SF2A 2018
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SOURCE ASSOCIATIONS FOR THE UPCOMING 4FGL

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Abstract. The upcoming 4FGL Catalog, based on 8 years of Fermi-LAT gamma-ray data, will comprise over 5000 sources. The procedure of association between gamma-ray sources and counterparts at other wavelengths is presented. It is based on two different methods, the so-called Bayesian method and likelihood-ratio method. Some preliminary results are given with special emphasis on Active Galactic Nuclei (AGNs), whose detailed results will be released in a separate catalog in preparation (4LAC).

Keywords: gamma-rays, catalogs

1 Introduction

Since its launch in 2008, the Fermi-LAT, detecting gamma-ray above 30 MeV, has allowed spectacular progress in our knowledge of the high-energy Universe. Source catalogs have contributed significantly to this progress, as testified by the large number of citations that they have attracted. The 4FGL will be the fourth general catalog released by the Fermi-LAT collaboration. Based on 8 years of data, it will be the first catalog using the recent Pass8 data set. The improved performance afforded by Pass8 leads to a 2.3 increase in Test Statistics relative to the earlier 3FGL catalog(Acero et al. 2015), for a period of operation twice as long (8 years vs. 4 years). A preliminary list, the so-called FL8Y comprising 5523 sources, was released in January 2018 and included many of the analysis improvements that will eventually be incorporated in 4FGL (see `https://fermi.gsfc.nasa.gov/ssc/data/access/lat/fl8y/`). The missing element before 4FGL can be produced is an updated version (optimized using Pass8 data) of the Galactic diffuse emission model, improving over the Pass7 version previously used. This talk presents the procedure used in the final step of the catalog creation, namely the association between the gamma-ray sources and counterparts at other wavelengths. The application to a refined version of FL8Y, called Cat8, which uses photons above 50 MeV (instead of 100 MeV for FL8Y) is described. Finally, the contents and preliminary findings of the 4LAC catalog, which will be a spin-off catalog devoted to Active Galactic Nuclei (AGNs) are presented.

2 Description of the association methods

The Bayesian method (Abdo et al. 2010) for the Fermi-LAT was developed by J. Knödelseder following the prescription devised by Mattox et al. Mattox et al. (1997) for EGRET. It relies on the fact that the angular distance between a LAT source and a candidate counterpart is driven by the position uncertainties in case of a real association while it is governed by the counterpart density in case of a false (random) association. In addition to the angular-distance probability density functions for real and false associations, the posterior probability depends on a prior. This prior is calibrated via Monte-Carlo simulations so that the number of false associations can consistently be estimated using the sum of the association-probability complements. A uniform threshold of 0.8 is applied to the posterior probability for the association to be retained. The list of counterpart

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catalogs includes known or plausible gamma-ray-emitting source classes: AGNs, Galaxies, Pulsars, Pulsar Wind Nebulae, Supernova Remnants, Globular Clusters, O-, Wolf-Rayet or Luminous Blue Variable stars, low- and high-mass X-ray binaries or surveys of candidate blazars at other frequencies (radio, IR, X-rays). The current list can be found in the FL8Y accompanying document *.

In complement to the Bayesian method, the Likelihood-Ratio (LR) method (Ackermann et al. 2011, 2015), following de Ruiter et al. (1977) and developed at ASDC provides supplementary associations with blazar candidates based on large radio and X-ray surveys (NVSS, SUMSS, ROSAT..). It is similar in essence to the Bayesian-method but the false association rate is derived from the density of objects brighter than the considered candidate. A final visual inspection of the broad-band spectral energy distributions (SED), checking for blazarness, is performed. While this method is able to handle large surveys, the downside is that the fraction of false associations is notably larger than in the Bayesian method (typically $\simeq$ 10% vs 2%). The overlap between the results of the Bayesian and LR methods is about 75%.

The reliability of the associations is assessed by verifying that the distribution of the angular offset between gamma-ray source and counterpart matches well the expected one in the case of a true association, i.e., a Rayleigh function with its width parameter given by the source positional uncertainty.

3 Association summary

Out of 5457 LAT sources in the E>50 MeV preliminary 8-year list, Cat8, 1834 are unassociated (34%). The association fraction (66%) is similar to that obtained in previous LAT catalogs. The largest source class is that of AGNs, with 3116 blazars and 61 other AGNs (including 38 radiogalaxies). The blazar sample comprises 761 Flat-Spectrum Radio Quasars (FSRQs, +55% relative to 3FGL), 1288 BL Lac-type objects (BL Lacs, +97%) and 1067 blazar candidates of unknown type (BCUs, +82%). The properties of the newly detected blazars are discussed further below. In addition, 9 nearby galaxies (4 of them being new) and 2 starburst galaxies complete the extragalactic census. The Galactic sources include 224 pulsars (+34%), 28 supernova remnants (SNRs, +65%), 18 pulsar wind nebulae (PWNs, +63%), 113 sources (referred to as "spp",+122%) overlapping with known SNRs or PWNs and thus candidates to these classes, 27 globular clusters (+80%) and 6 high-mass X-ray binaries (+100%). It must be noted that the association fraction goes down as sources get fainter (all bright sources are associated), in particular due to their larger error regions. This fraction also drops as sources get closer to the Galactic plane. It decreases from about 85% at high Galactic latitudes to $\simeq$ 40% close to the Galactic plane. The reason for such an effect is twofold. First of all, the number of unassociated sources is large in the region of the Galactic plane. Secondly, the flux limits of the extragalactic-counterpart catalogs are larger due to extinction effects in these directions.

