50% at 18° and 30% at 30° off the axis when operated in the wide-field mode. The point-spread function for incident gamma rays, which limits the spatial resolution of the imaging, is given by a Gaussian distribution that is nearly independent of incident direction, having a half-width at half-maximum that falls from $2\fdg8$ at 100 MeV to $0\fdg2$ near 10 GeV. Detailed descriptions of the EGRET instrument (Hughes et al. 1980; Kanbach et al. 1988, 1989; Hartman et al. 1992) and its calibration both before and after launch (Thompson et al. 1993) can be found elsewhere.

In viewing period (VP) 410.0 (1995 January 24–1995 February 14), *CGRO* was pointed at $(\alpha, \delta) = (337\fdg33, 18\fdg83)$, $24\fdg12$ degrees from the position of BL Lacertae. The data from this pointing were analyzed with maximum likelihood techniques (Mattox et al. 1996) to determine the positions, significance, flux, and spectra of objects within the field of view, taking into account the contributions of the isotropic and Galactic diffuse gamma-ray emission (Hunter et al. 1997). The EGRET data taken during that pointing revealed a 4.4 σ excess at a position essentially identical to that of BL Lacertae. The flux at the position of BL Lacertae for these observations is $(40 \pm 12) \times 10^{-8}$ photons cm^{-2} s^{-1} above 100 MeV. Systematic uncertainties are expected to be significantly less than the statistical errors (Thompson et al. 1993), so the quoted errors are statistical only. The corresponding luminosity, if the emission is isotropic, is $\mathscr{L} = 6.0 \times 10^{44}$ ergs s^{-1}, assuming a Friedmann universe with $q_0 = \frac{1}{2}$ and $H_0 = 75$ km s^{-1} Mpc^{-1}. This is toward the low end of the luminosity distribution for EGRET sources, which range from about 2×10^{44} to more than 10^{49} ergs s^{-1} (von Montigny et al. 1995). As explained in § 1, the gamma-ray emission from blazars like BL Lacertae is unlikely to be isotropic, so the actual luminosity is probably much less than this.

While the position of maximum likelihood is the best estimate of the source location, the true source of the gamma rays need not be located there. To investigate this possibility, we search for other likely sources of gamma rays within the 95% confidence region for the source's true location, defined by the points where the maximum likelihood test statistic of the excess drops to 6.0 below the peak value (i.e., where the significance is 2.45 σ below the peak value). As shown in Figure 1, the confidence region is quite large for this detection (an ellipse with semimajor axis $\sim 80'$ and semiminor axis $\sim 70'$) because of the relatively weak level of the detection. A search of High-Energy Astrophysics Science Archive Research Center (HEASARC) archives revealed 15 radio sources from the 87 Green Bank 4.84

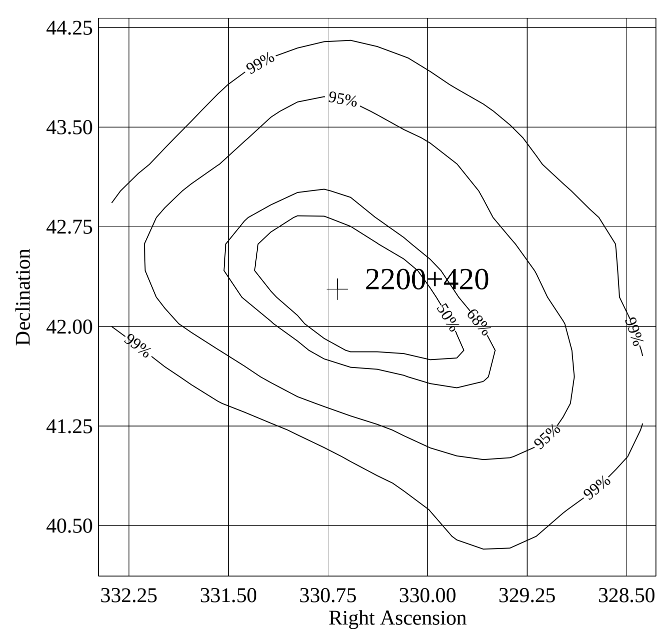

FIG. 1.—Maximum likelihood results for EGRET observations of BL Lacertae (2200+420) during viewing period 410.0. The contour lines show the confidence intervals for the true position of the source.

