Does the Blazar Gamma-ray Spectrum Harden with Increasing Flux? – What We Learned from EGRET

Giridhar Nandikotkur[1,2], Keith M. Jahoda[2], R. C. Hartman[2], Reshmi Mukherjee[3], P. Sreekumar[4], M. Boettcher[5], R. M. Sambruna[2], Jean H. Swank[2]

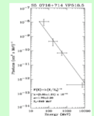
1 Univ. of Maryland at College Park   2 NASA(GSFC)   3 Barnard College & Columbia Univ.   4 Indian Space Research Org.   5 Astrophysical Institute, Ohio Univ.

ABSTRACT

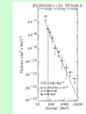
The Energetic Gamma Ray Experiment Telescope (EGRET) on the Compton Gamma Ray Observatory (CGRO) discovered gamma-ray emission from more than 67 blazars during its nine-year lifetime. We conducted an exhaustive search of the EGRET archives and selected all the blazars that were observed multiple times and were bright enough to enable a spectral analysis using standard power-law models. The sample consists of 18 flat-spectrum radio quasars (FSRQs), 6 low-frequency-peaked BL Lacs (LBLs) and 2 high-frequency-peaked BL Lacs (HBLs). We do not detect any clear pattern in the variation of spectral index with flux. Some of the blazars do not show any statistical evidence for spectral variability. The spectrum hardens with increasing flux in a few cases. There is also evidence for a flux-hardness anti-correlation at low fluxes in five blazars. The well observed blazars (3C 279, 3C 273, PKS 0528+134, PKS 1622-297, PKS 0208-512) do not show any overall trend in the long-term spectral dependence on flux, but the sample shows a mixture of hard and soft states. We observed a previously unreported spectral hysteresis at weekly timescales in all the three FSRQs for which data from flares lasting for 3-4 weeks were available. All three sources show a counterclockwise rotation despite the widely different flux profiles. We analyze the observed spectral behavior in the context of various inverse-Compton mechanisms believed to be responsible for emission in the EGRET energy range. *Our analysis uses the EGRET skymaps that were regenerated to include the changes in performance during the mission.*

ANALYSIS and SAMPLE

- *Use of Recalibrated Maps:* The detection efficiency of EGRET varied throughout the mission due to aging of the spark-chamber gas between refills and a hardware failure in 1997. An energy dependent effect was also observed in the degradation. The method used to calibrate the efficiency up to Cycle 4 did not deal with this energy-dependence adequately. Our analysis used the recalibrated maps.
- Four interval spectrum using energy (in MeV) intervals 30-100, 100-300, 300-1000, 1000-10000 for faint sources.
- Ten-interval spectrum 30-50, 50-70, 70-100, 100-300, 300-1000, 1000-2000, 2000-4000 and 4000-10000 for bright sources
- Flux > 100 MeV was another parameter of interest.
- Data from multiple viewing periods were combined to get a single spectrum when the source was faint.
- We reanalyzed *all 9 years of data from all the blazars* detected by EGRET. There are 97 sources: 66 FSRQs, 17 LBLs and 3 HBLs, 10 FSR sources & 1 radio galaxy
- 26 of these sources were observed multiple times, and were used for spectral variability studies. The sample consisted of 18 FSRQs, 6 LBLs and 2 HBLs, listed in the tables.



4-point spectrum from 0716+714



10-point spectrum from PKS 0528+134

HBLs
1101+384 (Mrk 421)
PKS 2155-304

LBLs
0219+428 (3C 66A)
0430+2859
0537-441 (PKS)
S5 0716+714
1219+285 (PKS,ON 231)
1222+216 (4C 21.35)
2200+420 (BL Lac

FSRQs	
0208-512 (PKS)	1406-076 (PKS)
0528+134 (PKS)	1611+343 (OS+319)
0827+243 (OJ 248)	1622-297 (PKS)
0917+449	1622-253 (PKS)
0954+556 (4C 55.7)	1633+382 (4C+38.41)
1156+295 (PKS)	1730-130 (NRAO 530)
1222+216 (4C 21.35)	1830-210
1226+023 (3C 273)	2230+114 (CTA 102)
1253-055 (3C 279)	2251+158 (3C 454.3)

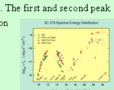
BLAZARS- OBSERVATIONAL FEATURES

Power Law spectrum:

The photon spectrum obeys a power law $dN/dE = k*E^{-\alpha}$ indicating that the radiation could be generated from a power law distribution particles.

