Characteristics of *Fermi*-LAT Unassociated Sources in the 2FGL Catalog

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Unassociated *Fermi* LAT sources provide a population with discovery potential. Using classification techniques exploiting only the gamma-ray properties, we separate the 2FGL sources into pulsar and AGN candidates, and compare them to the associated source populations.

Abstract

A significant fraction of gamma-ray sources detected by the Fermi Large Area Telescope are not associated with any known gamma-ray emitting object. These sources represent discovery space for new source classes, or new members of existing source classes. We discuss the spatial, spectral and temporal characteristics of the unassociated sources in the second Fermi-LAT source catalog (2FGL). We compare these distributions with the characteristics of the primary source classes (extragalactic vs. Galactic sources) to provide likely source classifications, and compare our results against the total predicted numbers of each source population. We also review the 1FGL unassociated source population, and discuss how changes in the catalog analysis have affected the resulting unassociated source sample.

Source Association in the LAT Catalog

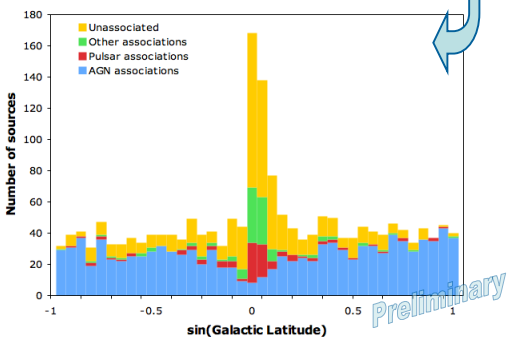
Associating *Fermi* LAT sources with counterparts of interest is performed using a Bayesian probability based on the position match and the chance coincidence in a given direction. The most likely source classes have been considered[1]:

- Blazars (BL Lacs, FSRQs, etc.) ~58%
- Other AGN (Seyferts, Radio Galaxies, etc.) >2%
- Pulsars and binaries (HMXBs, LMXBs, etc.) ~6%
- Other Galactic Sources (SNRs, PWNe, Globular Clusters, etc.) ~4%

Even after such searches, ~30% of *Fermi* LAT source detections remain unassociated with one of these potential counterparts. These sources represent areas of new discovery.

At this time, there is no clear indication of a significantly numerous new class of gamma-ray emitters in the Fermi LAT dataset[2].

2FGL Associations



2FGL Intrinsic Parameters[1]

Intrinsic source parameters for unassociated sources can be compared against patterns of known classes. For 2FGL, the primary intrinsic parameters for separating pulsars from AGN are variability and spectral curvature.

Variability Index

Variability in the gamma-rays is a signature of blazars, with only rare exception. In 2FGL, the variability indicator (TSvar) was provided by a likelihood ratio method which is distributed like χ^2 with 23 degrees of freedom (for the 24 months in the data set).

Curvature Significance

The 2FGL spectral analysis compared a simple power-law model with a curved log-parabola spectral model. For sources where the change in significance from the use of the curved model is significant, the curved model was used for the global fit. A significant curve to the spectrum is a signature of gamma-ray pulsars.

Flux Ratio(s)

The flux for each 2FGL source was determined in five separate energy bands. Hardness ratios and color difference both sample spectral shape without requiring a full fit. However, faint sources are often undetected in multiple bands, making these values somewhat less useful.

LAT Catalog Improvements

The first LAT catalog[4] (1FGL) had a number of known issues that were addressed to some extent in 2FGL[1]. These include:

- Smaller pixel size and shift in registration for the Galactic diffuse model
- Extended sources to reduce multiple detections (e.g. LMC)
- Curved spectra where tests show improvement in detection significance
- Exponentially cut-off power-law spectrum for known gamma-ray pulsars

1FGL used the deviation of the five band fluxes from the best-fit power-law spectrum as an estimate of curvature. 2FGL instead tested each source with both a power-law and a curved (log-normal) spectrum. This curvature significance has been used in the Classification Tree analysis. The spatial distribution of these classified sources types indicates that the pulsar and AGN candidates are distributed as one would expect for the modeled distributions, though source position was not used in the analysis.

The 1FGL unassociated source distribution had an excess of sources in the central degree (±0.5°) of the Galactic plane. We compared the 2FGL unassociated source population to that of 1FGL and found that this distribution is no longer so narrow. This result indicates that an edge effect of the diffuse model at b=0° may have contributed to the excess sources in this region in 1FGL.

