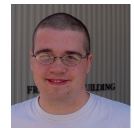
Analysis of Spatially Extended Sources with the Fermi-LAT



Joshua Lande (SLAC/KIPAC/Stanford)
on behalf of the Fermi LAT Collaboration
With Keith Bechtol, Markus Ackermann, and Stefan Funk

Abstract

A large number of candidate Fermi-LAT source classes, including SNRs, Molecular clouds, PWN, Galaxy clusters, and Dark Matter satellites are expected to have angular extents comparable to or smaller than the characteristic per-photon size of the point-spread function. For the detection and identification of these sources as well as for the interpretation of observations of the corresponding source classes, information on the angular extents of the emission regions is tremendously valuable. We present an analysis technique developed to address the finite angular sizes of the sources in analysis of LAT data and take the extension into account in spectral and morphological studies. We then describe a series of Monte Carlo simulations analyzed using this technique that demonstrate the LAT's ability to measure the extensions and spectral characteristics of gamma-ray sources.

Method

The Fermi Large Area Telescope (LAT) is a pair-conversion telescope operating in the energy range 20 MeV to >300 GeV. The LAT has 3 detector subsystems: an anticoincidence detector to identify charged particles entering the instrument, a tracker composed of sixteen tungsten conversion layers interleaved with silicon detector strips, and a calorimeter made up of cesium iodide crystals to measure particle energy.

Photon direction is primarily reconstructed by following the trajectory of electron-positron pairs through the tracker layers back to the photon interaction vertex. Detector geometry and physical processes such as multiple scattering determine the intrinsic PSF of the instrument.

The extension fitting method, named Sourcelike, works by convolving the intrinsic LAT PSF with a spatial model of the candidate source to create a "pseudo-PSF" of the expected source appearance. Parameters of the spatial extension model are then varied to find the shape that most closely matches the spatial distribution of observed photons. Centroid and source extension are fit simultaneously.

The foremost challenge of measuring angular extents with the LAT is to properly account for a PSF that ranges a full 2 orders of magnitude in size over the energy range of the instrument (See Figure 1) and has a long non-Gaussian tail. Photons must also be fit above a diffuse celestial background. Additionally, the front (thin) and back (thick) sections of the tracker are described by distinct PSFs due to the different thicknesses of tungsten foils. In order to address these complications, Sourcelike groups photons into separate energy bands. The photons also can be divided into separate front and back conversion types, effectively treating the LAT as two independent detectors. Photons in an energy band are grouped into spatial bins that scale in size with the changing PSF as a function of energy. The angular sizes of the bins used for analysis narrows at high energies to parallel the improved spatial resolution of the LAT. The model is fit to the data using a binned likelihood analysis.

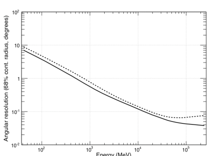


Figure 1: 68% containment radius of the PSF for events converting in the front section of the tracker as a function of energy for normal incidence (solid curve) and 60° off axis (dashed curve). The PSF for γ-rays converting in the back section of the tracker is about twice as wide. From [1].

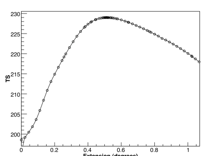


Figure 2: An example extension profile, TS (test statistic) vs. extension, for a high latitude 3e-8 ph cm^{-2} s^{-1} source with a spectral index of 2 and an extension of 0.5°. Sourcelike can used these to calculate errors on the fit extensions or upper limits.

Background components

The gamma-ray sky is filled by both structured and isotropic diffuse backgrounds. When fitting a candidate source, the absolute normalizations of both the source and background components are allowed to float until the PSF-convolved spatial model of the region mirrors the observation. The fraction of observed photons associated with the source can then be found directly from the relative normalizations of source and background in the best fit. The source signal fraction is computed independently in each energy band without the constraint of spectral models for source or background components.

Spectral analysis

Spectral analysis is a separate likelihood calculation following the localization and extension fitting step. Spectral fitting is independent of the particular spatial model because the flux in each energy bin can be calculated directly from the signal fraction in each energy bin. Therefore, the spectral fitting method can be applied to both point-like and extended gamma-ray sources. Spectral fitting proceeds using a similar binned likelihood maximization technique comparing the estimated number of observed source photons to the model predicted flux.

Extension Measurement

A large set of simulated observations of extended sources were simulated using Gtobssim in the LAT Science Tools. The simulation was of 1 year of data using a simulated survey mode pointing history. The diffuse galactic emission was simulated using the GALPROP code with a GALDEF file corresponding to 54_59Xvarh8S. The GALPROP model is described in [2] but an updated conventional model described in [3] was used.

The extragalactic diffuse emission was simulated as an isotropic power-law. Sources were simulated at a low galactic latitude (l=30°, b=2°) and a high galactic latitude (l=25°, b=85°). They were simulated with power-law spectra having photon spectral indices (Υ) of 1.5, 2, and 3 and with >100MeV fluxes of $3*10^{-9}$, 10^{-8}, $3*10^{-8}$, and 10^{-7} ph cm^{-2} s^{-1}. They were simulated with Gaussian extensions with %68 confinement radii of 0°, 0.1°, 0.25°, 0.5°, and 1.0°. For each configuration, 20 sources were simulated.

