EGRET SPECTRAL INDEX AND THE LOW-ENERGY PEAK POSITION IN THE SPECTRAL ENERGY DISTRIBUTION OF EGRET-DETECTED BLAZARS

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Received 1999 March 31; accepted 1999 June 22

ABSTRACT

In current theoretical models of the blazar subclass of active galaxies, the broadband emission consists of two components: a low-frequency synchrotron component with a peak in the IR to X-ray band and a high-frequency inverse Compton component with a peak in the gamma-ray band. In such models, the gamma-ray spectral index should be correlated with the location of the low-energy peak, with flatter gamma-ray spectra expected for blazars with synchrotron peaks at higher photon energies and vice versa. Using the EGRET-detected blazars as a sample, we examine this correlation and possible uncertainties in its construction.

Subject headings: galaxies: active — gamma rays: theory — radiation mechanisms: nonthermal — X-rays: galaxies

1. INTRODUCTION

It is now generally believed in a class of theoretical models (see, e.g., Ulrich, Maraschi, & Urry 1997 for a review) that the broadband spectrum of a blazar consists of two distinctive components: (a) a low-energy component, which is the result of synchrotron radiation of a beam of relativistic particles and which peaks, in the spectral energy distribution (SED) plot, in the IR to soft X-ray region, and (b) a high-energy component, which is the result of inverse Compton scattering of the same beam of relativistic particles on some ambient field of soft photons and which peaks in SED in the MeV-GeV-TeV region. These models are well known for their attempt to explain the most salient features of the broadband spectra of blazars from radio energies all the way to the TeV energies, an energy span of more than 20 orders of magnitude.

In this paper we examine an important prediction of this class of theoretical models with EGRET data. The two broad peaks in the SED of a blazar as described in such models, being the products of the same beam of relativistic particles, should be closely related to each other. Since the high-energy peaks in SEDs of various blazars pass through the EGRET energy range from ~30 MeV to 20 GeV, the spectral shapes of the EGRET-detected blazars in the EGRET energy range should change systematically with respect to the positions of the low-energy SED peaks in different objects. This prediction of these currently investigated theoretical models can be tested with EGRET data.

A brief and preliminary result of a study of this kind with EGRET data, based on the Second EGRET Catalog and its Supplement (Thompson et al. 1995, 1996), has already been published (Lin et al. 1998). In the present paper, we expand the scope of the previous study with additional information taken from the recently published Third EGRET Catalog (Hartman et al. 1999) and other publications to examine again in more detail the question of the possible correlation between EGRET spectral shapes and low-energy SED peak positions for the blazars that have been detected by EGRET.

2. THE DATA

We select 27 EGRET-detected blazars (Fichtel et al. 1994; Thompson et al. 1995, 1996; Hartman et al. 1999). These are the ones for which the SED can be found in the published data at least to the extent that the low-energy peak positions can be determined, and for which the EGRET photon spectra can also be determined. Four of the sources in this sample are traditionally regarded as X-ray–selected BL Lac objects (XBLs; see Ciliegi, Bassani, & Carolini 1995). Recently these objects have been reclassified as high-energy–peaked BL Lac objects (HBLs; see Ulrich et al. 1997). Another 11 of these sources are usually regarded as radio-selected BL Lac objects (RBLs; see Ciliegi et al. 1995) or reclassified as low-energy–peaked BL Lac objects (LBLs; see, e.g., Ulrich et al. 1997). The other 12 sources in the sample consist of what are generally referred to as flat-spectrum radio quasars (FSRQs). For two of the four XBLs (HBLs), Mrk 501 and PKS 2005−489, the EGRET detections are somewhat weak but still fairly certain (Kataoka et al. 1999; Sreekumar et al. 1999; Lin et al. 1997). Three of the four XBLs have been detected at TeV energies (see, e.g., Krennrich et al. 1999 or Macomb et al. 1995 for Mrk 421, Kataoka et al. 1999 or Krennrich et al. 1999 for Mrk 501, and Chadwick et al. 1999 for PKS 2155−304), while a good TeV flux upper limit exists for the fourth one (PKS...
2005—489; Roberts et al. 1998). Thus the SED of these four XBLs (HBLs) can be constructed well into the TeV energies with the high-energy peaks clearly seen. Furthermore, five of the EGRET-detected FSRQs have also been detected by OSSE and COMPTEL in the 0.05—15 MeV energy range. Combined spectra have been determined for these five sources through the OSSE/COMPTEL/EGRET energy ranges (3C 273, 3C 279, CTA 102, PKS 0528+134, and 3C 454.3; see McNaron-Brown et al. 1995). These five sources are all included in the sample here. The high-energy peaks of these five sources can be constructed in the MeV—GeV energy range with strict simultaneous data (McNaron-Brown et al. 1995). These peak positions are visible as spectral break points between the OSSE/COMPTEL data and the EGRET data.

