Searching for Gamma Ray Sources in the Extra-Galactic Space: A Statistical Analysis of the Fermi LAT Data

A. Sottosanti, D. Costantin, D. Bastieri & A.R. Brazzale
Department of Statistical Sciences, University of Padua

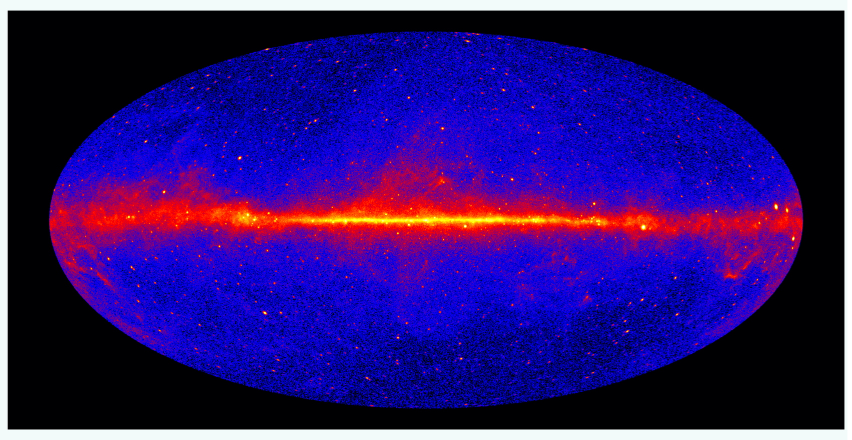
UNIVERSITÀ DEGLI STUDI DI PADOVA

Objectives

This work considers maps of cosmic ray counts of varying energy bins, which are spatially projected onto a rectangular and measured in Galactic coordinates.
We propose an extension of [2] to model the Fermi LAT γ-ray count map, as our data are characterized by a high rate of events and a more intensive background contamination which can not be assumed to be uniform. We abandon the *pixel-by-pixel* approach proposed in [3] to adopt an unsupervised algorithm that simultaneously estimates the number of sources in the cosmic map, their coordinates and their intensities.

The Fermi LAT data

- The LAT is an imaging high-energy γ-ray telescope covering the energy range from about 20*MeV* to more than 300*GeV*.
- We consider photons from the *extra-galactic space* (blue region in the map) with a minimal detected energy of 10*GeV*.



http://fermi.gsfc.nasa.gov/

- One of the main goals of the Fermi project is to detect new γ-ray sources in the *extra-galactic space*, such as *active galactic nuclei (AGN)*, *supernova renmants (SNR)* and *pulsar wind nebula (PWN)* and to distinguish them from the so-called *isotropic diffuse gamma-ray background (IGRB)*, a class of isotropic phenomena that emits γ-rays and is diffuse over the entire map.

Simple source model

- The *Point Spread Function* measures the spread of a single particle around its source.
- The position of a generic photon i emitted by a source j is randomly distributed as

$$(X_i, Y_i)|\mu_j \sim PSF(\mu_j), \tag{1}$$

where μ_j is the vector of coordinates of the origin.
- Because of high-energy counts, we do not use the *XMM Point Spread Function* as in [2], but instead we take into account the modified *King's Point Spread Function* proposed by the Fermi project.
Although this extension assumes that the spread of a particle depends also on its energy level, using high-energy photons we can neglect this assumption and consider the same density function for all the energy bins.

