

## PREDICTED EXTRAGALACTIC TeV GAMMA-RAY SOURCES

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### ABSTRACT

We suggest that low-redshift X-ray-selected BL Lacertae objects (XBLs) may be the only extragalactic  $\gamma$ -ray sources observable at TeV energies. We use simple physical considerations involving synchrotron and Compton component spectra for blazars to suggest why the observed TeV sources are XBLs, whereas mostly radio-selected BL objects (RBLs) and flat spectrum radio quasars (FSRQs) are seen at GeV energies. These considerations indicate that the differences between XBLs and RBLs cannot be explained purely as relativistic jet orientation effects. We note that the only extragalactic TeV sources that have been observed are XBLs and that a nearby RBL with a very hard spectrum in the GeV range has not been seen at TeV energies. We also note that of the 14 BL Lac objects observed by EGRET, 12 are RBLs, whereas only two are XBLs. We give a list of nearby XBLs that we consider to be good candidate TeV sources and predict estimated TeV fluxes for these objects.

*Subject headings:* gamma rays: theory — BL Lacertae objects: general —

BL Lacertae objects: individual (Markarian 421) — quasars: general

### 1. INTRODUCTION

Over 50 blazars have been detected as  $\gamma$ -ray sources in the GeV energy range by the EGRET detector on the *Compton Gamma-Ray Observatory* (Fichtel et al. 1994; Thompson et al. 1995, 1996). In contrast, only two or three blazars have been detected at TeV energies, only one of which is a detected GeV source. There are many EGRET blazars with differential photon spectra that are  $E^{-2}$  power laws or flatter. These sources would be detectable by telescopes such as the Whipple Telescope in the TeV energy range, assuming that their spectra extrapolate to TeV energies. In this Letter, we address the questions (1) why has only one of the EGRET sources has been detected at TeV energies?, and (2) which blazars are likely to be TeV sources?

We have already addressed part of this problem by pointing out the critical effect of absorption of high-energy  $\gamma$ -rays between the source and Earth by pair-production interactions with the intergalactic infrared background (Stecker, De Jager, & Salamon 1992). In a series of papers (Stecker & De Jager 1997 and references therein), we have shown that  $\gamma$ -rays with energies greater than  $\sim 1$  TeV will be removed from the spectra of sources with redshifts  $> 0.1$ . Absorption effectively eliminates flat spectrum radio quasars (FSRQs) as TeV sources. The nearest EGRET quasar, 3C 273, lies at a redshift of 0.16. This source is also a “miniblazar,” which, in any case, has a steep spectrum at GeV energies. The next closest EGRET quasar, 1510–089, has a redshift of 0.361. At this redshift, we estimate that more than  $\sim 99\%$  of the original flux from the source will be absorbed at TeV energies (Stecker & De Jager 1997). Although the source spectra of FSRQs may not extend to TeV energies, their distance alone makes them unlikely candidates as TeV sources. Therefore, we consider

here the more nearby blazars, which are all BL Lacertae objects.

### 2. SYNCHROTRON AND COMPTON SPECTRA OF XBLs AND RBLs

An extensive exposition of blazar spectra has recently been given by Sambruna, Maraschi, & Urry (1996). The spectral energy distributions (SEDs) of blazars were considered by type. With the sequence FSRQs, radio-selected BL Lac objects (RBLs), X-ray-selected BL objects (XBLs), they found a decreasing bolometric luminosity in the radio-to-X-ray region and an increasing frequency for the peak in the SED of the source. Two alternative explanations have been proposed to explain this. There is the “orientation hypothesis,” which states that these sources (or at least the BL Lac objects) have no significant physical differences between them; rather, the differences in luminosity and spectra result from relativistic beaming effects, with the jets of XBLs being observed with larger angles to the line of sight than those of RBLs (Maraschi et al. 1986; Ghisellini & Maraschi 1989; Urry, Padovani, & Stickel 1991; Celotti et al. 1993). In the alternative interpretation, the differences between RBLs and XBLs must be attributed, at least in part, to real physical differences (Giommi & Padovani 1994; Padovani & Giommi 1995; Kollgaard, Gabuzda, & Feigelson 1996; Sambruna et al. 1996).

