The F-GAMMA program: multi-wavelength AGN studies in the Fermi-GST era

E. Angelakis\textsuperscript{1}, L. Fuhrmann\textsuperscript{1}, I. Nestoras\textsuperscript{1}, J. A. Zensus\textsuperscript{1}, N. Marchili\textsuperscript{1}, V. Pavlidou\textsuperscript{2} and T. P. Krichbaum\textsuperscript{1}

\textsuperscript{1} Max-Planck-Institut f"{u}r Radioastronomie, Auf dem H"{u}gel 69, Bonn 53121, Germany
\textsuperscript{2} California Institute of Technology, 1200 East California Blvd., Pasadena CA 91125, USA

Abstract. The F-GAMMA program is a coordinated effort of several observing facilities to understand the AGN/blazar phenomenon via a multi-frequency monitoring approach, especially in the era of Fermi-GST. Some 60 prominent sources are monitored monthly with the Effelsberg 100-m telescope, the IRAM 30-m telescope and more frequently but in a less uniform fashion at the APEX 12-m telescope, covering from 2.64 to 345 GHz. The program has been running since January 2007 and here some of its findings are summarized. (a) There are two major variability patterns that the spectra of sources follow, one spectral-evolution-dominated and one achromatic. (b) The FSRQs show higher brightness temperatures indicative of larger Doppler factors at play and (c) a statistically significant radio-\(\gamma\)-ray correlation has been found with a method recently suggested by Pavlidou et al. (in prep.).

1. Introduction

According to our current and rather complete understanding, in terms of system configuration, of the magnificent phenomenon of Active Galactic Nuclei (AGNs), the inconceivable amounts of energy radiated by these systems are generated by a super-massive black hole living in the nuclear region of the host galaxy. The even more extended variety of AGN phenomenologies are attributed to the same system seen at different viewing angles by the admitted elegant unified model, reviewed by Urry & Padovani (1995). Blazars, as the most dramatic manifestation of the AGN phenomenon, display extreme observational characteristics due to their close to our line-of-sight orientation and the consequent boosting effects. Their double humped Spectral Energy Distribution (SED) is explained by means of two components. The low energy peaked one is explained as a synchrotron component whereas the high energy peaked one is assumed to be the result of inverse Compton processes either on external seed photons (from the disc, the torus or the broad line region) or synchrotron photons. What the exact mechanism is, is still unclear. Furthermore, what exactly causes the variability at vast timescale ranges is also unknown and so are numbers of fundamental questions.

Among the several incredible opportunities offered by Fermi-GST is the densely sampled \(\gamma\)-ray light curves and spectra it provides and which for the first time allow really simultaneous multi-energy studies. The F-GAMMA program is utilizing this approach for understanding some of these fundamental questions. In particular, roughly 60 sources have been monitored monthly since January 2007 with the Effelsberg 100-m telescope, the IRAM 30-m telescope and the APEX 12-m telescope covering vast frequency range. The observations at different telescopes are coordinated within 1 week. Here a few findings are discussed after a short introduction to the program.

2. The F-GAMMA program

It has been discussed elsewhere (Fuhrmann et al., 2007; Angelakis et al., 2009) that the F-GAMMA program is the coordinated effort for a multi-frequency study of AGN astrophysics in the light of Fermi-GST gathering data since January 2007. The pivotal facilities are the Effelsberg 100-m telescope covering the range between 2.64 and 43.00 GHz in 8 frequency steps, the IRAM 30-m telescope covering 86, 142, 220 GHz and the APEX 12-m telescope operating at 345 GHz. The monitoring is done monthly on a sample of 60 sources. The observations at these facilities are coordinated within roughly a week. Along with this effort there take place several other closely collaborating programs such as the OVRO monitoring program at 15 GHz, the IRAM 30-m polarization monitoring program (Thum et al. and Agudo et al. (2010)), and the Perugia AIT blazar monitoring (Tosti et al., 2002; Ciprini et al., 2008). Here we present Effelsberg data alone. The light curves produced and animated spectra are constantly updated at www.mpifr.de/div/vlbi/gamma.

3. The sample

The main motivation for this work has been the multi-band approach to AGN physics and especially the blazar phenomenon, in particular the investigation of correlations between the radio and \(\gamma\)-ray emission. For this reason the first sample consisted of 61 blazars (32 FSRQs, 23 BL Lacs, 3 radio galaxies and 3 unclassified blazars) selected mostly on their likelihood of being Fermi-GST detectable (earlier EGRET detections). The release of the LAT Bright AGN Source list (LBAS, Abdo et al., 2009) showed that 29 of the 61 sources (~47\%) were detected by LAT in the first three months of operation. In a major revision of the source sample, LBAS as well as the Fermi-LAT First Source Catalog, were consulted (Abdo et al.).
in order to build up a new source sample with maximum Fermi-LAT detectability and reasonably fast and intense variability. Currently the observed sample includes a total of 65 sources from which 60 are observed monthly. From these, 36 are clarified as FSRQs, 17 as BL Lac and 9 as unclassified blazars (classification by Massaro et al., 2005, 2008, 2009). Additionally, one source is classified as a Seyfert and three are radio galaxies.

