Extragalactic jets from every angle
Proceedings IAU Symposium No. 313, 2014
F. Massaro, C. C. Cheung, E. Lopez, A. Siemiginowska, eds.

doi:10.1017/S1743921315001787

Gamma-ray blazars and active galactic nuclei seen by the Fermi-LAT

B. Lott[1], E. Cavazzuti[2], S. Ciprini[2], S. Cutini[2], D. Gasparrini[2] on behalf of the Fermi-LAT collaboration

[1]Centre d Etudes Nucléaires de Bordeaux Gradignan, CNRS/IN2P3, Université de Bordeaux, UMR 5797, Gradignan, 33175, France
email: lott@cenbg.in2p3.fr

[2]Agenzia Spaziale Italiana (ASI) Science Data Center, I-00044 Frascati (Roma), Italy

Abstract. The third catalog of active galactic nuclei (AGNs) detected by the *Fermi*-LAT (3LAC) is presented. It is based on the third *Fermi*-LAT catalog (3FGL) of sources detected with a test statistic (TS) greater than 25 using the first 4 years of data. The 3LAC includes 1591 AGNs located at high Galactic latitudes, $|b| > 10$ (with 28 duplicate associations, thus corresponding to 1563 gamma-ray sources among 2192 sources in the 3FGL catalog), a 71% increase over the second catalog based on 2 years of data. A very large majority of these AGNs (98%) are blazars. About half of the newly detected blazars are of unknown type, i.e., they lack spectroscopic information of sufficient quality to determine the strength of their emission lines. The general properties of the 3LAC sample confirm previous findings from earlier catalogs, but some new subclasses (e.g., intermediate- and high-synchrotron-peaked FSRQs) have now been significantly detected.

Keywords. gamma rays: observations — galaxies: active — galaxies: jets — BL Lacertae objects: general

1. Introduction

Since its launch in 2008, the *Fermi*-LAT has revolutionized our knowledge of the gamma-ray sky. Its unique combination of high sensitivity, wide field of view, large energy range and nominal sky-survey operating mode has enabled a complete mapping and continuous monitoring of the gamma-ray sky to an unprecedented level. The successive AGN list and catalogs, LBAS (LAT Bright AGN Sample,), 1LAC (Abdo *et al.* 2010a) and 2LAC (Ackermann *et al.* (2011)), first and second LAT AGN catalogs respectively, have triggered numerous population studies provided suitable samples, e.g., to probe the Extragalactic Background Light offered suitable target lists to investigate the dichotomy between gamma-ray loud and gamma-ray quiet blazars at other wavelengths serve as references for works on individual sources, etc. Here we present the third catalog of AGNs detected by the *Fermi*-LAT (3LAC) after four years of operation. It makes use of the results of the 3FGL catalog, which includes 3032 sources with a test statistic greater than 25, 2192 sources of which are detected at $|b| > 10$ where b is the Galactic latitude. Among these 2192 sources, 1591 (73%) are associated with high confidence with AGNs and constitute the 3LAC. We will briefly review the association/classification procedure and then present the properties of the 3LAC sample. We will refer the reader to the 3FGL paper for technical details regarding the LAT data analysis.

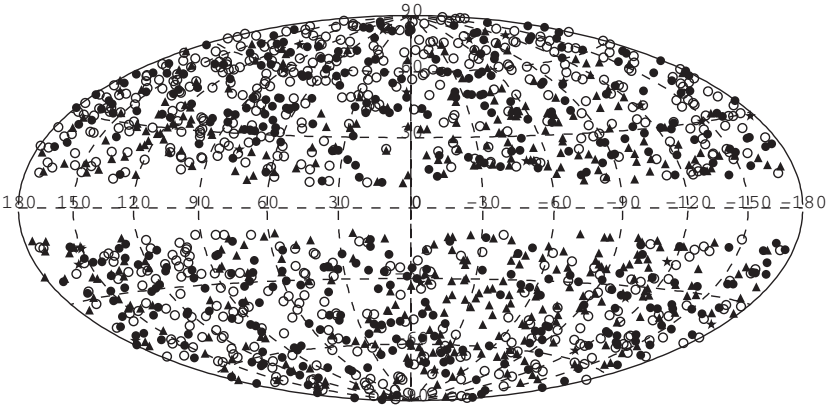

Figure 1. Locations of sources in the 2LAC Clean Sample. Solid circles: FSRQs, open circles: BL Lacs, stars: radio galaxies, triangles: AGNs of unknown type.

2. Associations and classifications

We made use of the same two association methods used in the 2LAC: the Bayesian method and the likelihood-ratio method. Both methods are based on the spatial coincidence between the gamma-ray source and the potential counterpart but are complementary as the likelihood ratio method can accommodate large surveys, while the Bayesian method cannot, at the expense of providing relatively low association probabilities. A total of 72% sources are associated by both methods. The reliability of the association procedure is confirmed by the good match between the distribution of spatial separation between the gamma-ray source and its counterpart and the theoretical expected distribution (also confirming that the size of the error boxes is under control). Besides the traditional optical classification (FSRQs and BL Lacs) based on the strength of the mission lines (only possible when a good quality spectrum is available, otherwise sources are labelled as blazar candidates of unknown type, BCUs), classification based on the position of the synchrotron peaked into low-, intermediate- and high-synchrotron peaked sources was made in a human-controlled fit for each source individually. This constitutes a significant improvement over 2LAC where the procedure was run in a fully automatic way.