This sample of 27 EGRET-detected blazars is listed in Table 1 together with EGRET fluxes, EGRET spectral indices, and the low-energy SED peak frequencies. The EGRET fluxes and spectral indices are taken from the recent Third EGRET Catalog (Hartman et al. 1999) unless noted otherwise. Most of the sources in the EGRET catalogs carry multiple flux values. The values quoted here in Table 1 are the first entries in the Third EGRET Catalog, upon which the source positions and the source identifications are determined. The EGRET spectral indices in the Third EGRET Catalog are those determined for the sum data of Cycles 1—4 (1991 April 22—1995 October 4). There is some evidence that the EGRET spectra of some blazars tend to become harder at higher flux levels (Mukherjee et al. 1997), but the variations are small and become apparent only for bright EGRET sources when the spectral indices can be determined with high degrees of accuracy. So the EGRET spectral indices listed in the Third EGRET Catalog and quoted here in Table 1, though calculated only as average values over long periods of time, are good representations of the actual spectral shapes. The low-energy SED peak frequencies in Table 1 are taken from published data. On average, the peak positions can be determined from the published data to an accuracy of about ±0.2 in the scale of log_{10} (frequency). Of the 27 sources studied here, four are found to have enough data to show the low-energy SED peak frequency at different epochs: PKS 0235+164, Mrk 421, 3C 279, and BL Lacertae (see references cited in Table 1). The ranges of the peak frequencies of these four sources are 0.5 for PKS 0235+164, 1.0 for Mrk 421, 0.3 for 3C 279, and 0.2 for BL Lacertae, in the scale of log_{10} (frequency). These variations in the low-energy SED peak frequencies are small compared with the full frequency range of all blazars studied here. For these four sources, we enter the peak frequencies corresponding to quieter times in Table 1, as these are the situations where more abundant data are available. Finally, some special features of the individual sources are included as remarks in the last column of Table 1. This source sample is not meant to be a complete