From the above discussion it is very clear that the F-GAMMA sample suffers severely from biases and therefore it is statistically incomplete. Nevertheless, extracted generalizations may be tested by careful comparison with other statistically complete samples. In any case, any generalization must be stated with caution.

4. Spectral Variability

Blazar variability has been attributed to several factors and accordingly certain models have been developed to interpret and quantitatively describe it. One could distinguish between two model categories: (a) models which attribute the variability to mechanisms that impose spectral evolution on the observed events such as shock-in-jet models (Marscher & Gear, 1985) or colliding relativistic plasma shells (Guetta et al., 2004) and (b) models which explain the variability in terms of geometrical effects such as systematic changes in the beam orientation (e.g. light-cone effect, Camenzind & Krockenberger, 1992) which could for instance cause a change in the Doppler factor and further induce achromatic changes in the observed radio spectrum. The expected bi-modality in the phenomenological behavior of the observed radio spectra is indeed seen in the F-GAMMA data.

Figure 1 shows the Effelsberg light curves and radio spectra for two representative cases that resemble what would be expected from the previous classification. In the case of 0235+164 the variability is dominated by spectral evolution (hereafter type 1), evidence of a three-stage evolutionary path (Compton, synchrotron and adiabatic losses, Marscher & Gear, 1985). The case of 0814 + 425 on the other hand is representative of achromatic variability indicating some geometrical effect (hereafter type 2).

Interestingly, from the point of view of the variability pattern followed by the observed spectra, all the sources fall in only five classes which comprise modifications of these two basic behaviors.

The fact that there must be a fundamental difference in the mechanism causing the variability becomes evident also from the evolutionary paths followed by the turnover frequency and flux density at that point (S_m, ν_m). In figure 2 are shown the evolutionary tracks for three cases of type 1 and three cases of type 2 after the subtraction of mean quiescent spectra (with S ∝ ν^α and α = −0.5). The former case seems to be described well by Marscher & Gear (1985) whereas type 2 needs a different interpretation. In a forthcoming publication (Angelakis et al. in prep.) we use this approach to estimate source parameters, and investigate the presence of possible quasi-periodicities in type 2 sources.

From average spectra a low and high frequency spectral index can be calculated in order to examine whether there is a significant differentiation between BL Lac and
Angelakis et al.: The F-GAMMA program: multi-wavelength AGN studies in the Fermi-GST era

1

10

10

1

10

100

Turnover Flux density (Jy)

Turnover Frequency (GHz)

0.059+58.1

0.0235+16.4

0.1156+29.5

Fig. 2. The evolution of the peaks of convex spectra in the $S_m - \nu_m$ space for three members of each of the two characteristic classes type 1 and type 2. In every case a quiescent spectrum of $-0.5$ is assumed ($S \propto \nu^{-0.5}$). Members of the same class follow qualitatively the same evolutionary paths.

Fig. 3. The distribution of high-frequency spectral indices for BL Lacs and FSRQs with the former centering around flatter values than the latter.

Fig. 2

10

10

10

1

10

100

Turnover Flux density (Jy)

Turnover Frequency (GHz)

0.0355+50.8

0.0727-11

0.0814+42.5

Using the mean rms $\langle \sigma \rangle$ averaged over all sources at each frequency as a measure of the variability amplitude, one can clearly see a monotonically rising trend as a function of frequency. That is expected from sources which are mostly spectral-evolution-dominated.

In order to investigate the presence of characteristic timescales in the acquired light curves, the first order Structure Function has been used (Rutman, 1978; Paltani et al., 1997; Simonetti et al., 1985). From the time series analysis applied to the first 2.5 years of data, the variability timescales range between 80 and 500 days. From the estimated timescales and on the basis of some fundamental assumptions (causality, a single emitting component), one can estimate the brightness temperatures $T_b = 4.5 \cdot 10^{10} \Delta S \left(\frac{D_L}{\tau(1+z)}\right)^2$, with $T_b$ in K, $\Delta S$ the flux density variations in Jy, $\lambda$ in cm, $D_L$ the luminosity distance in Mpc, $\tau$ the characteristic timescale in days and $z$ the redshift. Figure 4 shows the maximum brightness temperature distribution (calculated from the fastest time scales reliably detected) for FSRQs and BL Lacs. There is a clear and statistically significant separation between the two classes, with the FSRQs showing brightness temperatures systematically higher than the BL Lacs. A possible explanation for this could be that the former undergo stronger Doppler boosting.

