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A spectral study of gamma-ray emitting active galactic nuclei

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Abstract. In this paper we present a statistical analysis of the γ-ray spectra of flat-spectrum radio quasars (FSRQ) compared to those of BL Lacs. The average spectra and possible systematic deviations from power-law behaviour are investigated by summing up the intensity and the power-law fit statistic for both classes of objects. We also compare the time-averaged spectrum to that at the time of γ-ray outbursts.

The spectrum of the average AGN is softer than that of the extragalactic γ-ray background. It may be that BL Lacs, which on average have a harder spectrum than FSRQs, make up the bulk of the extragalactic background.

We also find apparent cut-offs at both low and high energies in the spectra of FSRQs at the time of γ-ray outbursts. While the cut-off at high energies may have something to do with opacity, the cut-off at low energies may be taken as indication that the γ-ray emission of FSRQs is not a one component spectrum.

Key words: methods: statistical – BL Lacertae objects: general – quasars: general – Gamma-rays: observations

1. Introduction

Up to the end of 1994 more than 50 extragalactic radio sources were detected as emitters of high-energy γ-rays by EGRET. The majority of the sources are flat-spectrum radio quasars (FSRQ) and about 20% are classified as BL Lacertae (BL Lac) objects. Especially in their flare state FSRQs often emit the bulk of their luminosity in the form of γ-rays (von Montigny et al. 1995). For a number of objects COMPTEL data at a few MeV (Schönfelder et al., 1996), OSSE data at a few hundred keV (McNaron-Brown et al. 1995) or the extrapolation of X-ray data imply a spectral break at a few MeV photon energy. This break may be attributed to incomplete cooling of radiating electrons (Dermer and Schlickeiser 1993, Sikora et al. 1994) or bremsstrahlung and annihilation emission of cooling pair plasma (Böttcher and Schlickeiser 1995).

Individual γ-ray spectra in the EGRET range, i.e. above 30 MeV, can generally be well described by power-laws. For the BL Lac Mrk421 the power-law behaviour extends up to TeV energies (Punch et al. 1992). Though a number of papers deal with the multifrequency spectrum of γ-ray AGN, to our knowledge no attempt has yet been made to investigate whether there are systematic deviations from power-law behaviour in the γ-ray spectra of AGN. Due to the different environmental conditions one might expect a different impact of opacity effects, for example, on FSRQs on one side and on BL Lacs on the other side.

In this paper we analyse the class-averaged spectra of AGN by summing the observed intensity and the statistic of power-law fits to the observed emission. We also derive the spectrum of the average γ-ray AGN which is to be compared to the spectrum of the diffuse extragalactic background. In the next section (Sect. 2) we consider the time-averaged behaviour of sources by using the summed EGRET data of Phases 1,2 and 3 corresponding to observation times between May 1991 and October 1994. Since many of the extragalactic sources are variable at γ-rays we discuss the behaviour at flare state in Sect. 3. A discussion of the results is in Sect. 4.

2. The average source

Here we have summed all EGRET data taken between May 1991 and October 1994 to obtain γ-ray allsky maps of counts and exposure. A quality cut has been imposed by restricting the field-of-view in the individual viewing periods to 30° off-axis angles before summing. At energies above 100 MeV we have performed a standard search for point sources using a maximum-likelihood technique (Mattox et al., 1996). The data in the energy range between 30 MeV and 100 MeV are usually neglected in this task since they add little to the statistics and source positioning, but require the energy-dependent point-spread function be averaged over an even larger energy range with corresponding systematic uncertainties. In total we found 148 excesses with a likelihood test statistic $TS = (2\ln\lambda_0 - 2\ln\lambda)$ of least 9, of which 44 are positionally coincident with AGN known to

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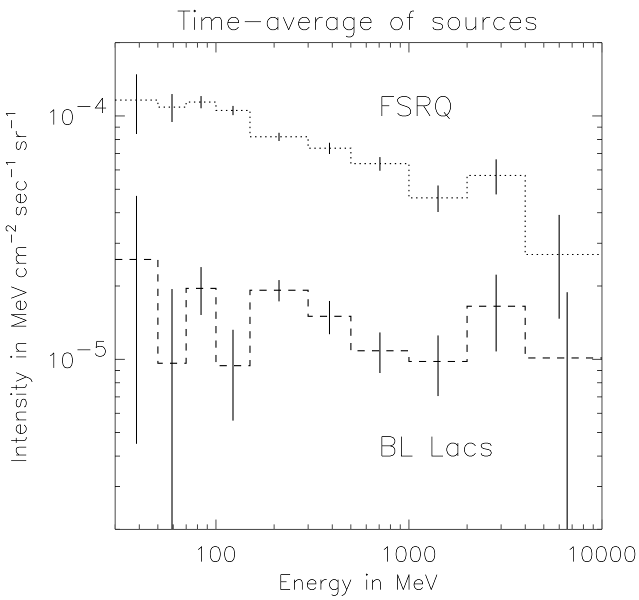