### Table 1

| Object       | Other Name | EGRET Flux E > 100 MeV (10^{-8} cm^{-2} s^{-1}) | EGRET Spectral Index γ | Low-E Peak log_{10} f_{peak} (f_{peak} in Hz) | References for Low-E Peak | Remark |
|--------------|------------|-----------------------------------------------|------------------------|---------------------------------------------|---------------------------|--------|
| 0208—512.... | ...        | 8.55 ± 0.45                                    | 1.99 ± 0.05            | 12.0                                        | 1 FSRQ                     |        |
| 0219+428.... | 3C 66A     | 1.87 ± 0.29                                    | 2.01 ± 0.14            | 13.0                                        | 2 RBL                      |        |
| 0235+164.... | ...        | 6.51 ± 0.88                                    | 1.85 ± 0.12            | 13.0                                        | 1 RBL                      |        |
| 0420—014.... | ...        | 5.02 ± 1.04                                    | 2.44 ± 0.19            | 12.3                                        | 1 FSRQ                     |        |
| 0454—234.... | PKS        | 1.47 ± 0.42                                    | 3.14 ± 0.47            | 13.5                                        | 2 FSRQ                     |        |
| 0458—020.... | ...        | 1.12 ± 0.23                                    | 2.45 ± 0.27            | 13.0                                        | 2 FSRQ                     |        |
| 0521—365.... | ...        | 3.19 ± 0.72                                    | 2.63 ± 0.42            | 13.5                                        | 2 RBL                      |        |
| 0528+134.... | PKS        | 9.35 ± 0.36                                    | 2.46 ± 0.04            | 12.0                                        | 1 FSRQ OSSE/COMPTEL        |        |
| 0537—441.... | ...        | 2.53 ± 0.31                                    | 2.41 ± 0.12            | 13.5                                        | 1 RBL                      |        |
| 0716+744.... | ...        | 1.78 ± 0.20                                    | 2.19 ± 0.11            | 13.8                                        | 3 RBL                      |        |
| 0735+170.... | ...        | 1.64 ± 0.33                                    | 2.60 ± 0.28            | 13.7                                        | 2 RBL                      |        |
| 0829+046.... | ...        | 1.68 ± 0.51                                    | 2.47 ± 0.40            | 13.6                                        | 2 RBL                      |        |
| 0851+202.... | OJ+287     | 1.06 ± 0.30                                    | 2.03 ± 0.35            | 13.0                                        | 2 RBL                      |        |
| 0954+658.... | ...        | 1.54 ± 0.30                                    | 2.08 ± 0.24            | 13.6                                        | 2 RBL                      |        |
| 1101+384.... | Mrk 421    | 1.39 ± 0.18                                    | 1.57 ± 0.15            | 16.0                                        | 4 XBL TeV detection        |        |
| 1156+295.... | 4C+29.45   | 5.09 ± 1.19                                    | 1.98 ± 0.22            | 13.0                                        | 2 FSRQ                     |        |
| 1219+285.... | W Comae    | 1.15 ± 0.18                                    | 1.73 ± 0.18            | 13.5                                        | 1 RBL                      |        |
| 1226+023.... | 3C 273     | 1.54 ± 0.18                                    | 2.58 ± 0.09            | 13.5                                        | 1 FSRQ OSSE/COMPTEL        |        |
| 1253—055.... | 3C 279     | 17.97 ± 0.67                                   | 1.96 ± 0.04            | 12.6                                        | 5 FSRQ OSSE/COMPTEL        |        |
| 1510—089.... | ...        | 1.80 ± 0.38                                    | 2.47 ± 0.21            | 13.0                                        | 2 FSRQ                     |        |
| 1635+382.... | 4C+38.41   | 10.75 ± 0.96                                   | 2.15 ± 0.09            | 12.3                                        | 1 FSRQ                     |        |
| 1652+398.... | Mrk 501    | 3.20 ± 1.30a                                   | 1.60 ± 0.50a           | 16.7                                        | 6 XBL TeV detection        |        |
| 2005—489.... | PKS        | 1.31 ± 0.46a                                   | 1.52 ± 0.24a           | 16.4                                        | 7 XBL TeV upper limit      |        |
| 2155—304.... | PKS        | 3.04 ± 0.77                                    | 1.71 ± 0.24a           | 17.0                                        | 8 XBL TeV detection        |        |
| 2200+016.... | BL Lacertae| 3.99 ± 1.16                                    | 2.60 ± 0.28            | 14.0                                        | 9 RBL                      |        |
| 2230+114.... | CTA 102    | 1.92 ± 0.28                                    | 2.45 ± 0.14            | 12.1                                        | 2 FSRQ OSSE/COMPTEL        |        |
| 2251+158.... | 3C 454.3   | 5.37 ± 0.40                                    | 2.21 ± 0.06            | 12.8                                        | 1 FSRQ OSSE/COMPTEL        |        |

* From Kataoka et al. 1999.
* From Lin et al. 1997.
* From Vestrand et al. 1995.

References for Low-E Peak.—(1) von Montigny et al. 1995; (2) Impey & Nuegebauer 1988; (3) Ghisellini et al. 1997; (4) Macomb et al. 1995; (5) Wehrle et al. 1998; (6) Kataoka et al. 1999; (7) Sambruna et al. 1995; (8) Chadwick et al. 1999; (9) Catanese et al. 1997.
one. We just try to construct a sample size that is sufficiently large to draw certain statistical conclusions.