6. Time series analysis

The level of variability present at all frequencies and in all sources becomes obvious as excess variance and has been quantified via a formal $\chi^2$ test for which a significance reference level of 99.9% has been adopted. For the first 2.5 years of observations (that is for the first target sample), $\chi^2$ tests show that almost all the sources appear significantly variable at all wavelengths (91% of the sources are significantly variable with the proportion of variable sources dropping towards higher frequencies due to larger measurement uncertainties at these frequencies).

6. Radio versus $\gamma$-ray fluxes

One of the remaining fundamental questions in AGN astrophysics is where and how high energy emission is produced. Searches for correlations between radio and $\gamma$-ray luminosities is used to study the connection between the mechanisms producing them and has been a rather debatable field. The situation becomes even more perplexing due to artifacts that may be introduced by selection biases, redshift dependencies, lack of simultaneity and so forth.

For a sample of 29 F-GAMMA sources from the first sample detected by Fermi-GST, simultaneous $\gamma$-ray and
Fig. 4. The brightness temperature distribution for FSRQs and BL Lacs separately.

radio data have been used to investigate the presence of such a correlation. Figure 5 shows that there indeed exists a correlation. A new Monte-Carlo method has been used to assess its significance and it shows that it is indeed intrinsic. The details of the newly applied method are describe by Pavlidou et al. (in prep.).

Fig. 5. Flux-flux correlation plots with three-month averaged radio data at 4.85 GHz.

7. Conclusions

After 3.5 years of observing, the F-GAMMA program has produced a large volume of data which allows very detailed blazar studies. Some of them have been discussed here:

- The spectrum variability is not erratic but follows only two behaviors: (a) one dominated by spectral evolution and (b) one achromatic variability pattern resembling rather a geometrically induced variability. All the sources fall in these categories and their modifications. Differences in the variability properties of sources from different classes must be sought.
- The high-frequency spectral indices imply a separation between FSRQs and BL Lacs, possibly due to the BL Lacs peaking at higher frequencies.
- A clear distinction in the brightness temperature distributions for BL Lacs and FSRQs may be due to higher Doppler factors at play in FSRQs.
- A newly suggested Monte-Carlo method assesses statistically significant radio and gamma-ray flux correlations.

Acknowledgements. Based on observations with the 100-m telescope of the MPIfR (Max-Planck-Institut für Radioastronomie) at Effelsberg. IN is a member of the International Max Planck Research School (IMPRS) for Astronomy and Astrophysics at the Universities of Bonn and Cologne. This work has made use of observations with the IRAM 30-m telescope.

References

Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010, ApJS, 188, 405
Abdo, A. A., Ackermann, M., Ajello, M., et al. 2009, ApJ, 700, 597
Agudo, I., Thum, C., Wiesemeyer, H., & Krichbaum, T. P. 2010, ApJS, 189, 1
Angelakis, E., Fuhrmann, L., Zensus, J. A., et al. 2009, ArXiv e-prints
Camenzind, M. & Krockenberger, M. 1992, A&A, 255, 59
Ciprini, S., Tosti, G., Nucciarelli, G., et al. 2008, in Blazar Variability across the Electromagnetic Spectrum
Fuhrmann, L., Zensus, J. A., Krichbaum, T. P., Angelakis, E., & Readhead, A. C. S. 2007, in American Institute of Physics Conference Series, Vol. 921, The First GLAST Symposium, ed. S. Ritz, P. Michelson, & C. A. Meegan, 249–251
Guetta, D., Ghisellini, G., Lazzati, D., & Celotti, A. 2004, A&A, 421, 877
Marscher, A. P. & Gear, W. K. 1985, ApJ, 298, 114
Massaro, E., Giommi, P., Leto, C., et al. 2009, VizieR Online Data Catalog, 349, 50691
Massaro, E., Sclavi, S., Giommi, P., Perri, M., & Piranomonte, S. 2005, Aracne, Roma, I
Massaro, E., Sclavi, S., Giommi, P., Perri, M., & Piranomonte, S. 2008, Aracne, Roma, I
Paltani, S., Courvoisier, T., Blecha, A., & Bratschi, P. 1997, A&A, 327, 539
Rutman, J. 1978, IEEE Proceedings, 66, 1048
Simonetti, J. H., Cordes, J. M., & Heeschen, D. S. 1985, ApJ, 296, 46
Tosti, G., Ciprini, S., & Nucciarelli, G. 2002, Memorie della Societa Astronomica Italiana, 73, 1024
Urry, C. M. & Padovani, P. 1995, PASP, 107, 803