Fig. 1. The summed intensity spectrum of the 33 identified FSRQ and 11 identified BL Lacs in the total EGRET allsky data above 100 MeV. The error bars are derived by Gaussian error propagation of the individual uncertainty measures. The spectrum of FSRQ is significantly softer than that of the diffuse background, while that of BL Lacs is consistent with it.

emit γ-rays in the EGRET range. Table 1 lists these sources which can be further divided into BL Lacs on one side (11 objects) and FSRQs on the other side (33 objects). All sources except one (2155-304) have been observed with likelihood test statistic higher than 25 in individual viewing periods or specific combinations thereof (Thompson et al. 1995, 1996). The source 2155-304 is observed with likelihood test statistic of 33 in a later viewing period (VP 404) during Phase 4 of the CGRO observing program (Vestrand et al. 1996). We do not intend to find new AGN in our sample, but select the already identified ones for further analysis. Our threshold criterion of $TS \geq 9$ thus corresponds to a detection significance of at least 3 σ in the time-averaged data. Some AGN which have been found with high significance in individual viewing periods fail to show up in Table 1 since they have been absent in other viewing periods so that their average signal is below threshold.

For all 44 AGN we have performed a spectral analysis. The positions of the γ-ray sources have been set to those of the corresponding radio sources before doing a likelihood analysis of all 148 excesses in ten energy bands. Since the best model for the data consists of diffuse emission and 148 sources, we have to fit all these quasisimultaneously although we are interested only in the results for the 44 AGN. Observations of γ-ray pulsars have shown that the calibrated effective area in the two low energy bins (30-50 MeV and 50-70 MeV) is overestimated. In the standard analysis the observed source flux is multiplied by a correction factor which accounts for the miscalibration. The accuracy of this correction factor can be estimated to be better

Table 1. A list of radio sources which can be identified with point sources in the summed EGRET data of the time period 5/91 to 10/94 at energies above 100 MeV. The sources are categorized to belong either to the BL Lac class or to the class of FSRQ. The second column indicates the EGRET reference with acronyms for the second EGRET catalogue (2EG, Thompson et al. 1995), its supplement (2EGS, Thompson et al. 1996), and the papers by Mukherjee et al. (1997) (M) and Vestrand et al. (1996) (V). If there is at least a moderate level of variability, the third column gives the viewing period number for the peak flux in standard EGRET notation. No entry in this column indicates no evidence for variability. Note the following constraints for the selection of the viewing period of peak flux: the total statistical significance is required to be $\geq 4\,\sigma$ and preference is given to data taken with smaller aspect angle in case of viewing periods of comparable duration and comparable source flux.

FSRQ	EGRET	Peak VP	BL Lacs	EGRET VP	Peak
0202+149	2EG	21	0235+164	2EG	21
0208-512	2EG	10	0521-365	2EG	
0234+285	2EG	21	0537-441	2EG	6
0420-014	2EG	21	0716+714	2EG	
0440-003	2EGS	337	0735+178	2EG	40
0446+112	2EG	36.5	0829+046	2EG	
0528+134	2EG	213	0954+658	2EG	228
0827+243	2EG		1101+384	2EG	
0836+710	2EG	22	1219+285	2EGS	308.6
0917+449	2EG	326	1604+159	2EG	25
0954+556	2EG	319	2155-304	M,V	
1127-145	2EG	206			
1156+295	2EG	206			
1222+216	2EG	204			
1226+023	2EG	308.6			
1229-021	2EG				
1253-055	2EG	3			
1406-076	2EG	205			
1424-418	2EGS	314			
1510-089	2EG	24			
1606+106	2EG	16			
1611+343	2EG	202			
1622-253	2EG				
1633+382	2EG	9.2			
1730-130	2EG	334			
1739+522	2EG	212			
1908-201	2EG	323			
1933-400	2EG	35			
2022-077	2EG	7.2			
2052-474	2EG	42			
2230+114	2EG				
2251+158	2EG	37			
2356+196	2EG				

than 30% at 30 MeV to 50 MeV and better than 10% at 50 MeV to 70 MeV (Fierro 1995, §3.4).

We have summed the observed intensity in the ten energy bands to derive the spectrum of the average AGN. This spectrum is what we would get as contribution to the diffuse extragalactic background if the AGN were unresolved. This ‘average’ AGN spectrum can not be directly compared to other studies in which power-law fits of the spectra of individual AGN are averaged (e.g. Mukherjee et al. 1997). However for the purpose of comparison with the diffuse extragalactic background co-adding of the observed intensity spectra without any normalization or fitting procedure is the appropriate method. Since the radio catalogues are incomplete near the galactic plane we do not expect – and in fact we do not get – identifications for sources located at $|b| \leq 10°$. Thus effectively there are only $\sim$10.4 steradian sky area which we have searched for point sources and which is to be used to derive the corresponding average γ-ray intensity. The results is shown in Fig.1 separately for FSRQs and BL Lacs.

