PREDICTED EXTRAGALACTIC TeV GAMMA-RAY SOURCES

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ABSTRACT

We suggest that low-redshift XBLs (X-ray selected BL Lacertae objects) may be the only extragalactic γ -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 RBLs and 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 which 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 Lacs observed by EGRET, 12 are RBLs, whereas only 2 are XBLs. We give a list of nearby XBLs which 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 – quasars:general BL Lacertae objects:individual (Mrk 421)

1. Introduction

Over 50 blazars have been detected as γ -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 which 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 paper, 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 γ -rays between the source and the 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 γ -rays with energies greater than ~ 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, 3C273, lies at a redshift of 0.16. This source is also a "mini-blazar" 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 Lacerate 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, RBLs, 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 the explain this. There is the "orientation hypothesis", which states that these sources (or at least the BL Lacs) have no significant physical differences between them; rather the differences in luminosity and spectra result from relativistic beaming effects, with XBLs jets being observed with larger angles to the line-of-sight than 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 and 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 νF_{ν} spectrum, is generally considered to be produced by synchrotron radiation of relativistic electrons in the jet. The higher energy part, which includes the γ -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, α_{rx} , which can be used to classify BL Lac objects as XBL-like or RBL-like, or alternatively HBLs (high frequency peaked BL Lacs) and LBLs (low frequency peaked BL Lacs) (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) (*e.g.*, Sambruna, *et al.* 1996). These electrons, in turn, should Compton scatter to produce higher energy γ -rays in XBLs than in RBLs.

In fact, of the over 50 blazars seen by EGRET in the GeV range, including 14 BL Lacs (based on the observations given by Thompson, *et al.* 1995, 1996; Vestrand, Stacy & Sreekumar 1995 and Fichtel, *et al.* 1996), only two, *viz.* Mrk 421 and PKS 2155-304, are XBLs.¹ In contrast, *only* XBLs have been seen at TeV energies. Thus, the γ -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 γ -ray sources which have been reported are nearby BL Lac objects. The GeV γ -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, 1ES2344+514, whose redshift is 0.044, was recently reported by the Whipple group as a tentative detection (Schubnell 1996). This could be the

¹It 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, Ghisellini, Tanzi & Treves 1986).

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 a radio-selected BL Lac object (RBL), whereas if $\log(F_X/F_r) > -5.5$, the object is classified as an X-ray selected BL Lac (XBL) (Giommi & Padovanni 1994). Using this criterion, only XBLs have been detected at TeV energies, whereas the RBL ON231 (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 SSC models. We further predict that only nearby XBLs will be extragalactic TeV sources.

4. SSC Models of BL Lacs

The most popular mechanisms proposed for explaining blazar γ -ray emission have involved either (1) the SSC mechanism, *viz.*, 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 AGN core (Dermer & Schlickheiser 1993), possibly scattered into the jet by surrounding clouds (Sikora, Begelman & Rees 1994).

During the simultaneous X-ray and TeV flaring of the XBL Mrk421 in May of 1994, it was observed that the flare/quiescent flux ratios were similar for both X-rays and TeV γ -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 which remained constant (Takahashi, *et al.* 1996). This leads to the important conclusion that the TeV γ -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 γ -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 ~ 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 ϵ is the energy of the soft photon being upscattered and E_{γ} is the energy of the high-energy γ -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 δ^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 which produces a Thomson-KN transition for soft photons near 10 eV is given by

$$\delta \approx 6\epsilon_{10}^{1/2} E_{\rm TeV}^{1/2} \tag{1}$$

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

From this condition, it follows that the Lorentz factor of the scattering electron in the source frame γ'_e , and the magnetic field strength B', obtained from the expression for the characteristic synchrotron frequency $\nu'_{\rm s} \simeq 0.19 (eB'/m_ec) \gamma'^2_e$ of the soft photon, are given by

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

and

$$B' \simeq 0.2 \epsilon_{\rm keV} \epsilon_{10}^{1/2} E_{\rm TeV}^{-3/2} \,\,{\rm G}$$
 (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 ϵ_{10} , ϵ_{keV} and E_{TeV} equal to unity in eq.(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 $L_{\rm C}/L_{\rm syn} = U'_o/U'_B \sim 1$, 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

$$U_o' = \delta^{-4} L_o / 4\pi r'^2 c \tag{4}$$

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

²This value of δ is consistent with the condition that the jet be transparent to γ -rays (see, *e.g.*, Mattox, *et al.* 1996).