3. THE ANALYSIS

To examine the correlation between the low-energy peak and the high-energy peak in the SED of a blazar, we should ideally try to match these two peaks over broad energy ranges that cover substantial segments of the spectrum. However, this is not feasible at present with existing data. Only a handful of sources have detailed measurements of the spectra from radio energies to TeV energies. Conclusions drawn from these few sources are likely to be biased in some way and not generally applicable to blazars as a class. Most of the blazars described in the literature have good measurements on their broadband spectra only around the low-energy SED peaks. For the EGRET-detected blazars in general, there are no existing data to show where the high-energy peak frequencies are located except for the few sources that are either the XBLs mentioned above or the ones that have also been detected by OSSE and COMPTEL (McNaron-Brown et al. 1995), also mentioned above. To examine the correlation between the two SED peaks, we need to rely on some specific properties of the broadband spectra in the two energy regions.

For the low-energy peaks in SEDs it is natural to examine the peak frequencies, as these are the prominent spectral features that can be determined fairly accurately from published data. Then, in the EGRET energy range, we examine the spectral shapes, or more specifically the spectral indices, to see whether they change systematically with the low-energy peak frequencies.

In addition to examining the model's predictions about the correlation between the low-energy SED peak frequency and the EGRET spectral index, which involves only experimental data as described above, we can also compare the observed EGRET spectral indices with the calculated spectral indices in the EGRET energy region from theoretical models of blazars currently under investigation (see, e.g., Ulrich et al. 1997). We take the illustrative theoretical curves plotted in Figure 12 of Fossati et al. (1998) and determine the slopes of these curves at 100 MeV as a function of the low-energy SED peak frequencies. We then compare these theoretical slopes with EGRET spectral indices of the sources listed in Table 1 as functions of the low-energy peak frequencies.

In Figure 1 we plot the EGRET spectral index $\gamma - 2 (f \sim E^{-\gamma})$ versus the low-energy SED peak frequency in $\log_{10}$ scale for the sample of 27 EGRET-detected blazars. The source designations, their low-energy SED peak frequencies, and the corresponding EGRET spectral indices are all listed in Table 1. The value $\gamma - 2$ corresponds to the spectral index in an SED plot. The five FSRQs that are also detected by OSSE/COMPTEL are indicated separately in the figure. In Figure 1 we also plot the theoretical prediction of the spectral slope at 100 MeV as a function of the low-energy SED peak frequency as described in the paragraph above. Some of the graph points in Figure 1 are slightly shifted in their abcissae to avoid graph congestion. The theoretically calculated spectral slopes at 100 MeV are connected with dotted lines.

As one can see in Figure 1, the EGRET spectral indices do not vary systematically with respect to the low-energy SED peak frequencies. The four XBLs (HBLs) may form the only exception to this general situation. The theoretical models seem to work well for the four EGRET-detected XBLs, but when the low-energy SED peak frequency moves toward lower values, the agreement between the theoretical prediction and the EGRET data ceases to exist. The EGRET spectral indices do not form a pattern that resembles the upturn of the theoretical curve toward smaller low-energy SED peak frequencies. Neither can one find a trend of any other kind in the EGRET spectral indices in Figure 1. The error margins in the EGRET spectral indices cannot accommodate the discrepancy between the theoretical prediction and the EGRET data. Many of the EGRET spectral indices have been determined with an accuracy better than $\sim \pm 0.15$.

We may also add that for the four EGRET-detected XBLs (HBLs), the EGRET spectral indices $\gamma (f \sim E^{-\gamma})$ all fall within the low range between 1.5 and 1.7, while the low-energy SED peak frequencies all fall within the high range between $10^{16}$ and $10^{17}$ Hz. This fact is consistent with the results of the theoretical model fits (see, e.g., Fossati et al. 1998). But when it comes to the individual spectral and peak frequency values, there is no correlation between the EGRET spectral indices and the low-energy SED peak frequencies for these four XBLs either. However, we must point out that the error margins in the EGRET spectral indices are large for these four XBLs and the lack of correlation found here does not carry much weight. But for the five EGRET-detected FSRQs that have also been detected by OSSE/COMPTEL, and as such the high-energy SED peak frequencies can also be determined with the combined OSSE/COMPTEL/EGRET data as the spectral break points in the 0.015 MeV to several GeV energy range (see Fig. 2 in McNaron-Brown et al. 1995), no correlation is shown between the low-energy SED peak frequencies and the high-energy SED peak frequencies. The blazars that can be detected by OSSE or COMPTEL are likely to be those with steep EGRET spectra because then the EGRET spectra will extend high into the COMPTEL/OSSE energy regions. We may expect to see better agreement between theory and data for these five sources alone where the EGRET spectral indices become high. But in Figure 1, these five sources do not follow the theoretical curve either.