To understand the spectra of blazars, their SEDs are broken into two parts. The lower frequency part, which can be roughly described by a convex parabolic  $\nu F_\nu$  spectrum, is generally considered to be produced by synchrotron radiation of relativistic electrons in the jet. The higher energy part, which includes the  $\gamma$ -ray spectrum, is usually considered to be produced by Compton radiation from these same electrons. In the SEDs of XBLs, the X-ray emission comes from the

high-energy end of the synchrotron emission, whereas in RBLs, the X-ray emission is from Compton scattering. This situation produces a bimodal distribution in the broad range radio-to-X-ray spectral index,  $\alpha_{rx}$ , which can be used to classify BL Lac objects as XBL-like or RBL-like, or alternatively HBLs (high-frequency peaked BL Lac objects) and LBLs (low-frequency peaked BL Lac objects) (Padovani & Giommi 1995, 1996; Sambruna et al. 1996; Lamer, Brunner, & Staubert 1996).

If real differences exist between RBLs and XBLs, one might suspect that XBLs are more likely to be TeV sources than RBLs. This is because in XBLs (HBLs), there is evidence from the synchrotron SEDs that relativistic electrons are accelerated to higher energies than in RBLs (LBLs) (see, e.g., Sambruna et al. 1996). These electrons, in turn, should Compton-scatter to produce higher energy  $\gamma$ -rays in XBLs than in RBLs.

In fact, of the over 50 blazars seen by EGRET in the GeV range, including 14 BL Lac objects (based on the observations given by Thompson et al. 1995, 1996; Vestrand, Stacy, & Sreekumar 1995; and Fichtel et al. 1996), only two, Mrk 421 and PKS 2155–304, are XBLs.<sup>1</sup> In contrast, *only* XBLs have been seen at TeV energies. Thus, the  $\gamma$ -ray observations lend further support to the LBL-HBL spectral difference hypothesis. We will consider this point quantitatively below.

### 3. BL LACERTAE OBJECTS AS TeV GAMMA-RAY SOURCES

In accord with our estimates of intergalactic absorption, the only extragalactic TeV  $\gamma$ -ray sources that have been reported are nearby BL Lac objects. The GeV  $\gamma$ -ray source Mrk 421, whose redshift is 0.031, was the first blazar detected at TeV energies (Punch et al. 1992). A similar BL Lac object, Mrk 501, whose redshift is 0.034, was detected more recently (Quinn et al. 1996), although it was too weak at GeV energies to be detected by EGRET. Another BL Lac object, 1ES 2344+514, whose redshift is 0.044, was recently reported by the Whipple group as a tentative detection (Schubnell 1996). This could be the third BL Lac object at a redshift less than 0.05 detected at TeV energies.

These observations are suggestive when considered in the context of radio and X-ray observations of BL Lac objects. If  $\log(F_X/F_r) < -5.5$  for a BL Lac object, the source falls in the observational category of an RBL, whereas if  $\log(F_X/F_r) > -5.5$ , the object is classified as an XBL (Giommi & Padovani 1994). Using this criterion, *only XBLs have been detected at TeV energies, whereas the RBL ON 231* ( $z = 0.1$ ), *with the hardest observed GeV spectrum* (Sreekumar et al. 1996), *was not seen at TeV energies*. We will show below that this result may be easily understood in the context of simple synchrotron self-Compton (SSC) models. We further predict that only nearby XBLs will be extragalactic TeV sources.

### 4. SSC MODELS OF BL LACERTAE OBJECTS

The most popular mechanisms proposed for explaining blazar  $\gamma$ -ray emission have involved either (1) the SSC mech-

anism, Compton scattering of synchrotron radiation in the jet with the same electrons producing both radiation components (Bloom & Marscher 1993 and references therein), or (2) Compton scattering from soft photons produced external to the jet in a hot accretion disk around a black hole at the active galactic nucleus (AGN) core (Dermer & Schlickeiser 1993), possibly scattered into the jet by surrounding clouds (Sikora, Begelman, & Rees 1994).

During the simultaneous X-ray and TeV flaring of the XBL Mrk 421 in May of 1994, it was observed that the flare/quiescent flux ratios were similar for both X-rays and TeV  $\gamma$ -rays, whereas the flux at and below UV frequencies and that at GeV energies remained constant. This observation can be understood in the context of an SSC model with the high-energy tail of the radiating electrons being enhanced during the flare and the low-energy electron spectrum remaining roughly constant (Macomb et al. 1995; Takahashi et al. 1996). It is plausible to assume that the SSC mechanism operates generally in BL Lac objects, since these objects (by definition) usually do not show evidence of emission-line clouds to scatter external seed photons.