The sum of the γ-ray intensity contribution of all 44 AGN is about 7% of the total diffuse background intensity. It is interesting to see that the γ-ray spectrum of the average BL Lac seems to be harder than that of the average FSRQ. The difference in spectral index is $\delta s = 0.12 \pm 0.08$ and is thus not very significant which is mainly due to the large uncertainties in the average BL Lac spectrum. This does not imply that in single viewing periods BL Lacs have always harder spectra than FSRQ. In fact we see a remarkable spread of spectral indices for both classes of objects when individual viewing periods are considered (Mukherjee et al., 1997). We also know that individual sources can change their spectrum: there is a trend that the spectrum hardens with increasing flux level (Mücke et al. 1996). But this concerns individual sources. The spectrum of the average in both object classes appears to be different, and therefore they would contribute with different spectral characteristic to the diffuse γ-ray background.

The spectrum of the average AGN is dominated by that of the FSRQs and it differs significantly from that of the observed diffuse extragalactic background (Kniffen et al. 1996; Sreekumar et al., 1997) as we show in Fig.2. When fitting the ratio of both spectra with a power-law we find the background spectrum harder than that of the average AGN by $\delta s = 0.15 \pm 0.04$ when all energy bins are considered and by $\delta s = 0.17 \pm 0.045$ when only the data with very good statistics between 70 MeV and 4 GeV are considered. The goodness-of-fit for a constant is $8 \cdot 10^{-3}$ and $3.5 \cdot 10^{-3}$, respectively, which corresponds to about 2.7σ significance. A Fischer-Snedecor-test indicates that with 3.5σ significance a linear relation is a better fit to the intensity ratio than a constant. Especially between 70 MeV and 4 GeV the uncertainty of the background intensity is so small that the assumption of Gaussian statistics for the uncertainty of the intensity ratio can be regarded as a reasonable approximation. Since we see some objects only at flare state when they tend to have harder spectra, the true average spectrum of AGN may be even softer and thus further away from agreement with the observed spectrum of the γ-ray background.

There is no cut-off visible in the γ-ray spectra with the possible exception of a weak deficiency below 100 MeV for the FSRQs which may be the outer extension of the usual roll-over at a few MeV (Schönfelder et al. 1996). However, the expected spectral form of the average intensity is not necessarily power-law. Here we have summed over many sources with different spectra. Also some of the individual sources have changed their γ-ray spectrum over the last years. A summation over different power-law like spectra results in a positive curvature of the average spectrum (Brecher and Burbidge 1972). Given the spread in spectral indices for the 44 sources we can estimate that the averaging should change the spectral index by around 0.1 between 100 MeV and 10 GeV.

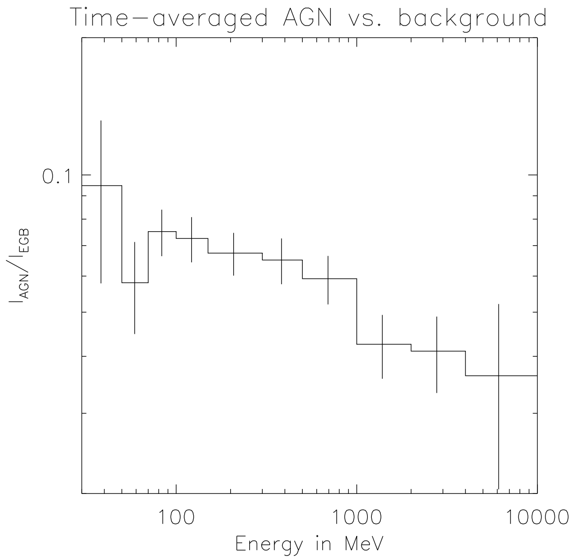

Fig. 2. The ratio of the average intensity of all observed AGN to that of the extragalactic diffuse γ-ray background. This ratio is not compatible with a constant and thus the observed AGN would, if they were unresolved, give a softer diffuse emission than we observe in the background. This implies that the background can not be the superposition of unresolved AGN with the same characteristics as the observed objects.

We have also searched for systematic deviations from power-law behaviour in the γ-ray spectra of the 44 AGN. For each individual AGN we have fitted a power-law spectrum to the data. The difference between this fit and the measured intensity in the ten energy bands weighted by the observational uncertainty, i.e. $\chi = (I_{fit} - I)/(\delta I)$, has been summed for all N FSRQ and BL Lacs, respectively, to obtain the net deviation

$$\chi_{tot} = \frac{1}{\sqrt{N}} \sum_{i=1}^{N} \chi_i \qquad (1)$$

where the applicability of Gaussian statistics has been assumed for the renormalization $\frac{1}{\sqrt{N}}$.

We have verified with Monte-Carlo simulations that there are no significant deviations from a Gaussian distribution of the number χ_{tot}. The results are shown in Fig.3. No significant deviations from power-law behaviour in the AGN spectra are observed, either for FSRQ or for BL Lacs. The BL Lac fit statistic is noisy.