Each source was analyzed using the Sourcelike code with both a point and an extended source hypothesis. For the measurement of angular extent, photons with energy between 200 MeV and 300 GeV were used. Photons below 200 MeV were excluded because of their large PSF. Spectral fitting of the source was performed using a power-law hypothesis and photons with energy between 200 MeV and 200GeV. The initial guess for the source position was picked randomly within a Dec of ±0.1° and a RA of ±0.1°/cos(Dec).

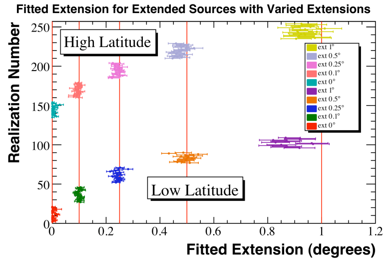


Figure 3: For a bright and hard spectrum source, the extension can be accurately measured anywhere in the sky. In the figure, the fitted sources have a Monte Carlo flux >100 MeV of 10^{-7} ph cm^{-2} s^{-1} and spectral index Υ=1.5. The spectral energy distribution is fit as $dN/dE = N_0\,(E/E_0)^{-\Upsilon}$. The underestimation of angular size at large sizes and low latitudes is being investigated.

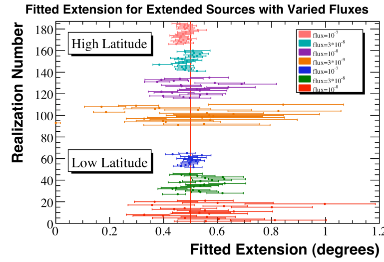


Figure 4: The LAT sensitivity to extension decreases for dimmer sources. Fitted sources have a spectral index Υ=1.5 and an extension of 0.5°.

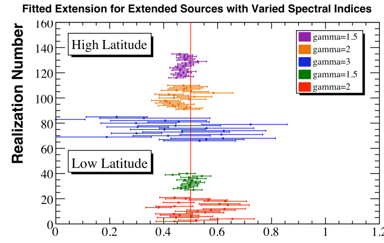


Figure 5: The LAT sensitivity to extension decreases for softer sources. Fitted sources have a flux of 10^{-7} ph cm^{-2} s^{-1} and an extension of 0.5°.

Spectral Measurement

Below are compared spectral fits of simulated extended sources with a point-like and an extended hypothesis. The spectral fits deviate from the generated values when using a point hypothesis but the effect is reduced when using extended hypotheses.

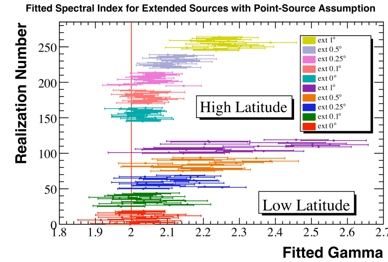


Figure 6: Spectral fitting of bright sources with a point hypothesis. The fit sources have a flux of 10^{-7} ph cm^{-2} s^{-1}. For large sources, the spectral index is biased when fitting with a point hypothesis.

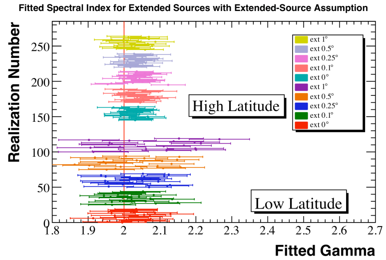


Figure 7: Spectral fitting of the same sources in figure 6 with a Gaussian hypothesis. The spectral bias is reduced when the extended sources are fit with an extended hypothesis.

Conclusion

Over an important range of source flux and spectral index, the LAT is sensitive to source extension. The LAT's sensitivity decreases for softer sources, for dimmer sources, and for brighter backgrounds. This information about angular extent will be valuable for source identification in crowded regions of the sky by providing a method of ruling out possible source associations as well as for interpretation of these sources. Furthermore, for large sources it is important to account for the angular size of a source when performing a spectral analysis to avoid spectral bias.

Acknowledgments

The Fermi LAT Collaboration acknowledges the generous support of a number of agencies and institutes that have supported the Fermi LAT Collaboration. These include the National Aeronautics and Space Administration and the Department of Energy in the United States, the Commissariat à l'Energie Atomique and the Centre National de la Recherche Scientifique / Institut National de Physique Nucléaire et de Physique des Particules in France, the Agenzia Spaziale Italiana and the Istituto Nazionale di Fisica Nucleare in Italy, the Ministry of Education, Culture, Sports, Science and Technology (MEXT), High Energy Accelerator Research Organization (KEK) and Japan Aerospace Exploration Agency (JAXA) in Japan, and the K. A. Wallenberg Foundation and the Swedish National Space Board in Sweden.

References

[1] Atwood, W. B. et al. 2009, ApJ arXiv:0902.1089v1.
[2] A. W. Strong, et al., Astrophys. J. 613, 962 (2004).
[3] Abdo, A. et al. 2009, (submitted to PRL).