GHz radio survey (Gregory & Condon 1991) within the 95% confidence region. With a flux of 3500 mJy, BL Lacertae is by far the brightest radio source in the error box. None of the others have a flux above 80 mJy. Also, the only X-ray source in the 95% confidence region for this detection in HEASARC archival databases of the *Einstein*, *ASCA*, and *ROSAT* X-ray satellites is BL Lacertae. Finally, no AGNs besides BL Lacertae are found in the error box (Hewitt & Burbidge 1993; Véron-Cetty & Véron 1993). The lack of any other prominent radio or X-ray sources in the EGRET error box, combined with the fact that all of the identified high Galactic latitude EGRET sources are AGNs of the blazar class, makes it very likely that the gamma-ray flux detected in this region arises from BL Lacertae. Definitive confirmation would be obtained if an episode of variable emission were detected with correlated emission at another wavelength.

BL Lacertae was also in the EGRET field of view several times before VP 410.0. As shown in Table 1, none of these observations revealed a significant excess, although only VP 034.0 and 203.0 have flux limits that are inconsistent with the phase 4 detection. The combined observations in phases 1, 2, and 3 give a 2.4 σ excess corresponding to a 95% confidence upper limit of 14×10^{-8} photons cm^{-2} s^{-1}. Thus the gamma-ray emission from BL Lacertae does seem to be variable, as has been seen in many other blazars detected by EGRET (e.g., Kniffen et al. 1993; Mattox et al. 1993).

2.2. *Whipple Observatory Results*

The VHE observations reported in this paper were made with the atmospheric Cerenkov imaging technique (Cawley & Weekes 1995), using 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, is mounted in the focal plane of the reflector and records images of atmospheric Cerenkov radiation from air showers produced by gamma rays and cosmic rays (Cawley et al. 1991). The Cerenkov light pool for air showers at the telescope's elevation has a relatively flat, circular distribution with a radius of 120 m, beyond which the light intensity drops off rapidly. Therefore, the area over which the telescope can detect air showers is very large ($\gtrsim \pi r^2 = 4.5 \times 10^8$ cm^2). The energy threshold of the observations reported here is 350 GeV.

Cerenkov light images are classified according to their angular size and orientation. Gamma-ray images are typically smaller and more elliptical than background hadronic images. Also, the gamma-ray images that originate from a putative source will be preferentially oriented with their major axes pointing toward the source location. The orientation angle α, defined as the angle between the major axis of the ellipse and the source position, is used to select these events. The basic data selection was based on the Supercuts criteria described elsewhere (Reynolds et al. 1993). However, some modifications have been made to account for recent changes to the telescope that reduced the detector energy threshold and increased the background from event triggers caused by fluctuations in night-sky background light and events caused by Cerenkov signals from single local muons. The criteria used were optimized using observations of the Crab Nebula in the 1994–1995 observing season and are described in detail elsewhere (Catanese et al. 1996).

The majority of the observations reported in this paper were taken in the TRACKING mode, in which the source is tracked continuously without taking data off-source in a control region. Events with orientations such that they are not from the direction of the source are used to determine the background level. The on-source events are those with α-parameter values between 0° and 10°, while the off-source events have $\alpha = 15°–65°$. A small subset of the observations were taken in the more standard ON/OFF mode, in which the object is tracked on-source and compared to a control observation taken at the same declination as the object but offset in right ascension so that both data sets cover the same region of the sky in altitude and azimuth. The ON/OFF observations were taken to determine the factor that converts the off-source events taken in the TRACKING mode (i.e., events with $\alpha = 15°–65°$) to a background estimate. This factor is 5.59 ± 0.40 where the errors are statistical.

Between 1995 October 17 and 1995 November 25, 39.1 hr of data were collected on BL Lacertae under good weather conditions. All data were taken when BL Lacertae was at elevations above 55°. The TRACKING mode observations resulted in 1194 on-source events and an estimated back-