Finding Pulsars

Currently detected LAT pulsars are typically:

- Non-variable (VI <41.6 in 2FGL)
- Average cutoff at 2.3 GeV
- Hard $F_{0.1\text{-}0.3}/F_{0.3\text{-}1}$ flux ratio (~1.4) below the cut-off

Blind searches[6] of previously unassociated LAT sources that appear pulsar-like has proved extremely successful at identifying new pulsars. To date, 25 new radio-faint/quiet gamma-ray pulsars have been identified from such sources.

In addition, a consortium of radio astronomers is working closely with the LAT team to provide accurate timing models for radio pulsars. By following up on strong LAT detections, this group has discovered 31 new millisecond and 2 new young pulsars[2].

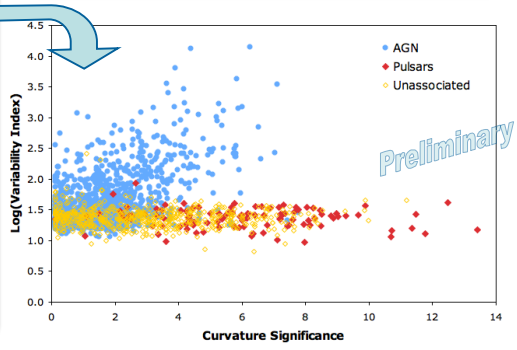
Finding Blazars

Typical blazar characteristics in the LAT are:

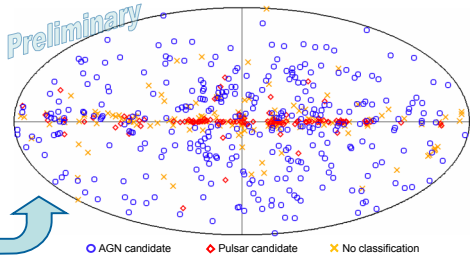
- Time-variable (TSvar > 41.6)
- High probability of association with a known blazar[3]

Since gamma-ray background is significantly higher near the plane, a blazar at low-Galactic latitude must be significantly more luminous to be well-localized. Identifying new blazars from LAT unassociated sources is typically the result of significant variability in the source.

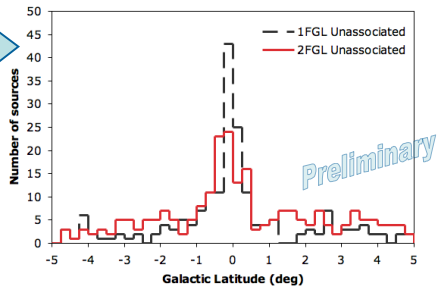
Such transient activity must be followed up by multi-wavelength observations in order to secure a blazar classification. An ongoing program of radio observations is working to fill in the low-Galactic latitude region of AGN surveys. This has significantly improved the AGN association rate at low latitudes.



Classification Tree Results - Spatial Distribution



Galactic Plane Sources



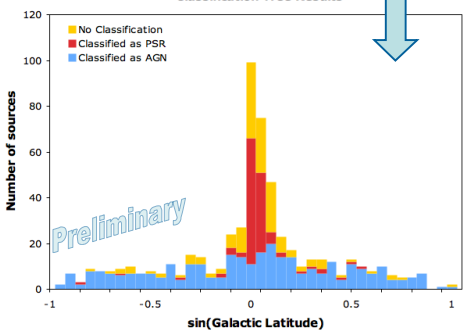
Training the Classification Tree

We considered intrinsic parameters for point sources from the 2FGL Fermi-LAT catalog[1], using the source associations from that catalog. 1077 sources associated with AGN and 108 sources with pulsar associations were used as a training sample for a Classification Tree analysis[2]. The intrinsic parameters that provide significant signal to separate the two source classes (in order of decreasing significance) are:

- Variability Index and Spectral Index
- Curvature Significance and Color difference
- High-energy flux (3-10 and 10-100 GeV bands)
- Low-to-High energy hardness ratio

We then used the model to classify the 2FGL unassociated source population into 315 AGN candidates and 114 pulsar candidates. 144 sources were unable to be classified by this method.

Classification Tree Results



References

1 - Abdo, A.A. et al., 2011, eprint arXiv:1108.1435
2 - Ackermann, M. et al., 2011, eprint arXiv:1108.1202
3 - Ackermann, M. et al., 2011, eprint arXiv:1108.1420
4 - Abdo, A.A. et al., 2010, ApJS, 188, 405.

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