Analysis of the Spectral Energy Distributions of Fermi bright blazars

S. Cutini, D. Gasparrini, and P. Giommi
ASI Science Data Center, ASDC, ESRIN, Frascati, Italy

M.N. Mazziotta
Istituto Nazionale di Fisica Nucleare, Sezione di Bari, 70126 Bari, Italy

C. Monte
Istituto Nazionale di Fisica Nucleare, Sezione di Bari, 70126 Bari, Italy and Dipartimento di Fisica "M. Merlin" dell’Università e del Politecnico di Bari, Italy

on behalf of Fermi LAT collaboration

Blazars are a small fraction of all extragalactic sources but, unlike other objects, they are strong emitters across the entire electromagnetic spectrum. In this study we have conducted a detailed investigation of the broad-band spectral properties of the gamma-ray selected blazars of the Fermi LAT Bright AGN Sample (LBAS). By combining the accurately estimated Fermi gamma-ray spectra with Swift, radio, NIR-Optical and hard-X/gamma-ray data, collected within three months of the LBAS data taking period, we were able to assemble high-quality and quasi-simultaneous Spectral Energy Distributions (SED) for 48 LBAS blazars.

I. INTRODUCTION

The Large Area Telescope (LAT) on board of the Fermi Gamma Ray Space Telescope, launched on 11 June 2008, provides unprecedented sensitivity in the $\gamma$-ray band (20 MeV to over 300 GeV, Atwood et al. 2009) with a large increase over its predecessors EGRET [Thompson et al. 1993], and AGILE [Tavani et al. 2008]. The first three months of operations in sky-survey mode led to the compilation of a list of 205 $\gamma$-ray sources with statistical significance larger than 10$\sigma$ [Abdo et al. 2009a].

As largely expected from the previous results, most of the high Galactic latitude sources in this catalog are blazars [Abdo et al. 2009b]. One of the most effective ways of studying the physical properties of blazars is through the use of multi-frequency data. This approach has been followed assembling the Spectral Energy Distributions (SEDs) of many radio, X-ray, and gamma-ray selected blazars. In all cases, however, the effectiveness of the method was limited by the availability of only sparse, often non-simultaneous, flux measurements covering a limited portion of the electromagnetic spectrum.

With Fermi, Swift, and other high-energy astrophysics satellites simultaneously on orbit, complemented by other space and ground-based observatories, it is now possible to assemble high-quality data to build simultaneous and well sampled SEDs of large and unbiased samples of AGN.

We derive the detailed SED of a subsample of 48 Fermi blazars using simultaneous or quasi-simultaneous data obtained from Swift and other ground and space based observatories.

II. MULTI FREQUENCY OBSERVATIONS

We describe the multi-frequency observations of LBAS blazars carried out between August and October 2008 with Fermi, and between May 2008 and January 2009 with Swift and other space and ground-based facilities.

A. Fermi LAT data analysis and gamma-ray energy spectra

The Fermi-LAT data from 4 August to 31 October 2008 have been analyzed, selecting for each source only photons belonging to the diffuse class (Pass6 V3 IRF) [Atwood et al. 2009]. Events within a 15° Region of Interest (RoI) centered around the source have been selected. In order to discard photons from the Earth albedo, events with zenith angles larger than 105° with respect to the Earth reference frame [Abdo et al. 2009a] have been excluded from the data samples.

A maximum likelihood analysis (gtlike) has been used to reconstruct the source energy spectrum. A model is assumed for the source spectrum as well as for the diffuse background components, depending on a set of free parameters. The Galactic diffuse emission is modeled using GALPROP package while the extragalactic one is described by a simple power law [Abdo et al. 2009a]. The method has been implemented to estimate the parameters in each individual energy bin (2 bins per decade, starting from 100 MeV), and the parameters obtained from the fits are used to evaluate the sources fluxes. For each energy bin the source under investigation and all nearby sources in the RoI are described by one parameter.
representing the integral flux in that energy bin. The
diffuse background components are modeled with one
single parameter each, describing the normalization.
For each bin, only fit results with a significance larger
than $3\sigma$ have been retained. Depending on the flux
and energy spectrum, 4 to 7 bins had positive detec-
tions for each AGN in the sample.

Once the differential flux in each energy bin $\phi(E)$
has been evaluated, the corresponding SED is then
obtained by multiplying the differential flux by the
square of the central energy value of that bin, i.e.,
$\nu F(\nu) = E^2 \phi(E)$ where $E = h\nu$. The vertical error
bars represent only the statistical errors. The system-
atic uncertainties in the effective area for the Pass6
V3 DIFFUSE event selection have been estimated to
be 10% at 100 MeV, 5% at 562 MeV and 20% for
energies greater than 10 GeV [Abdo et al. 2009].