TABLE 1

EGRET OBSERVATIONS OF BL LACERTAE

VP	Start	End	Aspect	σ	Flux[a] ($E > 100$ MeV)
002.0......	1991 May 30	1991 Jun 08	23.21	2.2	<39
007.1......	1991 Aug 08	1991 Aug 15	21.95	0.0	<25
034.0......	1992 Jul 16	1992 Aug 06	17.96	0.0	<16
203.0......	1992 Dec 01	1992 Dec 22	18.41	0.9	<18
212.0......	1993 Mar 09	1993 Mar 23	23.80	2.5	<47
302.0......	1993 Sep 07	1993 Sep 09	18.58	0.5	<108
303.2......	1993 Sep 22	1993 Oct 01	18.58	0.5	<29
303.7......	1993 Oct 17	1993 Oct 19	18.58	0.0	<80
318.1......	1994 Feb 01	1994 Feb 08	26.03	0.4	<53
328.0......	1994 May 04	1994 May 31	29.46	1.5	<67
331.0......	1994 Jun 07	1994 Jun 10	29.46	2.8	<165
331.5......	1994 Jun 14	1994 Jun 18	29.46	0.0	<53
333.0......	1994 Jul 05	1994 Jul 12	29.46	1.5	<78
401.0......	1994 Oct 04	1994 Oct 18	26.98	0.0	<30
410.0......	1995 Jan 24	1995 Feb 14	24.12	4.4	40 ± 12

[a] Fluxes are in units of 10^{-8} photons cm^{-2} s^{-1}. Flux limits are at the 95% confidence level.

ground of 1272 events. The ON/OFF observations resulted in 205 on-source events and 228 background events. Combining these data sets, we obtain a significance of $-0.99\ \sigma$, indicating no signal in the data. From the number of on-source and off-source events, we set an upper limit on the mean number of gamma rays, $N_{\rm ul}$, using the method of Helene (1983) and convert to a flux limit using the equation:

$$I(>E) < \frac{N_{\rm ul}}{(A_{\rm eff})(T_{\rm live})}, \tag{1}$$

where $A_{\rm eff}$ is the effective area of the telescope that accounts for factors such as the efficiency of the analysis for detecting gamma rays, and $T_{\rm live}$ is the live time of the data collection. Monte Carlo studies indicate that for a gamma-ray spectrum of $dN/dE \propto E^{-2.4}$, $A_{\rm eff}$ is 3.5×10^8 cm^2, and the energy threshold for the flux limit is 350 GeV. A spectral index of 2.4 was used in the calculation of $A_{\rm eff}$ and the energy threshold because that was the estimated spectral index of the TeV gamma-ray spectrum for the Crab Nebula (Vacanti et al. 1991), the standard candle for VHE gamma-ray observations. Using the above procedures, we set the upper limit at the 99.9% confidence level to be $I(E > 350\ {\rm GeV}) < 0.53 \times 10^{11}$ cm^{-2} s^{-1}. This corresponds to an upper limit of about 0.06 times the Crab Nebula flux.

3. DISCUSSION

Observations of BL Lacertae were taken at radio and millimeter-submillimeter wavelengths during and near the EGRET observations and are shown in Figure 2. Observations at 22 and 37 GHz were made at the Metsähovi Radio Research Station, Finland (Teräsranta et al. 1992). The 150, 230, 270, and 375 GHz measurements were made with the James Clerk Maxwell Telescope on Mauna Kea (Stevens et al. 1994). During VP 410.0, the fluxes at these wavelengths were at about the average levels for BL Lacertae and also were similar to their values during the other EGRET observation periods when BL Lacertae was in the field of view but was not detected (Stevens et al. 1994). A few months after the EGRET observations, overlapping the time of the Whipple observations, the 22 to 375 GHz emission of BL Lacertae had approximately doubled. Because the EGRET observations do not continue after VP 410.0, it cannot be determined whether the high state of radio emission in BL Lacertae is correlated with the apparent increase in gamma-ray emission that resulted in the EGRET detection.

In Figure 3 we show the spectral energy distribution, plotted as the power per logarithmic bandwidth, νF_ν, versus log ν. For this plot, the EGRET data have been divided to give flux estimates in four energy bands: 30–100 MeV, 100–300 MeV, 300–1000 MeV, and 1–10 GeV. The error bars for these points are statistical. The EGRET photon spectrum derived from these points is

$$\frac{dN}{dE} = (4.3 \pm 1.2) \times 10^{-10}\left(\frac{E}{1\ {\rm GeV}}\right)^{-2.2 \pm 0.3} \times \text{photons cm}^{-2}\ \text{s}^{-1}\ \text{MeV}^{-1}\ .$$