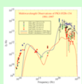
Broad band spectral features:

A plot of $\nu*F\nu$ (ergs/cm^2/s) versus ν(Hz) shows two peaks. The first and second peak are generated by synchrotron and inverse-compton radiation respectively



Classification based on peak-position:

Source	1st Peak Freq.	2nd Peak Freq.
FSRQ	Far-IR to IR	Gamma rays (GeV)
LBL	IR-Optical	Gamma rays (GeV)
HBL	X-rays	Gamma rays (TeV)



RESULTS 1: SPECTRAL AVERAGES and SPECTRAL VARIABILITY

A plot of spectral index vs. Log(synchrotron peak frequency) separates the space into FSRQs, LBLs, HBLs

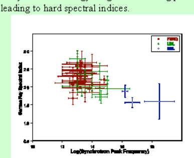
FSRQs have lowest peak frequency. EGRET energy range lies on decreasing portion of the inverse-Compton peak leading to soft spectral indices.

HBLs have highest peak frequency. EGRET energy range lies on rising portion of the inverse-Compton peak leading to hard spectral indices.

LBLs are in between.

Spectral Averages

66 FSRQs : 2.26 +/- 0.03
17 LBLs : 2.14 +/- 0.08
3 HBLs : 1.68 +/- 0.09

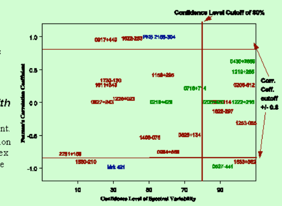


Long Term Variability

- Using Chi-squared test.
- We detect statistical evidence for spectral variability (at a confidence level of >80%) in 10 of the 26 blazars
- Low confidence levels due to large error bars.

Correlation of Spectral index with Flux (> 100 MeV)

- Using Pearson's correlation coefficient.
- Using a cutoff of 0.8 for the correlation coefficient, we found the spectral index to be correlated with flux in 10 of the 26 blazars (including those with two observations where there was visual evidence).



RADIATIVE PROCESSES IN BLAZAR JETS

Synchrotron Radiation:

Plasma particles gyrate around the magnetic field lines and produce synchrotron radiation.

Inverse Compton Radiation:

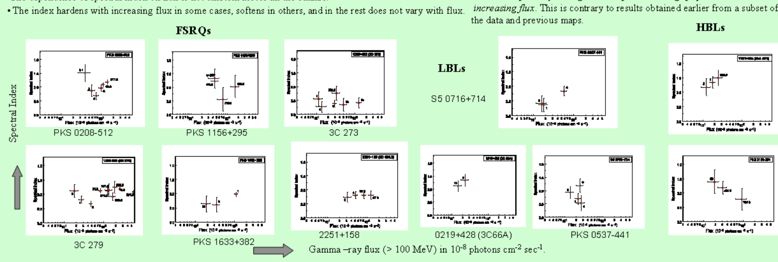
Photons scatter off relativistic electrons gaining energy in the process and are observed at a higher electromagnetic frequency.

The *"seed-photons"* for inverse-Compton radiation can come from

- Synchrotron radiation from the jet
  (Self Synchrotron Compton mechanism **SSC**)
- Directly from accretion Disk.
  Since these photons are external to the jet, the process is dubbed "External Compton from Disk" **ECD**
- Accretion disk photons scattered off broad line region clouds
  "External-Compton from cloud" **ECC**
- Infra-red (IR) photons reflected from the dusty torus surrounding the black hole: **ERC(IR)**

SAMPLE GRAPHS: SPECTRAL DEPENDENCE ON FLUX

- The dependence of spectral index on flux is not uniform across all the blazars.
- The index hardens with increasing flux in some cases, softens in others, and in the rest does not vary with flux.
- *We do not find any strong evidence for hardening of spectral index with increasing flux.* This is contrary to results obtained earlier from a subset of the data and previous maps.



PROCESSES UNDERLYING SPECTRAL VARIABILITY

Spectral variability: An interplay between self synchrotron-Compton (SSC), external component process due to infra-red dust ERC (IR), accretion disk ECD and broad emission line cloud (ECC) photons.

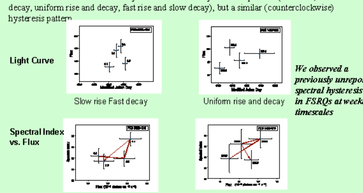
The peak emission frequency for ERC(IR), ECD, ECC processes increases in that order with the latter two influencing the EGRET energy range more.

At low-intermediate EGRET fluxes, SSC process is comparable to the other three. As the source flares, contribution from ERC processes increases. The spectrum is hard or soft based on relative contribution from these processes.