Although the fraction of identification of high-galactic sources is fairly large ($\simeq$72%), some identifications are clearly missed as a significant asymmetry between northern and southern galactic hemispheres is observed (only 38% of BL Lacs are observed at $b < -10°$, while little asymmetry is observed for the whole 3FGL sources), manifesting the incompleteness of the parent catalogs.

Among these 2192 sources, 1591 (73%) are associated with high confidence with AGNs and constitute the 3LAC. The 3LAC represents a sizeable improvement over the 2LAC as it includes 71% more sources (1591 vs. 927). The sample includes 467 FSRQs, 632 BL Lacs, 460 BCUs and 32 non-blazar AGNs. The latter comprise 12 Fanaroff-Riley I, 3 Fanaroff-Riley II, 8 compact steep-spectrum (CSS)/steep-spectrum radio sources, 5 narrow-line radio-loud Seyfert I galaxies. Twenty eight sources have duplicate associations. We define a "clean sample" of sources with single counterparts and no analysis flags ensuring reliable gamma-ray parameters. That sample includes 1444 sources (414 FSRQs, 604 BL Lacs, 402 blazar candidates of unknown type (BCUs) and 24 non-blazar AGNs). Note that the BCU population number now almost exactly matches that of FSRQs.

https://doi.org/10.1017/S1743921315001787 Published online by Cambridge University Press

3. Properties of the 3LAC sources

3.1. *Photon spectral index and flux*

One expects the newly detected sources to be fainter, located further or with softer spectra than the 2LAC sources. The newly-detected FSRQs are slightly softer than the 2LAC ones (2.53±0.03 vs. 2.41±0.01), indicating that the LAT gradually detects more lower energy-peaked blazars. In contrast, there is no significant spectral difference between the two sets of BL Lacs, except for the BL Lac LSPs (2.28±0.04 vs. 2.20±0.02). For BCUs, the distribution of the new sources extend further out on the high-index end ($\Gamma > 2.4$), where the overlap with the BL Lac distribution becomes very small. The corresponding sources seem likely to be FSRQs. A fairly strong anticorrelation is observed between the photon spectral index and the position of the synchrotron peak for optically-classified blazars. A similar trend is seen for BCUs as well.

The photon-flux limit is very dependent on the spectral index, as hard sources are easier to detect against the background. This bias essentially vanishes when considering the energy-flux (and in turn the luminosity) limit instead.

3.2. *Redshift*

The redshift distribution shows a broad peak around z=1 for FSRQs. The newly detected FSRQs are located at slightly higher redshift than the 2LAC ones ($\langle z \rangle$=1.33±0.08 vs. 1.17±0.03). The highest redshift for a high-confidence 3LAC FSRQ is $z = 3.10$, the same as in 1LAC and 2LAC. For comparison, the maximum redshift in BZCAT (Massaro *et al.* (2009)) is for an FSRQ with $z > 5$.

The redshift distribution of new BL Lacs is somewhat narrower than that of the 2LAC sources, with a maximum near z=0.3. The redshift distributions gradually spread out to higher redshifts when moving from LSP-BL Lacs to HSP-BL Lacs, a feature already seen in 2LAC. However, the HSP distribution extends to higher redshifts relative to 2LAC, with four HSPs having measured redshifts greater than 1 and one (MG4 J000800+4712) having a redshift greater than 2. Note that only 50% of 3LAC BL Lacs have measured redshifts. Since the release of the 2LAC, lower and upper limits on the redshifts of 134 BL Lacs have been measured by Shaw *et al.* (2013). It was noted by these authors that the average lower limit exceeded the average measured redshift for BL Lacs, indicating that the measured redshifts are biased low. The redshift ranges determined from these limits are very similar for the different subclasses and all cluster at high redshifts, with a median around z=1.2. This is in good agreement with the predictions of Giommi *et al.* (2013).

3.3. *Spectral curvature*

First observed for 3C 454.3 (Abdo *et al.* (2009)) early in the *Fermi* mission, a significant curvature in the energy spectra of many bright FSRQs and some bright LSP-/ISP-BL Lacs is now a well-established feature (Abdo *et al.* (2010), Abdo *et al.* 2010a). The break energy obtained from a broken power-law fit has been found to be remarkably constant as a function of flux, at least for 3C 454.3 (Abdo *et al.* (2011)). Several explanations have been proposed to account for this feature, including $\gamma\gamma$ attenuation from He II line photons Poutanen & Stern (2010), intrinsic electron spectral breaks (Abdo *et al.* (2009)), Lyα scattering (Ackermann *et al.* (2010)), Klein-Nishina effects taking place when jet electrons scatter BLR radiation in a near-equipartition approach (Cerruti *et al.* (2013)) and hybrid scattering (Finke & Dermer (2010)). A total of 91 FSRQs (57 in 2LAC) including all the brightest ones, 32 BL Lacs (12 in 2LAC) and 8 BCUs show significant curvature at a confidence level >99%.

https://doi.org/10.1017/S1743921315001787 Published online by Cambridge University Press

3.4. *Variability*

A variability index was constructed from a likelihood test based on the monthly light curves, with the null (alternative) hypothesis corresponding to the source being steady (variable). A source is identified as being variable at the 99% level if the variability index is equal or greater than 72.44, TS_{VAR} being distributed as a χ^2 function with 47 degrees of freedom.