The errors quoted are statistical, and additional unknown systematic errors exist, particularly because of this source's proximity to the Galactic plane. The Whipple Observatory flux limit is converted to a single-point upper limit by assuming the spectrum follows a power law of the form

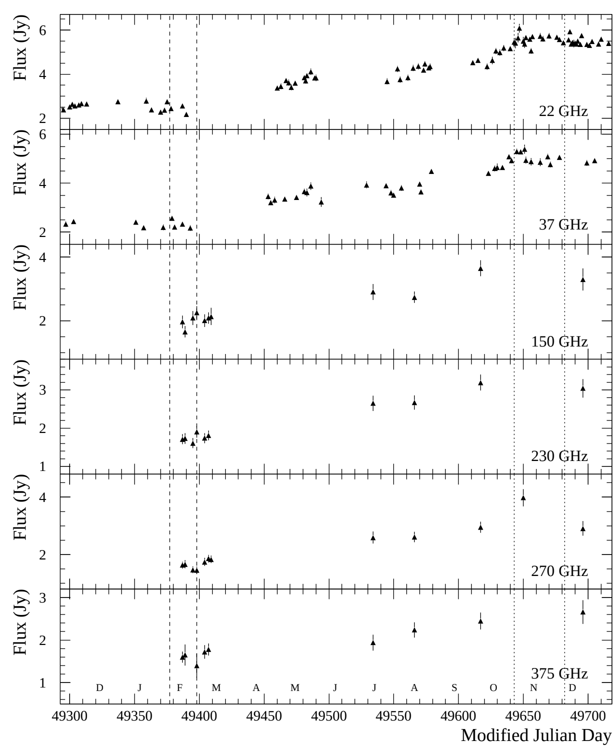

FIG. 2.—Light curves for BL Lacertae for the period 1994 November to 1995 December. The dashed vertical lines indicate the EGRET viewing period 410, where the EGRET detection of BL Lacertae occurred. The regions between the dotted lines indicate the times of the Whipple Observatory observations. The letters at the bottom of the plot indicate the beginning of each month.

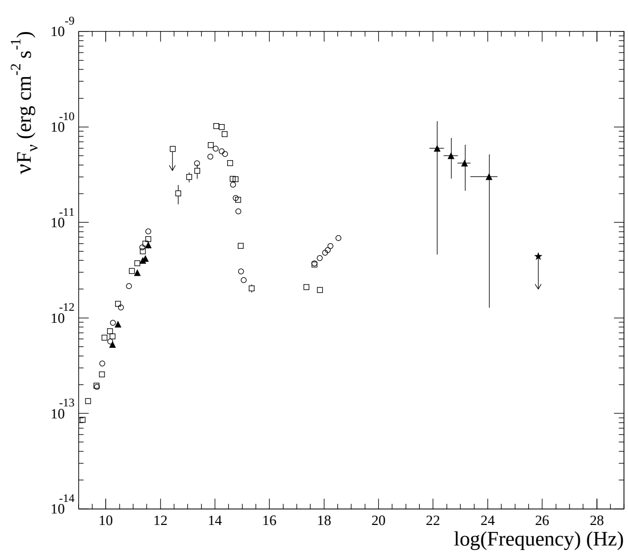

FIG. 3.—Spectral energy distribution of BL Lacertae. The simultaneous EGRET, radio, and millimeter-submillimeter observations from this work are indicated by the filled triangles. The Whipple Observatory upper limit is indicated by the filled star. The open squares are archival data indicative of the mean flux for BL Lacertae. Radio to submillimeter is from Stevens et al. (1994) and NED, far-infrared is from Impey & Neugebauer (1988), near-IR to optical is from Cruz-Gonzalez & Huchra (1984), ultraviolet is from Edelson et al. (1992) and Paltani & Courvoisier (1994), and X-ray is from Perlman et al. (1996), and from Ciliegi, Bassani, & Caroli (1993, 1995). The open circles are data taken contemporaneously in 1988, adapted from Kawai et al. (1991).

$E^{-2.4}$, which is what was used in the upper limit calculation (see § 2.2). The radio and millimeter-submillimeter points are the average of the measurements taken at each frequency during the EGRET observation period. The other data points in the νF_ν plot are archival, and, although they are probably a reasonable estimate of the average energy distribution for this object, they may not be completely indicative of the energy distribution of BL Lacertae when it was detected by EGRET.