3. The peak spectra

A large fraction of AGN is variable at γ-ray energies. Any cut-off arising from opacity effects will be more prominent at high flux levels since then the intrinsic photon density of the source

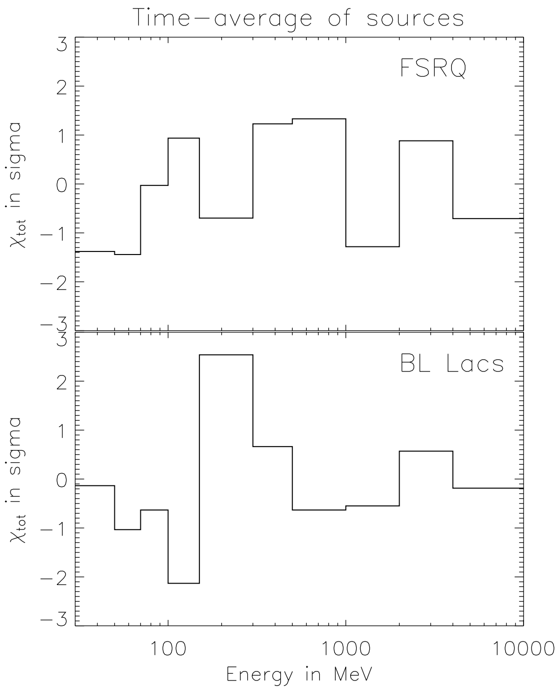

Fig. 3. The summed power-law fit statistic of the 33 identified FSRQ and 11 BL Lacs in the total EGRET allsky data according to Eq.1. There is no significant deviation from power-law behaviour in the average FSRQ and BL Lac spectrum. The two extreme values with opposite sign between 100 MeV and 300 MeV in the BL Lac result are unlikely to be real.

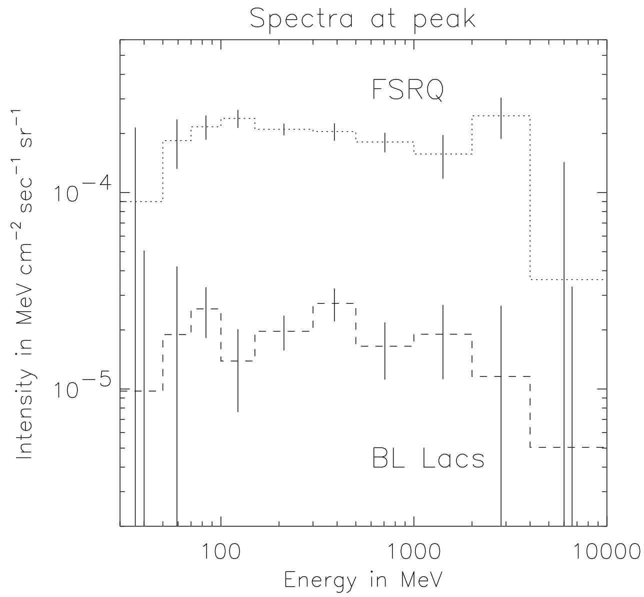

Fig. 4. The summed intensity spectrum of the 28 variable FSRQ and 6 variable BL Lacs at the time of the highest flux level above 100 MeV. The error bars are derived by gaussian error propagation of the individual uncertainty measures. The FSRQ spectrum at peak is significantly harder than the spectrum of the average FSRQ in Fig.1.

is high. We have therefore chosen a subsample of AGN for which at least a moderate level of variability can be found. These sources are indicated in the variability column in Table 1. The light curves of the individual sources have been taken from the second EGRET catalogue (Thompson et al., 1995) and from the standard viewing period analysis of the EGRET group at MPE. In total we are left with 28 FSRQs and only 6 BL Lacs which are variable. The analysis is now similar to that described in the previous section except that the spectra are not derived on the basis of the summed data of Phases I-III but only on data of the viewing periods in which the sources showed the highest flux levels. We should note that detections with formal significance $\leq 4\,\sigma$ have not been considered. In case of two or more viewing periods of comparable duration and comparable source flux preference has been given to data taken with smaller aspect angle. The results for the summed spectra are presented in Fig.4 while the summed power-law fit statistic is shown in Fig.5.

There is not very much change compared to the average behaviour in case of BL Lacs. One has to keep in mind that we are now left with 6 objects and the statistics are not sufficient to distinguish general trends from pathological individuals.