B. Swift data analysis

The Swift Gamma-Ray-Burst (GRB) Explorer
[Gehrels et al. 2004] is a multi-frequency, rapid re-
response space observatory that was launched on 20
November 2004. To fulfill its purposes Swift car-
ties three instruments on board: the Burst Alert
Telescope [BAT, Barthelmy et al. 2003] sensitive in
the 15-150 keV band, the X-Ray Telescope [XRT,
Burrows et al. 2005] sensitive in the 0.3-10.0 keV
band, and the UV and Optical Telescope (170-600 nm)
[UVOT, Roming et al. 2005]. The very wide spectral
range covered by these three instruments is of crucial
importance for blazar issues as it covers where the
transition between the synchrotron and inverse Com-
ton emission usually occurs.

The primary objective of the Swift scientific pro-
gram is the discovery and rapid follow up of GRBs. How-
ever, there are periods when Swift is not en-
gaged with GRB observations and the observatory
can be used for different scientific purposes. The
sources observed through this secondary science pro-
gram are usually called Swift fill-in targets. Since
the beginning of its activities Swift has observed hun-
dreds of blazars as part of the fill-in program [e.g.,
Giommi et al. 2007]. With the launch of AGILE
and Fermi, the rate of Swift blazar observations in-
creased significantly, leading to the observation (and
detection) of all but 6 blazars in the LBAS sample.

The Swift database currently includes 119 observa-
tions of 48 LBAS blazars that were carried out ei-
er either simultaneously or within three months of the
Fermi LBAS data taking period. We used the UVOT,
XRT and BAT data of these observations to build our
SEDs. Some blazars were observed several times in
the period that we consider in this paper; in such cases
we considered only the exposures where the source was
detected at minimum and maximum intensity by the
XRT instrument.

1. UVOT data analysis

Swift observations are normally carried out so
that UVOT produces a series of images in each of the
lenticular filters (V, B, U, UVW1, UVM2, and
UVW2).

Counts were extracted from an aperture of 5", ra-
dius for all filters and converted to fluxes using the
standard zero points [Poole et al. 2008].

The fluxes were then de-reddened using the appro-
priate values of $E(B - V)$ for each source taken from
Schlegel et al. 1998 with $A_H/E(B - V)$ ratios cal-
culated for UVOT filters using the mean interstellar
extinction curve from [Fitzpatrick 1999].

2. XRT data analysis

The XRT is usually operated in Auto State mode
which automatically adjusts the readout mode of the
CCD detector to the source brightness, in an attempt
to avoid pile-up (for details of the XRT observing
tools) [Burrows et al. 2005]. Given the low count
rate of our blazars most of the data were collected us-
ing the most sensitive Photon Counting (PC) mode
while Windowed Timing (WT) mode was used for
bright sources with shorter exposures.

The XRT data were processed with the XRTDAS
software package (v. 2.4.1) developed at the ASI Sci-
ence Data Center (ASDC) and distributed by the
NASA High Energy Astrophysics Archive Research
Center (HEASARC) within the HEASoft package
(v. 6.6.1). Event files were calibrated and cleaned with
standard filtering criteria with the xrtpipeline task
using the latest calibration files available in the Swift
CALDB. Events in the energy range 0.3-10 keV with
grades 0–12 (PC mode) and 0–2 (WT mode) were used
for the analysis.

Events for the spectral analysis were selected
within a circle of 20 pixel (∼47 arcsec) radius,
which encloses about 90% of the PSF at 1.5 keV
Moretti et al. 2003, centered on the source position.
For PC mode data, when the source count rate is
above ∼0.5 counts s$^{-1}$ data are significantly affected
by pile-up in the inner part of the Point Spread Func-
tion (PSF). For such cases, after comparing the ob-
served PSF profile with the analytical model derived by
Moretti et al. 2003, we removed pile-up effects
by excluding events detected within up to 6 pixels
from the source position, and used an outer radius of
30 pixels. The value of the inner radius was evaluated
individually for each observation affected by pile-up,
depending on the observed count-rate.

Source spectra were binned to ensure a minimum of
20 counts per bin to utilize the $\chi^2$ minimization fitting
technique.

We fitted the spectra adopting an absorbed power
law model with photon index $\Gamma_x$. When deviations from a single power law model were found, we adopted a log-parabolic law of the form $F(E) = KE^{(−α+b \log(E))}$ [Massaro et al. 2004] which has been shown to fit well the X-ray spectrum of blazars [e.g., Giommi et al. 2005, Tramacere 2009]. This spectral model is described by only two parameters: $a$, the photon index at 1 keV, and $b$, the curvature of the parabola. For both models the amount of hydrogen-equivalent column density ($N_H$) was fixed to the Galactic value along the line of sight [Kalberla et al. 2005].