The radio through UV part of the spectrum is consistent with synchrotron emission (Kawai et al. 1991). The emission at X-ray energies and above appears to form a distinct part of the spectrum because it does not lie on the continuous connection between infrared and optical/UV, and the X-rays have a very different slope than the optical to UV part of the spectrum. As with the other EGRET-detected BL Lac objects (von Montigny et al. 1995), the EGRET points are comparable to the highest points in the power spectrum at any wavelength, but the gamma-ray emission does not dominate the power spectrum as it does in many of the non–BL Lac EGRET blazars (e.g., 3C 279).

The Whipple Observatory flux upper limit clearly indicates a large reduction in the power output between the EGRET and Whipple Observatory energy ranges. If we assume the gamma-ray spectrum for BL Lacertae is a simple power law between EGRET and Whipple energies (i.e., $dN/dE \propto E^{-\Gamma}$), the EGRET detection and the Whipple upper limit imply that the spectral index is limited to the range $\Gamma > 2.4$. This is toward the high end of the range of spectral indices ($\Gamma = 1.4$–3.0) for blazars detected by EGRET (von Montigny et al. 1995), but the EGRET data points in the νF_ν plot can incorporate the Whipple upper limit because of their large uncertainties.

If the gamma-ray spectrum of BL Lacertae does extend to TeV energies with a spectral index greater than 2.4, it would imply a very different power distribution than that of Mrk 421 or Mrk 501, for which the fluxes at TeV energies indicate a comparable power output to those at GeV energies (Buckley et al. 1997; Quinn et al. 1996). Such a difference would be consistent with predictions from inverse-Compton emission models. Both in models where the photon fields that are upscattered originate outside the jet (Sikora et al. 1994) and in those where the fields are part of the jet's synchrotron spectrum (Marscher & Travis 1996; Bednarek, Mastichiadis & Kirk 1996), the location of the break in the synchrotron spectrum determines the maximum energy of the gamma rays from an object. The synchrotron cutoff is in the optical/UV range for BL Lacertae, while for Mrk 421 and Mrk 501 the synchrotron emission appears to extend up to X-ray energies (e.g., Macomb et al. 1995; Buckley et al. 1997; Mufson et al. 1984). BL Lacertae's rollover is at a similar location to that of 3C 279, for which Sikora et al. (1994) predict a maximum energy in gamma rays just above the EGRET energy range.

Two other issues less intrinsic to BL Lacertae's central engine may also explain the lack of TeV emission. First, BL Lacertae's emission at EGRET energies appears to be variable, as the sum of the observations previous to VP 410.0 limit the average flux to well below that of VP 410.0. It may be that during the Whipple Observatory observations, BL Lacertae had dropped to a lower level of emission so that the TeV emission fell below the sensitivity threshold of the Whipple Observatory telescope. The Whipple collaboration has observed BL Lacertae repeatedly in the past four years (Kerrick et al. 1995; Quinn et al. 1995) with no evidence of emission, but, given its low duty cycle ($\sim 10\%$), the possibility that a variable TeV component of the gamma-ray emission is occasionally above the Whipple Observatory telescope's threshold sensitivity cannot be ruled out.

Second, to explain the lack of TeV emission from other EGRET sources besides BL Lac objects like Mrk 421, Dermer & Schlickeiser (1994) have suggested that clouds associated with broad-line regions that produce the strong emission lines seen in many AGNs could absorb TeV gamma rays at the source. BL Lac objects would then, in general, be strong candidates for TeV gamma-ray emission because, by definition, they have weak or nonexistent emission lines. In 1995 May, strong Hα- and Hβ-line emission from BL Lacertae was detected for the first time (Vermeulen et al. 1995). Hence, it may be that BL Lacertae does produce TeV gamma rays, but they do not escape the source because of pair production on the radiation from the broad-line region.

In summary, the detection of gamma rays with energies above 100 MeV from BL Lacertae is consistent with EGRET-detected AGNs exhibiting a flat spectrum, core-dominated structure, superluminal radio emission, rapid optical variability, and high optical polarization. It also supports the pattern that radio-selected BL Lac objects, in general, seem more likely to be emitters of high-energy gamma rays than X-ray–selected BL Lac objects (Lin et al. 1996). The many pointings for which there is no detectable emission from BL Lacertae support the tenet that all core-dominated, flat-spectrum AGNs may be high-energy gamma-ray emitters some of the time.

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