The behaviour of FSRQs during their peak phase is more interesting. At first we see that the flare spectra are harder than the average, at least between 100 MeV and a few GeV. This is a confirmation of a claim by Mücke et al. (1996) who found a hardening of the γ-ray spectra with increasing flux level for 8 highly variable AGN. When fitting a power-law to the intensity ratio of average FSRQ at peak and total average FSRQ we find the spectrum of the average FSRQ at peak harder than that of the time-average by $\delta s = 0.19 \pm 0.05$ when all energy bins are considered and by $\delta s = 0.18 \pm 0.06$ when only the data with very good statistics between 70 MeV and 4 GeV are considered. The goodness-of-fit for a constant is $2.5 \cdot 10^{-3}$ and $7.5 \cdot 10^{-3}$, respectively, which corresponds to about 2.7σ significance. A Fischer-Snedecor-test indicates that with 4.0σ significance a linear relation is a better fit to the intensity ratio than a constant.

We also see that at energies below 70 MeV and at energies above 4 GeV the peak spectra show some evidence of a cut-off which is more prominent in summed fit statistic than in the summed intensity. It should be noted that the error bars for the summed intensity are mainly determined by sources with poor statistics, i.e. short exposures or large off-axis angles. These sources usually contribute very little to the summed fit statistic since both at low and high energies the uncertainty in counts exceeds the number of detected counts. Thus the χ_i that goes into the summation in Eq.1 is practically restricted to $-1 \ll \chi_i \leq 1$. This is different for sources with good statistics for which even at highest energies the number of observed and expected counts is roughly between 0.5 and 10. Thus the summed fit statistic is dominated by sources with good statistics and its results can not be compared directly to the summed intensity spectra.

At high energies a cut-off would be the expected behaviour since the strength of opacity effects depends directly on the flux level. Though the low-energy deficit is significant at 50-70 MeV the average flux *per source* at flare state is still a factor of

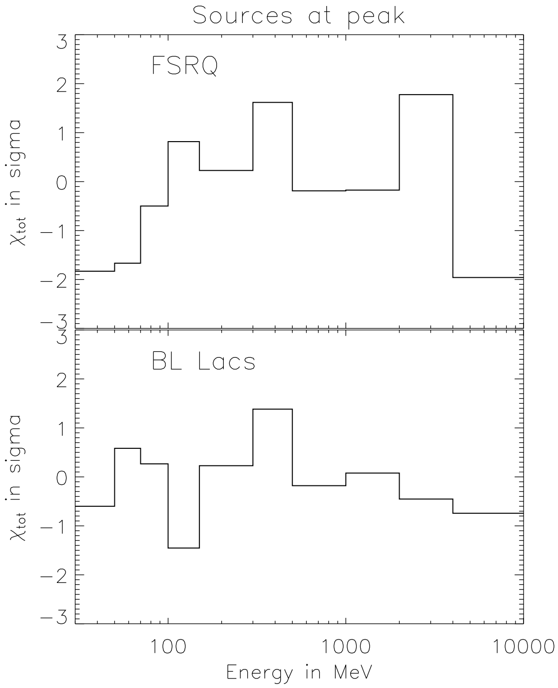

Fig. 5. The summed power-law fit statistic of the 28 variable FSRQs and 6 variable BL Lacs at the time of the highest flux level. There are deviations from power-law behaviour in the peak FSRQ spectrum at high energies and at lowest energies. The BL Lacs at peak do not show a signature of spectral structure.

2.0 ± 0.6 higher than in the time-averaged case (cf. Fig.1). The flux per source at 30-50 MeV is the same as in the time-averaged case. Thus it appears that the γ-ray flux below $\sim$ 50 MeV does not change, or at least not in phase with the γ-ray flux above 100 MeV.

If the γ-ray flaring spectrum of FSRQ is indeed a power-law above 70 MeV, which is then cut off at a few GeV due to increasing opacity, we may underestimate the significance level of this cut-off in our analysis. The reason is that the power-law fit tries to fit both the power-law part and the cut-offs, and therefore will underestimate the power-law part at medium energies which is in principle the null hypothesis in the statistical test for cut-offs. This effect can be observed in Fig.5 as a strong preponderance of positive deviations between 100 MeV and 4 GeV.

To get a better idea of the significance level of the cut-offs we have repeated the power-law fits for the peak phases of FSRQs under the constraint that now the fit is based on the energy band of 70 MeV to 4 GeV and then extended to calculate the true deviations in the outer energy bands. The result is shown in Fig.6. At energies below 70 MeV there is a deficiency of intensity compared to power-law behaviour with total statistical significance of 3.0σ while at high energies above 4 GeV we observe an intensity deficit with 2.6σ significance. As mentioned before the statistical significance has to be inferred from the summed fit statistic and it cannot be easily compared to the summed intensity spectrum.