3. **BAT hard X-ray data analysis**

We used survey data from the Burst Alert Telescope (BAT) on board Swift to produce 15-200 keV spectra of the blazars presented in this analysis. In order to do so, we used three years of survey data [see Ajello et al. 2009 for details] and extracted the spectra of those blazars that are significantly detected in the 15–55 keV band. Because of the very long integration time these data are not simultaneous with our Fermi data.

Only 15 blazars, among those presented here, were detected by BAT at a significance $\geq 4\sigma$. The spectral extraction is performed as described in [Ajello et al. 2008] and the background-subtracted spectra represent the average emissions of the sources within the time spanned by the BAT survey.

4. **Swift observations of LBAS blazars carried out before May 2008 or after January 2009**

The Swift database includes a number of observations of LBAS blazars that were carried out outside the period that we consider useful to build our quasi-simultaneous SEDs. These measurements are particularly important for the case of blazars that have never previously been observed by any X-ray astronomy satellite and were below the detection threshold of the ROSAT all sky survey. When these Swift observations have been analyzed and published by other authors we use the flux intensities reported in the literature, with particular reference to the latest on-line version of the BZcat catalog [2]. For the cases where the Swift results have not yet appeared in the literature we estimates the X-ray fluxes from the standard pipeline processing that is run at ASDC on all Swift XRT data shortly after they are added to the archive.

C. **Other multi-frequency data**

In order to improve the quality of our SEDs we complemented the Fermi and Swift quasi-simultaneous data with other multi-frequency flux measurements obtained from a number of on-going programs from ground and space-based observatories.

1. **Effelsberg radio observations**

Quasi-simultaneous radio data for 25 sources of the first Fermi bright source catalog were obtained within a Fermi-related monthly broad-band monitoring program including the Effelsberg 100-m radio telescope of the MPIfR [E-GAMMA project Fuhrmann et al. 2007, Angelakis et al. 2008]. From this program, radio spectra covering the frequency range 2.6 to 42 GHz were selected to be within the time period 4 August 2008 to 31 October 2008, i.e., quasi-simultaneous to the Fermi and Swift observations.

2. **OVRO radio data**

Quasi-simultaneous 15 GHz observations of 24 Fermi LBAS sources were made using the Owens Valley Radio Observatory (OVRO) 40 m telescope. These observations were made as part of an on-going Fermi-LAT blazar monitoring program. In this program, all 1158 CGRaBS blazars north of declination $−20°$ have been observed approximately twice per week or more frequently since June 2007 [Healey et al. 2008]. For each source, the maximum and minimum observed 15 GHz flux densities during the 4 August to 31 October, 2008 period were included in the quasi-simultaneous SEDs.

3. **RATAN-600 1-22 GHz radio observations**

Among the 48 objects for which we present Swift and Fermi simultaneous SEDs 32 were observed between September 10 and October 3, 2008 with the 600-meter ring radio telescope RATAN-600 [Korolkov & Parijskij 1979]. The Special Astrophysical Observatory, Russian Academy of Sciences, located in Zelenchukskaya, Russia. These observations, which produced 1–22 GHz instantaneous radio spectra, are part of a long-term program [e.g., Kovalev et al. 2002] to monitor continuum spectra of active galactic nuclei with a strong parsec-scale component of radio emission.

4. **Radio, mm, NIR and optical data from the GASP-WEBT collaboration**

In the period considered in this work, the GLAST-AGILE Support Program (GASP) originated from the
Whole Earth Blazar Telescope (WEBT) \cite{3} \cite[see e.g., Villata et al. 2007, Raiteri et al. 2008a] {3} carried out \( \sim 3000 \) optical (\( R \) band) observations of 19 LBAS blazars, while \( \sim 700 \) near-IR (\( JHK \), Campo Imperatore), and \( \sim 600 \) microwave (230 and 345 GHz, SMA) and radio data (5 to 43 GHz, Medicina, Noto, UMRAO) observations were taken on the same sources. In the SED plots we report the average, maximum and minimum values at each observed frequency in the period 4 August – 31 October, 2008\cite{4}.

5. Mid-infrared VISIR observations

The MIR observations were carried out from 2006 to 2008 using VISIR \cite{Lagage et al. 2004}, the ESO/VLT mid-infrared imager and spectrograph, composed of an imager and a long-slit spectrometer covering several filters in N and Q bands and mounted on Unit 3 of the VLT (Melipal). We performed broad-band photometry in 3 filters, PAH1 (\( \lambda=8.59\pm0.42 \mu m \)), PAH2 (\( \lambda=11.25\pm0.59 \mu m \)), and Q2 (\( \lambda=18.72\pm0.88 \mu m \)) using the small field in all bands (19.2” x19.2” and 0.075” plate scale).