The features already reported in 2LAC are confirmed, with a large fraction of FSRQs found to be variable (69%), with a fraction for BL Lacs much lower on average (23%) and with a steadily decreasing trend as ν^S_{peak} rises (39%, 23%, 15% for LSPs, ISPs and HSPs respectively).

Please note that the monthly light curves will be extended beyond 48 months. The LAT team will continuously update them and post them on the ASDC site †.

3.5. *Gamma-ray luminosity*

Sources with high gamma-ray luminosity (essentially all FSRQs) are found to have softer spectra on the average than low-luminosity sources (mostly BL Lacs). This correlation between the spectral photon index and the gamma-ray luminosity has been intensively discussed in the context of the blazar sequence. However since 50% of BL Lacs are missing measured redshift, conclusions must be drawn with care. Because of the bias on the measured redshift mentioned above, the HSPs with both limits are more luminous on the average than those with measured redshifts, thus populating a previously scarcely occupied area in the L_γ-Γ diagram. This observation has profound consequences for the significance of the blazar sequence.

3.6. *Synergy with other bands*

The synergy with the neighboring bands is excellent. The 3LAC has 85 sources in common with the Swift BAT 70-month survey (only 9 BAT FSRQs and 7 BL Lacs are missing from 3LAC). It is also worth noting that 96 3LAC sources are present in the V38 INTEGRAL source catalog‡. The synergy is even better with the TeV band as 55 out of the 56 known TeV AGNs are listed in 3LAC. Only 28 of them are found to be variable in the GeV band though.

3.7. *Comparison with BZCAT*

The blazars detected in gamma-rays after 4 years of LAT operation represent a sizeable fraction of the whole population of known blazars as listed in BZCAT. BZCAT represents an exhaustive list of sources ever classified as blazars but is by no means complete. Although a comparison between the gamma-ray detected and non-detected blazars within that sample has no strong statistical significance in terms of relative weights, it is nevertheless useful to look for general trends. The overall LAT-detected fraction is 24% (409/1707) for FSRQs, 44% (543/1221) for BL Lacs and 27% (59/221) for BCUs. A comparison between the redshift, radio-flux density at 1.4 GHz, optical R magnitude and X-ray (0.1-2.4 keV) flux distributions of LAT-detected and non-LAT-detected BZCAT sources shows that the distributions are quite similar, although the former are slightly closer and brighter at all bands than the latter. This observation supports the conjecture that they belong to the same population of sources intermittently shining in the gamma-rays, i.e, their detection is primarily driven by a duty-cycle effect.

† http://www.asdc.asi.it
‡ http://www.isdc.unige.ch/integral/science/catalogue

https://doi.org/10.1017/S1743921315001787 Published online by Cambridge University Press

4. Conclusion and prospects

The 3LAC represents a significant improvement over the 2LAC and should be made public the end of 2014. A master list of ever LAT-detected AGNs is maintained at the ASDC web site, including those sources reported in previous catalogs and now missing from 3LAC. The 4LAC will use more then 5 years of data and will make use of improved data selection and IRFs (Pass8). It will probably constitute another notable step forward. The Fermi mission lifetime is expected to extend at least till 2018.

Acknowledgements

The *Fermi*-LAT Collaboration acknowledges support for LAT development, operation and data analysis from NASA and DOE (United States), CEA/Irfu and IN2P3/CNRS (France), ASI and INFN (Italy), MEXT, KEK, and JAXA (Japan), and the K.A. Wallenberg Foundation, the Swedish Research Council and the National Space Board (Sweden). Science analysis support in the operations phase from INAF (Italy) and CNES (France) is also gratefully acknowledged.

References

Abdo *et al.*, 2009, *ApJ*, 699, 817
—. 2010, *ApJ*, 710, 1271
—. 2010, *ApJ*, 715, 429
—. 2011, *ApJL*, 733, L26
Ackermann, M., *et al.* 2010, *ApJ*, 721, 1383
—. 2011, *ApJ*, 743, 171
Cerruti, M., Dermer, C. D., Lott, B., Boisson, C., & Zech, A. 2013, *ApJL*, 771, L4
Finke, J. D. & Dermer, C. D. 2010, *ApJL*, 714, L303
Giommi, P., Padovani, P., & Polenta, G. 2013, *MNRAS*, 431, 1914
Massaro, E., Giommi, P., Leto, C., *et al.* 2009, *A&A*, 495, 691
Poutanen, J. & Stern, B. 2010, *ApJL*, 717, L118
Shaw, M. S., *et al.* 2013, *ApJ*, 764, 135