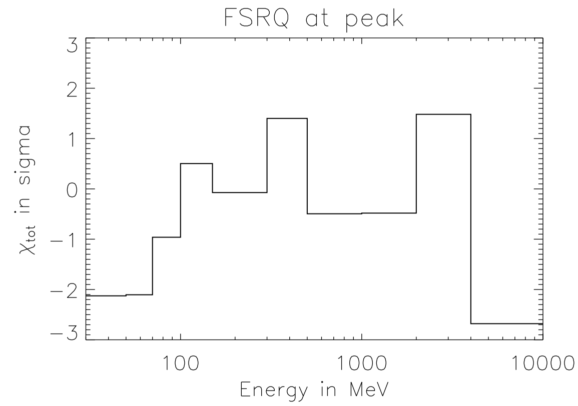

Fig. 6. The summed power-law fit statistic of the 28 variable FSRQ at the time of their peak flux level. In contrast to Fig.5 here the power-law fit is based only on the data between 70 MeV and 4 GeV, i.e. omitting the outer energy bands for which a deviation was suspected. The total statistical significance of the spectral breaks is 3.0σ at low energies and 2.6σ at high energies.

This result is stable against the choice of source. The highest flux level of a source does not necessarily imply the highest significance. We have tested whether our analysis is influenced by data with poor statistics by excluding all sources with formal significance of less than $6\,\sigma$ in the viewing period of peak flux. There was no change in the summed fit statistic beyond small statistical fluctuations. On the other hand, some sources have strong secondary maxima in their γ-ray light curves or have been observed at similar flux levels in adjacent viewing periods. To do the opposite test we have extended our data base by including all observations which yielded an integrated flux of $S \geq 10^{-6}$ cm^{-2} sec^{-1} or for which the derived flux was within $2\,\sigma$ of the peak value. Again our conclusion remained unchanged. The problem with the latter test is that though the statistical basis improves, individual sources, which appear three or four times, start to influence the result. The fact that our result is indeed robust and does not depend on a specific selection criteria, gives us confidence that it is real.

3.1. Possible systematics

Pulsar data show that at low energies the effective area of EGRET needs to be decreased from the value determined by the pre-flight calibrations. The accuracy of this correction factor can be estimated to be better than 30% at 30 MeV to 50 MeV and better than 10% at 50 MeV to 70 MeV (Fierro 1995, §3.4). There is another source of uncertainty at low energies which has to do with spill-over. At γ-ray energies below 100 MeV EGRET's effective area decreases rapidly (Thompson et al. 1993). Hence photons with original energy of around 100 MeV, which are misidentified as of lower energy, get a strong weight and mimic a high intensity at low energies. For the typical E^{-2} spectrum around 10% of the low energy photons are due to this spill-over. Standard EGRET software for spectral fits accounts for this spill-over as far as the relation between counts and intensity is concerned. However this effect also influences the effective point-spread function at low energies which is calculated under the assumption of an $E^{-2.1}$ spectrum. Since the possible error in the point-spread function is around 10% we expect corresponding uncertainties in the likelihood fits of similar order. In total we estimate less than 50% systematical uncertainties in the intensity level at lowest γ-ray energies and around 20% in the second energy band which is to be compared to the total statistical uncertainty in the summed intensity spectrum of quasars in Fig.4 where we have 130% at 30 MeV to 50 MeV and 32% at 50 MeV to 70 MeV. In both cases the statistical uncertainties are much larger than the systematic uncertainties so that the former are a fair measure of the total uncertainty at low γ-ray energies.

At high γ-ray energies the spill-over does not play a strong rôle, since EGRET's effective area changes only weakly with energy in this range. Nevertheless possible calibration errors of effective area and point-spread function may influence the result. Also if a significant fraction of the γ-ray sources is misidentified, then by using the positions of the radio sources we may underestimate the number of observed photons at high energies where the point-spread function is most narrow. Here it is instructive to compare Fig.6 to the corresponding result for the average emission of FSRQs in Fig.3. There we had no signal for a high-energy cut-off. We have tested this also for the case that the power-law fit is derived only between 70 MeV and 4 GeV (as in Fig.6) with similar result: there is not even a 1σ indication for a cut-off beyond 4 GeV. Since any systematic effect should influence also the average FSRQ spectrum we can be sure that the observed high energy cut-off in the peak FSRQ spectrum is real. A misidentification of the γ-ray sources with FSRQ in general, such that the γ-ray spectra discussed here are not those of FSRQ, has been found extremely unlikely in statistical studies (Mattox et al. 1997).

We have tested the reliability of our method by Monte-Carlo simulations. These simulations would detect systematic problems in the analysis tools, which may arise from the small photon numbers both at low and at high γ-ray energies. We did not detect significant systematic deviations from a Gaussian distribution of the variable χ_{tot} of Eq.1.

4. Discussion

4.1. The deficit at low energies

We have seen in the previous section that in case of FSRQ the γ-ray spectra deviate from power-law below 70 MeV. This is most significant with 3.0σ when the emission of variable sources at flare state is considered. In the time-averaged spectrum the effect is less pronounced which indicates that if there is a deficit in the average spectra, it will be weaker since we have better statistics there.