The fact that the TeV photons did not flare much more dramatically than the X-rays implies that the enhanced high-energy electrons were scattering off a part of the synchrotron SED that remained constant (Takahashi et al. 1996). This leads to the important conclusion that the TeV  $\gamma$ -rays are not the result of the inverse-Compton scattering off the X-rays, even though the synchrotron-produced luminosity peaked in the X-ray range.

This observation can be understood if the TeV  $\gamma$ -rays were produced by Compton scattering off photons in the UV and optical regions of the SED in which the luminosity remained constant during the flare. This situation could have occurred during the flare if scatterings off optical and UV photons occurred in the Thomson regime whereas scatterings off the more dominant X-rays would have been suppressed by being in the Klein-Nishina (KN) range. We therefore deduce that during the flare, the transition between the Thomson and KN regimes occurred at a soft photon energy of  $\sim 10$  eV. Thus, scatterings off X-ray photons would have occurred in the extreme KN limit.

The boundary between Compton scattering in the Thomson and KN limits is given by the condition  $\epsilon E_\gamma / \delta^2 m^2 c^4 \sim 1$ , where  $\epsilon$  is the energy of the soft photon being upscattered,  $E_\gamma$  is the energy of the high-energy  $\gamma$ -ray produced, and  $\delta = [\Gamma(1 - \beta \cos \theta)]^{-1}$  is the Doppler factor of the blazar jet. (We denote quantities in the rest system of the source with a prime. Unprimed quantities refer to the observer's frame.) The factor of  $\delta^2$  results from the Doppler boosting of both photons from the rest frame of the emitting region in the jet. According to the above condition, the Doppler factor that produces a Thomson-KN transition for soft photons near 10 eV is given by

$$\delta \approx 6\epsilon_{10}^{1/2} E_{\text{TeV}}^{1/2}, \quad (1)$$

where  $\epsilon_{10} = (\epsilon/10 \text{ eV})$  and  $E_{\text{TeV}} = (E_\gamma/1 \text{ TeV})$ .<sup>2</sup>

From this condition, it follows that the Lorentz factor of the scattering electron in the source frame  $\gamma'_e$ , and the magnetic field strength  $B'$ , obtained from the expression for the charac-

<sup>1</sup> It is not clear whether the physics of the sources favors RBLs as GeV sources or whether this is a demographic effect. Observed RBLs may be an order of magnitude more abundant than XBLs (Padovani & Giommi 1995); however, this may be due to selection effects (Urry & Padovani 1995; see also Maraschi et al. 1986).

<sup>2</sup> This value of  $\delta$  is consistent with the condition that the jet be transparent to  $\gamma$ -rays (see, e.g., Mattox et al. 1997).

TABLE 1  
PREDICTED  $\gamma$ -RAY FLUXES FOR LOW-REDSHIFT XBLs

IES Name	Other Name(s)	$z$	$\phi(>0.1 \text{ GeV})$ ( $10^{-7} \text{ cm}^{-2} \text{ s}^{-1}$ )	$\phi(>0.3 \text{ TeV})$ ( $10^{-11} \text{ cm}^{-2} \text{ s}^{-1}$ )	$\phi(>1 \text{ TeV})$ ( $10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$ )
IES 0145+138 .....		0.125	0.07	0.55	0.26
IES 0229+200 .....		0.139	0.08	0.28	0.11
IES 0323+022 .....	1H	0.147	0.11	0.40	0.15
IES 0347-121 .....		0.188	0.05	0.38	0.08
IES 0446+449 .....		0.203	0.04	0.09	0.02
IES 0548-322 .....	PKS, 1H	0.069	0.56	1.3	1.2
IES 0927+500 .....		0.188	0.06	0.12	0.02
IES 1101+384 .....	Mrk 421	0.031	1.43	2.3	3.6
IES 1118+424 .....	EXO	0.124	0.15	0.38	0.18
IES 1133+704 .....		0.046	1.5	0.94	1.2
IES 1212+078 .....	Mrk 180, S5	0.136	0.22	0.07	0.03
IES 1239+069 .....		0.150	0.01	1.2	0.43
IES 1255+244 .....		0.141	0.41	0.88	0.34
IES 1312-423 .....	MS	0.105	0.19	0.24	0.15
IES 1440+122 .....		0.162	0.16	0.12	0.03
IES 1652+398 .....	Mrk 501, S4	0.034	1.4	2.1	3.2
IES 1727+502 .....	1 Zw 187	0.055	0.18	0.51	0.59
IES 1741+196 .....		0.083	0.21	0.43	0.35
IES 1959+650 .....		0.048	1.8	1.9	2.3
IES 2005-489 .....	PKS	0.071	0.70	0.91	0.84
IES 2155-304 .....	PKS	0.116	3.9	1.7	0.88
IES 2321+419 .....		0.059	0.15	0.13	0.14
IES 2344+514 .....		0.044	0.54	0.61	0.80