6. Non-simultaneous Spitzer Space Telescope observations

The Spitzer Space Telescope is a 0.85-meter class telescope launched on 25 August 2003. Spitzer Space Telescope obtains images and spectra in the spectral range between 3 and 180 micron through three instruments on board: the InfraRed Array Camera (IRAC), which provides images at 3.6, 4.5, 5.8 and 8.0 microns, the Multiband Imaging Photometer for Spitzer (MIPS), which performs imaging photometry at 24, 70 and 160 micron, and the InfraRed Spectrograph (IRS) which provides spectra over 5-38 microns in low (\( R \sim 60-127 \)) and high (\( R \sim 600 \)) spectral resolution mode. The Spitzer Science Archive include MIPS observations of 8 sources belonging to the LBAS sample, all of them performed earlier than three months from the start of LBAS data taking period.

7. AGILE \( \gamma \)-ray data

The \( \gamma \)-ray data collected by the Gamma-Ray Imaging Detector (GRID) on board of AGILE \cite{Tavani et al. 2008} for energies greater than 100 MeV used in this paper (blue star symbols in the SED figures) are extracted from the First AGILE Catalog of high-confidence sources detected by AGILE during the first 12 months of operations, from 9 July 2007 to 30 June 2008 \cite{Pittori et al. 2009}. The differential AGILE flux values appearing in the SED figures at fixed energy point (\( E=300 \) MeV) have been rescaled from the mean flux above 100 MeV, obtained with a simple power law source model with fixed spectral index \(-2.1\).

III. BLAZAR SED OBSERVATIONAL PARAMETERS

We now estimate some key observational parameters that characterize the SED of our blazars, namely, the peak frequency and peak flux of the synchrotron component (\( \nu_S^{\text{p}} \) and \( \nu_S^{\text{p}} F(\nu_S^{\text{p}}) \)), and the peak frequency and flux of the inverse Compton part of the SED (\( \nu_{IC}^{\text{p}} \) and \( \nu_{IC}^{\text{p}} F(\nu_{IC}^{\text{p}}) \)).

As fitting function we used a simple third degree polynomial:

\[

\nu F(\nu) = a \cdot \nu^3 + b \cdot \nu^2 + c \cdot \nu + d.

\]
FIG. 2: The SED of 0FGL J0722.0+7120 = S50716+714 (left) and of 0FGL J0730.4-1142 = PKS0727-11 (right)

There are some objects (e.g. J0722.0+7120 and J1221.7+2814) in which the soft X-ray band is still dominated by synchrotron radiation, and only the Fermi data can be used to constrain the inverse Compton component, so the above method is subject to large uncertainties. For this reason, in these cases, we have used the ASDC SED interface to fit the simultaneous data points to a SSC model with a log-parabolic electron spectrum [Tramacere 2009]. The best fit to both the synchrotron and inverse Compton components appear as dashed lines in Figs. 2 and 3.

The details regarding the estimation of Spectral Energy Distribution observational parameters are accurately reported in the S. Rainó et al. “Interpretation of blazar SEDs based on broadband quasi-simultaneous observations” Proceedings.

FIG. 3: The SED of 0FGL J1512.7-0905 = PKS 1510-089 (left) and of 0FGL J1522.2+3143 = B2 1520+31 (right)

IV. CONCLUSIONS

We have carried out a detailed investigation of the broad-band (radio to high-energy) spectral properties of the LBAS sample of Fermi bright blazars using a large number of multi-frequency simultaneous observations as well as literature and archival data. Using data obtained with Fermi, Swift, radio/mm telescopes, infra-red, and optical facilities. For the first time high-quality quasi-simultaneous SED of blazars are available for a considerable number of blazars and this subset is representative of the entire LBAS. We have been able to assemble simultaneous or quasi-simultaneous SEDs of a sizable and representative fraction of an homogeneous sample (~45%) of blazars detected during an all sky survey. This collection of high-quality, well sampled, nearly simultaneous, broad-band SEDs for a large number of blazars is unprecedented and allowed us to estimate a number of important parameters characterizing the SED of selected blazars and to address some key aspects of blazar demographics and physics. Indeed we conclude that the distribution of the synchrotron peak frequency is very different for the FSRQ and BL Lac subsamples. In fact for FSRQs it starts at ~10^{12.5} Hz, peaks at ~10^{13.3} Hz and it does not extend beyond ~10^{14.5} Hz, the distribution of BL Lacs is much flatter, starts at ~10^{13} Hz and reaches much higher frequencies (~10^{17} Hz) than that of FSRQs.

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FIG. 4: The SED of 0FGL J1159.2+2912 = 4C29.45 (left) and of 0FGL J1221.7+2814 = ON231= W Comae (right)

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