The extrapolation of X-ray data or the OSSE spectra for many sources imply a spectral break at a few MeV energies. These breaks have to be extended features regardless of their origin, even if an annihilation feature is superimposed. This is because the standard radiation processes like inverse Compton scattering are not monochromatic, when the target photon distribution is neither beamed or monochromatic. So even if there were a sharp break in the electron spectrum, the corresponding break in the γ-ray spectrum would be smeared out. It is, however, questionable whether this is sufficient to account for the observed deficit below 70 MeV, which is a factor 10 higher in energy than the typical break energy. EGRET's statistics are limited in this energy range, and hence it needs some effort to produce such a strong signal at 50-70 MeV. We would then also expect a signal at 70-100 MeV where the statistics are much better.

We therefore prefer to interprete our result in the sense that the γ-ray emission of FSRQ between a few hundred keV and a few GeV is not a one-component spectrum, but rather the superposition of different emission processes.

If the jet material consists of pair plasma we may expect annihilation and lepton-lepton bremsstrahlung to dominate the spectrum up to a few tens of MeV while inverse-Compton scattering is more efficient at higher energies (Böttcher and Schlickeiser 1995). The comptonisation part of the spectrum is related to the electron spectrum at high particle energies where the physical reaction timescales are shortest. This may explain why at flare state we see a deficit below 70 MeV.

In case the jet is made of ordinary matter we have to consider bremsstrahlung and Coulomb interactions besides the inverse Compton scattering.

Generally the observed behaviour can also be caused by a low-energy cut-off in the electron injection spectrum (Böttcher and Schlickeiser 1996).

4.2. The cut-off at high energies

BL Lacs are defined as having only weak, if any, optical lines. That translates to them having only little backscattering material in the vicinity of the central machine. Hence we can expect different environmental conditions in BL Lacs and quasars, as far as opacity is concerned. The main source of opacity – photon-photon pair production – requires a sufficient number of target photons of the energy

$$\epsilon \geq \frac{2\left(m_e\, c^2\right)^2}{(1-\mu)\, E_\gamma} \tag{2}$$

where μ is the collision angle cosine in the observers frame, and E_γ is the energy of the γ-ray to be absorpted.

Standard calculations show that the interaction of γ-rays with themselves is reduced due to the equivalent of the Klein-Nishina effect, which applies when the target photon energy is very much larger than the limit given by Eq.2 (Pohl et al. 1995, Dermer and Gehrels 1995). Interactions of γ-rays with the X-ray continuum may affect the total γ-ray spectrum. What we observe, a cut-off only at highest energies, looks more like an additional target photon source coming into play. This could be an accretion disk, accretion disk emission backscattered by thermal clouds, or synchrotron photons produced in the jet itself.

For γ-rays with dimensionless energy ϵ_1 the optical depth for pair production by collisions with ambient photons of energy ϵ is

$$\tau_{\gamma\gamma} = 2\pi \int dz \int d\mu\,(1-\mu) \int_{\frac{2}{\epsilon_1(1-\mu)}} d\epsilon\; \sigma\, n_{ph} \tag{3}$$

where

$$\sigma = \frac{3\,\sigma_T}{16}(1-\beta^2)\left[(3-\beta^4)\ln\frac{1+\beta}{1-\beta} - 2\beta(2-\beta^2)\right] \tag{4}$$

with

$$\beta = \sqrt{1-\frac{2}{\epsilon\epsilon_1(1-\mu)}}\;. \tag{5}$$

For the original accretion disk photon the collision angle is unfavorable ($\mu \approx 1$) so that the UV photons can only interact with γ-rays of 100 GeV energy or more (Böttcher and Dermer 1995). In the direct comptonization of the accretion disk photons the Klein-Nishina cut-off may lead to spectral turn-overs at around 10 GeV (Böttcher et al. in prep.): that is a basic characteristic of the emission process and can not account for cut-offs which occur only at flare state.

In case of the backscattered accretion disk photons

$$n_{ph} = \frac{\eta L\, z_c}{6(4\pi)^2 \epsilon\, z^3 c}\,\delta(\epsilon-\epsilon_0) \tag{6}$$

a target photon energy $\epsilon \approx 50$ eV is sufficient to produce a cut-off at a few GeV observed γ-ray energy. Here the delta-function is a simple approximation of the accretion disk spectrum with luminosity L and $\eta z_c/z^2 \ll 1$ is the assumed re-scattering rate with scattering optical depth $\tau_{rs} = \eta z_c/z$. Then

$$\tau_{\gamma\gamma} \simeq \frac{L_{46}\tau_{rs,-5}}{z_{-2}} \int_0^{\sqrt{1-\frac{1}{\epsilon_0\epsilon_1}}} d\beta\, \frac{\beta}{(1-\beta^2)^2} \times \left[(3-\beta^4)\ln\frac{1+\beta}{1-\beta} - 2\beta(2-\beta^2)\right] \tag{7}$$

with z in units of 0.01 pc and $\tau_{rs,-5}$ in units of 10^{-5}. If $\tau_{rs,-5}$ is larger than unity, $\tau_{\gamma\gamma}$ increases sharply beyond unity and produces a cut-off in the γ-ray spectrum at around 6 GeV (before redshift). However, correlations between optical depth and γ-ray flux above 100 MeV can only occur when the γ-ray outburst is due to an increased level of target photons, for instance an accretion disk flare. Any variation in the spectrum of radiating electrons in the jet will have no impact on the optical depth.