teristic synchrotron frequency  $\nu'_s \simeq 0.19(eB'/m_e c)\gamma_e'^2$  of the soft photon, are given by

$$\gamma_e' \simeq 3 \times 10^5 \epsilon_{10}^{-1/2} E_{\text{TeV}}^{1/2} \quad \text{from} \quad E_\gamma \sim \frac{4}{3} \gamma_e'^2 \epsilon \quad (2)$$

and

$$B' \simeq 0.2 \epsilon_{\text{keV}} \epsilon_{10}^{1/2} E_{\text{TeV}}^{-3/2} \text{ G}, \quad (3)$$

where  $\epsilon_X = 1 \epsilon_{\text{keV}}$  keV is the characteristic X-ray synchrotron photon energy  $h\nu_s$ , resulting from electrons with energy  $\gamma_e' mc^2$  in a  $B$ -field of strength  $B'$ . Taking  $\epsilon_{10}$ ,  $\epsilon_{\text{keV}}$ , and  $E_{\text{TeV}}$  equal to unity in equation (3), we obtain a value of  $B' \sim 0.2$  G, which is consistent with other estimates (Takahashi et al. 1996).

For Mrk 421, we find that the ratio of bolometric Compton to synchrotron luminosities  $L_C/L_{\text{syn}} = U'_o/U'_B \sim 1$ , where  $U'_o$  is the rest-frame energy density in the IR-to-UV range (that of the seed photons), and  $U'_B = B'^2/8\pi$  is the magnetic energy density. From this analysis, we can also obtain an estimate for the size of the optical emitting region,  $r'$ , by noting that

$$U'_o = \delta^{-4} L_o / 4\pi r'^2 c \quad (4)$$

(see, e.g., Pearson & Zensus 1987), where  $L_o$  is the luminosity of the source in the optical-UV range  $\sim 2 \times 10^{44} \text{ ergs s}^{-1}$ . From this, one obtains

$$r' \sim 2 \times 10^{16} \epsilon_{10}^{-3/2} E_{\text{TeV}}^{1/2} \epsilon_{\text{keV}}^{-1} \text{ cm}, \quad (5)$$

The optical variability timescale, given by  $\tau_o \sim r'/c\delta$ , is much longer than the X-ray and TeV flare timescales. This implies that during the flare, impulsive acceleration of the high-energy tail of the relativistic electron distribution occurred over a much smaller region than that occupied by the bulk of the relativistic electron population.

##### 5. XBL TeV SOURCE CANDIDATES

Within the SSC scenario justified above for Mrk 421, we have used simple scaling arguments to predict the  $\gamma$ -ray fluxes

in different energy bands. A general property of the SSC mechanism is that the Compton component has a spectrum that is similar to the synchrotron component but is upshifted by  $\sim \gamma_e'^2$  (up to the KN limit), where  $\gamma_{e, \text{max}}$  is the maximum electron Lorentz factor. Thus, by comparing the synchrotron and Compton spectral components of Mrk 421, which are both roughly parabolic on a logarithmic  $\nu F_\nu$  plot (Macomb et al. 1995), we find an upshifting factor  $\sim 10^9$  is required. The implied value of  $\gamma_{e, \text{max}} \sim 10^{4.5}$  is consistent with that given in equation (2). We note that the radio-to-optical and 0.1–1 GeV photon spectral indices of the EGRET source XBLs are flatter than  $E^{-2}$  (Vestrand et al. 1995; Sreekumar et al. 1996) and the X-ray and Mrk 421 TeV spectra are steeper than  $E^{-2}$  (Mohanty et al. 1993; Petry et al. 1996), as expected for the parabolic spectral shapes.