4. DISCUSSION

Many of the EGRET-detected blazars suffer from poor statistical accuracy because of limited photon counts; in
those cases, the spectral indices are very poorly determined. However, in Figure 1 it is apparent that the greatest discrepancy between the data and the theoretical prediction is at the lowest synchrotron-peak frequencies, where most of the best-determined EGRET indices are found. In the unified blazar scenarios it might be expected that the objects with synchrotron-peak frequencies below $10^{13}$ Hz are all FSRQs; note, however, that all of these are far below the (extrapolation of the) theoretical curve. The typical differences between the observed and predicted spectral indices are $\sim 0.8$, whereas the typical errors in those EGRET spectral indices are $\sim 0.15$; thus the discrepancies are clearly not due to statistical limitations. The EGRET-detected FSRQs clearly have much harder spectra than the theory predicts.

The RBLs also do not agree well with the theoretical curve, although the cluster of points extends both above and below it. In this case the discrepancy appears as a broader distribution around the theoretical curve than would be expected from the errors in the EGRET indices. For example, four of the 11 points are more than 2 $\sigma$ away from the theoretical curve, whereas statistically no more than 1 $\sigma$ would be expected.

It is well known that the low-energy SED peak frequencies of blazars may vary with flux levels. Since most of the SED spectra studied in this paper were constructed with noncontemporaneous data, one would have to consider the possibility that the lack of correlation between the low-energy SED peak frequency and the EGRET spectral index in Figure 1 could have been caused by the shift of the low-energy SED peak positions in different epochs. We are fairly certain that the EGRET spectra do not change appreciably with flux (Mukherjee et al. 1997). As for the shift of the low-energy SED peak positions, the well-studied sources such as those mentioned at the end of § 2 indicate that the sizes of the changes are no bigger than $\sim 1.0$ in the scale of $\log_{10}$ (frequency), or about 1 order of magnitude in frequency. But if we want to bring the FSRQs or RBLs with hard EGRET spectra in Figure 1 to agree with the theoretical curve, we would have to shift their low-energy SED peak frequencies by at least 3 orders of magnitude. Such a large change in the position of the low-energy SED peak has never been observed, at least for the majority of the blazars under study in the literature.

Another possible inconsistency between the theoretical models and the EGRET data may become evident when the spectral shapes of all EGRET blazars, not just the 27 sources listed in Table 1, are viewed together. The currently studied theoretical blazar models require that some of the EGRET spectra should show clear spectral breaks when the high-energy SED peaks pass through the EGRET energy range, much like the spectral breaks of the five sources detected by all three instruments, OSSE, COMPTEL, and EGRET, with spectral breaks in SED clearly seen between the OSSE/COMPTEL data and the EGRET data (McNaron-Brown et al. 1995). But in all of the spectral fits that have been carried out by the EGRET team (Fichtel et al. 1994; Thompson et al. 1995, 1996; Hartman et al. 1999 and references therein), it has never been found necessary to introduce spectral breaks or spectral cutoffs in order to fit the EGRET data properly. It is of course entirely possible that some of the EGRET blazar spectra will eventually prove to be too complicated to analyze with single power laws when the measurements become sufficiently accurate. In fact, even with the existing EGRET data, Reimer et al. (1999) and Bertsch et al. (1999) are currently carrying out studies to see whether functional forms more complicated than single power laws will provide better fits for some of the EGRET blazars. But we must point out that in the EGRET energy range, spectral breaks as conspicuous as those displayed in McNaron-Brown et al. (1995) or spectral cutoffs well below the GeV energy range can easily be recognized in the EGRET data. Thus if a theoretical model requires that some of the EGRET sources should possess spectral breaks or spectral cutoffs beyond what the statistical uncertainties in the EGRET data can accommodate, then the theoretical model will be inconsistent with EGRET data.

The EGRET team gratefully acknowledges support from the following: Bundesministerium für Forschung und Technologie, grant 50 QV 9095 (MPE authors); NASA grant NAG5-1742 (H. S. C.); NASA grant NAG5-1605 (Stanford University); and NASA contract NAS5-31210 (G. A. C.).

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