4 Further improvements

In previous FGL catalogs, only high-confidence (P>0.8) associations were reported. However, there is value in bringing lower-confidence associations to the community's knowledge as well. This should foster further investigations and clarify why some detections claimed by different groups (including from the LAT collaboration) do not appear in our catalog. There are 120 extra associations with 0.5<P<0.8, with an estimated number of false associations of 27. On top of 6 high-confidence associations with IRAS counterparts, 3 more have 0.45<P<0.8. We will also report matches with non-identified counterparts in multiwavelength surveys, like the Planck or radio/X-ray surveys. Associations resulting from follow-up observations (e.g., using VLBI) based on earlier LAT-catalogs will be listed with specific flags.

5 Towards 4LAC

The 4LAC catalog will be a companion catalog to 4FGL, devoted to AGNs. It has been a tradition to publish back-to-back general-source and AGNs catalogs since the launch of the Fermi mission. The LAC catalogs include AGNs at $|b| > 10^\circ$, since counterpart catalogs are not as complete in directions close to the Galactic plane as they are elsewhere. Most ($\simeq$98%) of the 4LAC AGNs will be blazars, the others being radio-galaxies or AGNs of different types (Seyfert, Narrow-Line Seyfert 1...). In addition to the information provided in 4FGL, including the optically-based classes (FSRQ, BL Lac or BCU), the 4LAC will list the redshifts and the classes

*https://fermi.gsfc.nasa.gov/ssc/data/access/lat/fl8y/FL8Y_description_v8.pdf

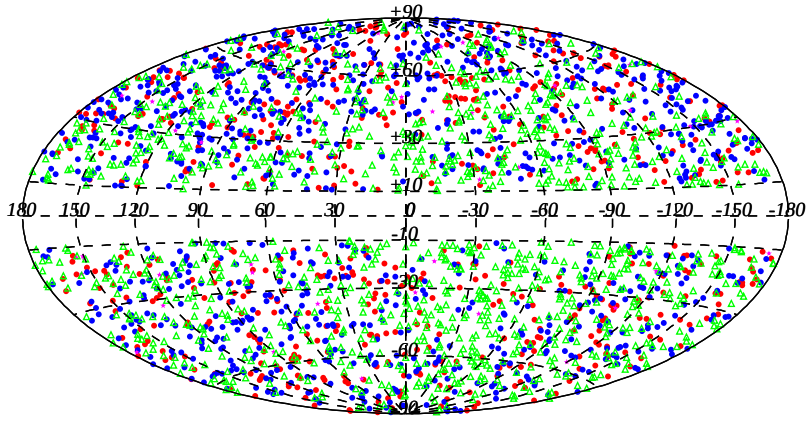

Fig. 1. Locations of Cat8 AGNs above |b|=10° in Galactic coordinates. Red circles: FSRQs, blue circles: BL Lacs, green triangles: blazars of unknown type, magenta stars: other AGNs.

derived from the positions of the synchrotron-peak (ν_{peak}) using archival data as Low-, Intermediate-, High-Synchrotron-Peaked sources (LSP, ISP, HSP resp.) depending on whether $\log(\nu_{peak})$ is lower than 14, between 14 and 15 or greater than 15 respectively. In the making of the 4LAC, SEDs of all AGNs were fit manually by 22 people, leading reliable values of ν_{peak} for $\simeq$75%of sources overall and 87% for FSRQs and BL Lacs together. FSRQs are essentially all LSPs while BL Lacs are more diverse, contributing to all subclasses with 381 LSPs, 326 ISPs and 271 HSPs in Cat8. BCUs with measured SED-based classes are mainly LSPs. Figure 1 displays the loci of the Cat8 blazars in Galactic coordinates. From a visual impression of this Figure, it is clear that sources of different classes are not uniformly distributed, with regions predominantly blue (BL Lacs) and others green (BCUs). This anisotropy results from blazar catalogs being more complete in the Northern Hemisphere than in the Southern one. The excess of BL Lacs in the North is actually quite well compensated by a deficit of BCUs in that region. The overall blazar count mismatch between the Northern and Southern Galactic Hemispheres is about 8%.

The spectral hardness, assessed by means of the photon index from a power-law function fit to the data, is found to be quite different between FSRQs and BL Lacs, confirming the trend observed in previous LAC catalogs. There is little overlap between the photon index distributions of the two classes, with a boundary photon index of 2.2 (most FSRQs have softer spectra while most BL Lacs have harder spectra than a power-law function with such an index). The BCU index distribution straddles that of the two classes and extends beyond 2.6. Interestingly, newly detected blazars (i.e., not reported in previous LAC catalogs) have significantly softer (photon index difference $\simeq$0.15) spectra than the previously reported ones, possibly indicating the emergence of a new population of sources, with SED peaking at lower energy. Although a power-law photon index represents a convenient way to compare the spectral hardness of different sources, essentially all bright FSRQs and BL Lacs show significant spectral curvature.

Variability is a defining properties of blazars. In 4FGL, two sets of lightcurves will be produced using yearly and bi-monthly time bins. Yearly lightcurves have been produced as an exercise for Cat8. A variability index is derived from a comparison of the lightcurves with a constant flux. At the 99% confidence level, 73% of the Cat8 FSRQs and 35% of the BL Lacs are found variable with this approach.

6 Summary

The 4FGL will have an association rate similar to 3FGL (66%) thanks to more complete catalogs and smaller error regions. The number of associated sources (3621 in the preliminary Cat8 list) will be 77% greater than in 3FGL. AGNs will represent approximately 89% of the associated sources ($\simeq$3200 AGNs). The 4LAC, devoted specifically to AGNs, will be released back-to-back with 4FGL.

7 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. This work performed in part under DOE Contract DE-AC02-76SF00515.

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