We assume for simplicity that all XBLs have the same properties as those found for Mrk 421. Both XBLs that have been detected by EGRET, Mrk 421 and PKS 2155–304, have  $L_C/L_{\text{syn}} \sim 1$ . We will assume that this ratio is the same for all XBLs. The similarity between the synchrotron and Compton components, with the upshifting factor of  $\sim 10^9$  discussed above, allows us to derive the following scaling law:

$$\frac{\nu_o F_o}{L_{\text{syn}}} \simeq \frac{\nu_{\text{GeV}} F_{\text{GeV}}}{L_C} \quad \text{and} \quad \frac{\nu_X F_X}{L_{\text{syn}}} \simeq \frac{\nu_{\text{TeV}} F_{\text{TeV}}}{L_C}. \quad (6)$$

From this equation, and assuming that  $L_C/L_{\text{syn}} \sim 1$ , we obtain the energy fluxes for the GeV and TeV ranges,

$$\nu_{\text{GeV}} F_{\text{GeV}} \sim \nu_o F_o \quad \text{and} \quad \nu_{\text{TeV}} F_{\text{TeV}} \sim \nu_X F_X. \quad (7)$$

In order to select good candidate TeV sources, we have used the *Einstein* slew survey sample given by Perlman et al. (1996) to choose low-redshift XBLs. Using equation (7), we then calculated fluxes above 0.1 GeV for these sources. We have normalized our calculations to the observed EGRET flux for Mrk 421. The energy fluxes  $F_o$  and  $F_X$  which we used in the calculation are from Perlman et al. (1996). The prime uncer-

tainties in our calculations stem from our assumption that  $(L_C/L_{\text{syn}}) \sim 1$  for all XBLs, from the nonsimultaneity of the data in different energy bands, and from the fact that the synchrotron and Compton SEDs are not identical. In order to calculate integral fluxes for these sources, we have assumed that they have  $E^{-1.8}$  photon spectra at energies between 0.1 and 10 GeV, the average spectral index for BL Lac objects in this energy range. We have also assumed an  $E^{-2.2}$  photon source spectrum above 0.3 TeV for all of these sources, based on preliminary data on Mrk 421 from the Whipple collaboration (Mohanty et al. 1993). We have taken account of intergalactic absorption by using an optical depth that is an average between Models 1 and 2 of Stecker & de Jager (1997). Table 1 lists 23 XBLs at redshifts less than 0.2, giving our calculated fluxes for these sources for energies above 0.1 GeV, 0.3 TeV, and 1 TeV.

## 6. CONCLUSIONS

Within the context of a simple physical model, we have chosen 23 candidate TeV sources that are all nearby XBLs and have predicted fluxes for these sources for energies above 0.1 GeV, 0.3 TeV, and 1 TeV. Our calculations give fluxes that agree with all of the existing GeV and TeV  $\gamma$ -ray observations, including EGRET upper limits, to within a factor of 2–3.

Having normalized the Mrk 421 flux to a value of  $1.43 \times 10^{-7} \text{ cm}^{-2} \text{ s}^{-1}$  for  $E_\gamma > 0.1 \text{ GeV}$  (Sreekumar et al. 1996), we predict a flux of  $2.3 \times 10^{-11} \text{ cm}^{-2} \text{ s}^{-1}$  above 0.3 TeV. This prediction is within 20% of the average flux observed by the Whipple collaboration over a 4 yr time period (Schubnell

et al. 1996). For Mrk 501, we predict a flux above 0.3 TeV, which should be observable with the Whipple telescope (as is indeed the case), whereas the corresponding 0.1 GeV flux is predicted to be on the threshold of detection by EGRET. (Mrk 501, as of this writing, has not been detected by EGRET.) We predict a flux for PKS 2155–304 of  $3.9 \times 10^{-7} \text{ cm}^{-2} \text{ s}^{-1}$  above 0.1 GeV. For this source, a flux of  $(2.7 \pm 0.7) \times 10^{-7} \text{ cm}^{-2} \text{ s}^{-1}$  above 0.1 GeV was detected during a single EGRET viewing period (Vestrand et al. 1995), close to our predicted value. The tentative Whipple source 1ES 2344+514 is one of our stronger source predictions. According to our calculations, PKS 2155–304, a southern hemisphere source that has not yet been looked at, should be relatively bright above 0.3 TeV, but not above 1 TeV, owing to intergalactic absorption. Thus, TeV observations of this particular source may provide evidence for the presence of intergalactic infrared radiation.

As Sambruna et al. (1996) have pointed out, it is difficult to explain the large differences in peak synchrotron frequencies between XBLs and RBLs on the basis of jet orientation alone. The recent  $\gamma$ -ray evidence discussed here suggests that similar large differences in peak Compton energies carry over into the  $\gamma$ -ray region of the spectrum via the SSC mechanism, supporting the hypothesis that real physical differences exist between XBLs (HBLs) and RBLs (LBLs).

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