Internal factors: Particle injection energy, injection spectrum cutoff energies, magnetic field, bulk Lorentz factor of the plasma. Current multiwavelength data do not have the energy and time resolution to explore the effect these factors on spectral variability

RESULTS 2: SPECTRAL HYSTERESIS DURING FLARES

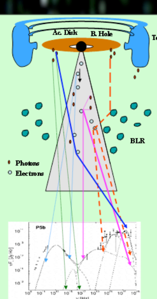
- Hysteresis in the spectral index (30 MeV–10 GeV) vs. Flux (>100 MeV) space at weekly timescales.
- Points showed a counterclockwise progression in time as the flare evolved.
- Effect observed in *all* 3 FSRQs for which flare data from at least 4 contiguous viewing periods was available.
- Flares lasted for about 20~30 days and showed widely different profiles (slow rise, fast decay, uniform rise and decay, fast rise and slow decay), but a similar (counterclockwise) hysteresis pattern



We observed a previously unreported spectral hysteresis in FSRQs at weekly timescales

CONCLUSIONS

1. The gamma-ray spectral index shows a transition from FRSQs to LBLs to HBLs with FSRQs having the softest spectral index and HBLs having the hardest.
2. We did not observe any clear correlation between the gamma-ray spectral index and flux. A majority of blazars did not show any overall trend. The spectra hardened with increasing flux in some, while it softened in some energy intervals for few others. In blazars where the spectra varied and did not show an overall trend, the sample consisted of a mixture of hard and soft states.
3. We observed a previously unreported counterclockwise hysteresis at weekly timescales in the spectral index vs. flux space. The effect was consistently seen in the flare data from all the 3 FSRQs which were observed for least 4 contiguous viewing periods during the flare. The flux profiles of these sources were very different from each other.
4. Gamma-ray spectral variability can arise out of a combination of several physical parameters that are both internal and external to the jet. The current data do not have the required energy and time resolution to narrow down the parameter-space used in the models due to EGRET's limitations. Future missions like GLAST should be able to provide more accurate spectral information at a higher time resolution.
5. We obtained a value of 2.25 +/- 0.03 for the average spectral index of all the blazars observed by EGRET. This is very close to the spectral index of 2.24+/-0.01 for the extragalactic gamma-ray background observed below 2 GeV which make blazars as one of the significant contributors to the EGRB. But the EGRB data beyond 2 GeV suggest the necessity of increased contribution from other sources.



Peak 1: Synchrotron Radiation

Peak 2. Accretion Disk Black Body

Peak 3. Self Synchrotron Emission (SSC)

Peak 4. External Compton Disk (ECD)

Peak 5. External Compton clouds (ECC)

Inverse Compton emission for FSRQs and LBLs consists of contributions from ECC, ECD, ERC(IR) mechanisms whereas in the case of HBLs, SSC mechanism is the main source for Inverse-Compton emission.

RESULTS 3: HOW DO BLAZARS CONTRIBUTE TO THE EXTRA-GALACTIC GAMMA-RAY DIFFUSE BACKGROUND?

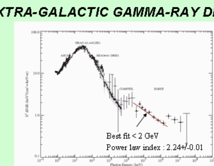
A bulk of the extra-galactic gamma-ray background (EGRB) is assumed to be from unresolved blazars which is based upon the following facts

1) The previously measured average spectral index of all observed blazars is 2.15+/-0.04 (Mukherjee et al. 1997 ApJ 490) which is quite close to the spectral index for diffuse gamma-ray background determined to be 2.10+/-0.10 (Sreekumar et al. 1998, ApJ 194)

2) Assuming the flaring state of blazars to be harder than the quiescent state (as suggested by prior results), Stecker& Salamon (1996, ApJ 464, 600) were able to fit the concave shape of EGRB extracted from previous maps.

Strong et al. (2004, ApJ 613, 956) published a more current shape of EGRB using recalibrated data. The broadband spectrum shows a break at 2GeV. The points below the break seem to obey a power law but the emission increases beyond 2GeV.

Our analysis *does not support* the assumption that the flaring-state in blazars have a harder spectrum than the quiescent states. Hence, any discussion of blazars as sources of EGRB has to rest on the proximity of the spectral indices.



Strong et al.(2004) ApJ 613, 956

Our best fit to EGRB (from Strong et al. 2004) *below 2 GeV* has an index of 2.24 +/- 0.01

Average Spectral Index of all Blazars from our analysis: 2.25 +/- 0.03

The proximity of the two indices below 2 GeV makes blazars a prime candidate for sources of diffuse emission. The current EGRET blazar data does not have the sensitivity to measure the blazar spectrum accurately beyond ~2 GeV. But the current theoretical models *do not point* towards a possible break in the blazar spectrum ~2 GeV. The blazar broadband spectrum under predicts the EGRB beyond 2 GeV. This suggests the necessity of increased contribution from other sources at energies >2 GeV