$$r' \sim 2 \times 10^{16} \epsilon_{10}^{-3/2} E_{\text{TeV}}^{1/2} \epsilon_{\text{keV}}^{-1} \text{ cm},$$
 (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 γ -ray fluxes in different energy bands. A general property of the SSC mechanism is that the Compton component has a spectrum which is similar to the synchrotron component, but upshifted by $\sim \gamma_{e,max}^{\prime 2}$ (up to the KN limit), where $\gamma_{e,max}^{\prime}$ 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 νF_{ν} plot (Macomb, *et al.* 1995), we find an upshifting factor $\sim 10^9$ is required. The implied value of $\gamma_{e,max} \sim 10^{4.5}$ is consistent with that given in eq.(2). We note that the radio to optical and 0.1 to 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 which have been detected by *EGRET*, Mrk421 and PKS2155-304, have $L_{\rm C}/L_{\rm syn} \sim 1$. 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:

$$\frac{\nu_o F_o}{L_{\rm syn}} \simeq \frac{\nu_{\rm GeV} F_{\rm GeV}}{L_{\rm C}} \quad \text{and} \quad \frac{\nu_x F_x}{L_{\rm syn}} \simeq \frac{\nu_{\rm TeV} F_{\rm TeV}}{L_{\rm C}},\tag{6}$$

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

$$\nu_{\rm GeV} F_{\rm GeV} \sim \nu_o F_o \text{ and } \nu_{\rm TeV} F_{\rm TeV} \sim \nu_x F_x$$
(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 Eq.(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 uncertainties in our calculations stem from our assumption that $(L_C/L_{syn}) \sim 1$ for all XBLs, from the non-simultaneity 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 Lacs 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 which 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 which 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 which agree with all of the existing GeV and TeV γ -ray observations, including *EGRET* upper limits, to within a factor of 2 to 3.

Having normalized the Mrk 421 flux to a value of 1.43×10^{-7} cm⁻²s⁻¹ for $E_{\gamma} > 0.1$ GeV (Sreekumar, *et al.* 1996), we predict a flux of 2.3×10^{-11} cm⁻²s⁻¹ above 0.3 TeV. This prediction is within 20% of the average flux observed by the Whipple collaboration over a four year 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 of $(2.7 \pm 0.7) \times 10^{-7}$ cm⁻²s⁻¹ above 0.1 GeV was detected during a single *EGRET* viewing period (Vestrand, *et al.* 1955), close to our predicted value. The tentative Whipple source 1ES2344+514 is one of our stronger source predictions. According to our calculations, PKS 2155-304, a southern hemisphere source which 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, is is difficult to explain the large differences in peak synchrotron frequencies between XBLs and RBLs on the basis of jet orientation alone. The recent γ -ray evidence discussed here suggests that similar large differences in peak Compton energies carry over into the γ -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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1ES	Other	Z	$\phi(>0.1~{\rm GeV})$	$\phi(>0.3 \text{ TeV})$	$\phi(>1 { m TeV})$
Name	Name(s)		$10^{-7} \mathrm{cm}^{-2} \mathrm{s}^{-1}$	$10^{-11} \mathrm{cm}^{-2} \mathrm{s}^{-1}$	$10^{-12} \mathrm{cm}^{-2} \mathrm{s}^{-1}$
1ES0145 + 138		0.125	0.07	0.55	0.26
1ES0229 + 200		0.139	0.08	0.28	0.11
1ES0323 + 022	1H	0.147	0.11	0.40	0.15
1ES0347 - 121		0.188	0.05	0.38	0.08
1ES0446 + 449		0.203	0.04	0.09	0.02
1ES0548 - 322	PKS, 1H	0.069	0.56	1.3	1.2
1ES0927 + 500		0.188	0.06	0.12	0.02
1ES1101 + 384	Mrk 421	0.031	1.43	2.3	3.6
1ES1118 + 424	EXO	0.124	0.15	0.38	0.18
1ES1133 + 704		0.046	1.5	0.94	1.2
1ES1212 + 078	Mrk 180, S5	0.136	0.22	0.07	0.03
1ES1239 + 069		0.150	0.01	1.2	0.43
1ES1255 + 244		0.141	0.41	0.88	0.34
1ES1312 - 423	MS	0.105	0.19	0.24	0.15
1ES1440 + 122		0.162	0.16	0.12	0.03
1ES1652 + 398	Mrk 501, S4	0.034	1.4	2.1	3.2
1ES1727 + 502	1 Zw 187	0.055	0.18	0.51	0.59
1ES1741 + 196		0.083	0.21	0.43	0.35
1ES1959 + 650		0.048	1.8	1.9	2.3
1ES2005 - 489	PKS	0.071	0.70	0.91	0.84
1ES2155 - 304	PKS	0.116	3.9	1.7	0.88
1ES2321 + 419		0.059	0.15	0.13	0.14
1ES2344 + 514		0.044	0.54	0.61	0.80

Table 1: Predicted γ -ray fluxes for low-redshift XBLs