If electrons with Lorentz factors of $\sim 10^6$ do exist in the jets (as is required for the TeV emission of BL Lacs), then these will produce a synchrotron continuum up to X-ray energies, which provides a large number of target photons for pair production. The optical depth for this process is

$$\tau_{\gamma\gamma} \simeq 4\,\frac{L_{47}}{r_{1d}\,\delta_{10}^4}\left(\frac{E_\gamma}{5\,\mathrm{GeV}}\right) \tag{8}$$

where δ is the Doppler factor of the jet in units of ten, r_{1d} is the effective jet radius in light days ($3\cdot 10^{15}$ cm) in the jet frame, and L_{47} is the $\nu\,F(\nu)$ synchrotron luminosity at energy $2\delta^2(m_e\,c^2)^2/E_\gamma$ in units of 10^{47} ergs/sec. So if a γ-ray outburst is caused by the injection of a large number of high-energy electrons, the γ-ray emission above a few GeV may be self-damped. However, detailed simulations of cooling pair plasma including first order and second order Fokker-Planck coefficients for all interaction processes (Böttcher, Pohl, and Schlickeiser, in prep.) show that the high end of the synchrotron spectrum is likely to be swamped by synchrotron-self-Compton emission, which may have a hard spectrum in the relevant energy range so that L_{47} in Eq.7 increases with ϵ, i.e. decreases with E_γ. In that case the cut-off would be very smooth and the energy at which it occurs would vary strongly for different X-ray luminosities and Doppler factor. Thus there would be no good argument why the bulk of FSRQ considered here should show the cut-off at roughly the same energy.

To summarize: though opacity can in principle account for cut-offs at a few GeV photon energy, and seems to be required to explain the correlation with the γ-ray flux level, there is no clear answer as to the source of the target photons for the photon-photon pair production. However, our findings will further constrain models and simulations for the evolution of pair jets.

4.3. The relation to the diffuse γ-ray background

We have seen that the time and source averaged γ-ray spectrum of AGN is softer than that of the extragalactic γ-ray background. The spectrum of the average AGN is dominated by that of FSRQ, partly since we have three times more objects of this class than BL Lacs, partly since individual FSRQ are on average brighter. It is interesting to see that the average BL Lac has a spectrum which is compatible with that of the γ-ray background and harder than that of FSRQ. If unresolved AGN would indeed be responsible for the bulk of the γ-ray background, the BL Lacs may have to play a stronger rôle than previously thought. Here we outline a scenario which would account for this.

The BL Lacs have on average a much smaller redshift with values between 0.031 and 0.94, while more than 50 % of the objects in the FSRQ class have redshifts in excess of 1.0. This indicates that in case of FSRQ we observe a fair range of the luminosity function directly, in contrast to the BL Lac case where we see only the tip of the iceberg. In other words, we expect the γ-ray $\log N/\log S$ distribution of BL Lacs to peak at lower γ-ray fluxes than that of FSRQ. As a result the contribution of BL Lacs to the diffuse extragalactic γ-ray background may be strong despite the small number of directly observed objects, and hence it may be that BL Lacs provide the bulk of the γ-ray background. This would of course require that FSRQ and BL Lacs do not have drastically different evolution properties. The reader should note that at least for radio selected BL Lacs co-adding of undetected sources has resulted in a excess of around 3σ significance (Lin et al. 1997), which provides further evidence that this class of sources does emit γ-rays at lower flux levels.

There is yet another effect by which BL Lacs can contribute to the extragalatic γ-ray background. Distant BL Lacs may emit γ-rays at energies higher than 100 GeV like the close-by objects seen by Whipple. These γ-rays will pair produce on the low-energy extragalactic background before reaching us. Since the pairs will immediately comptonize the microwave background, the energy of the TeV γ-rays will go into an electromagnetic cascade and finally reappear in the form of γ-rays at only a few GeV energy (Coppi and Aharonian 1997). Depending on the luminosity distribution between GeV and TeV emission of the average BL Lac, this process may dominate over the direct contribution to the GeV background for particular redshifts z. This effect would results in a hardening of the background spectrum in the EGRET energy range.

We should however not completely exclude the possibility that the spectrum of the extragalactic γ-ray background is ill-determined. The separation of background and galactic emission due to cosmic ray interactions with thermal gas is relatively easy to do by correlation between intensity and the gas column density. In contrast the expected spectrum of the inverse Compton emission is similar to that of the extragalactic background and the intensity varies little with position at high latitudes, so that we we cannot exclude the possibility that part of the background intensity at higher γ-ray energies is misidentified inverse Compton emission.

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