Background model

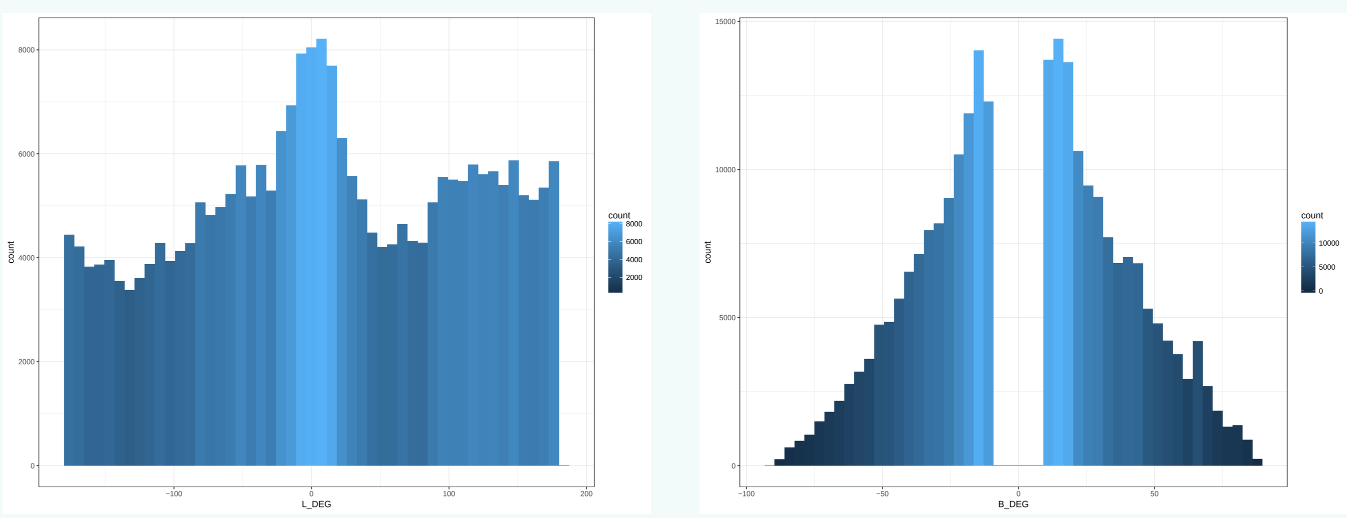


Figure 1: Left, histogram of longitude values of Fermi LAT photons. Right, histogram of latitude values.

- Maps of γ-ray counts are generally characterised by a great amount of photons, due to the nature of the generating phenomena.
- As it emerges from marginal histograms, the assumption of uniform distribution for the background contamination over the map is not realistic.
- Since we concentrate on the region of the extra-galactic space $\chi = \{(x, y) : x \in (-180°, -10°),\ y \in (10°, 90°)\}$, we extend the model specification given in [2] by considering

$$(X_i, Y_i)|\sigma_b \sim Unif(-180, -10) \times Exp(\sigma_b). \tag{2}$$

- The two components can be taken as independent because of the assumption of the background isotropy.

Bayesian mixture modelling

- In practice, we have no information about the real number of sources and their coordinates in space. The origin of each photon is unknown.
- We translate these assumptions into a finite mixture model

$$(X_i, Y_i)|\mu, \sigma_b \sim \omega_0 g_b(X_i, Y_i|\sigma_b) + \sum_{j=1}^{K} \omega_j f_j(X_i, Y_i|\mu_j), \tag{3}$$

where $f_j(.|.)$ is the density of the *Point Spread Function* (1) and $g_b(.|.)$ is the background density (2).
- The a priori distributions for the mixture weights ω and the μ_j's are chosen as in [2], while for σ_b we choose an Inverse Gamma distribution. Moreover, K is itself an unknown parameter, and so we consider

$$K \sim Poi_t(\kappa, \kappa_{min}, \kappa_{max}), \tag{4}$$

where Poi_t is a truncated Poisson, defined over the interval $[\kappa_{min}, \kappa_{max}]$.

Reversible Jump MCMC

- The Reversible Jump MCMC is a simulation algorithm that automatically jumps across parametric spaces of different dimensions. The first step updates the parameters $\Theta_K = (\omega, \mu, \sigma_b)$ fixing the dimension of the mixture. In the second step, a trans-dimensional jump is proposed as follows:
  1. Choose randomly to add or remove a source in the model through *split*, *combine*, *birth* or *death* moves. All of these have probability 0.25 to be selected.
  2. Evaluate the change of dimensionality through a Metropolis ratio and store the results.
- The background contamination is left unchanged and therefore it will never be excluded from the model.
- The final estimate of K corresponds to its posterior mode.

Results

	Known Sources	*Unknown Groups*
Sim.1	105	65
Sim.2	108	62
Sim.3	108	62
Sim.4	105	65

Table 1: Four different runs of the algorithm with 10,000 iterations.

	Selected Clusters	*Know Sources*
Sim.1	93	78
Sim.2	84	71
Sim.3	92	76
Sim.4	93	69

Table 2: Results of the heuristic analysis based on ω.

- We put an upper limit $\kappa_{max} = 170$. After this bound, the algorithm becomes computationally unstable. All the chains converge to this value.
- Although different simulations do not identify the same clusters, more than 100 sources are detected, according to the recent *3FHL catalogue* (Table 1).
- A heuristic analysis of the posterior distribution of the weights ω was used to explore the real nature of the clusters (Table 2).

Conclusion

- Our procedure is capable to estimate simultaneously the number of sources and their positions.
- Fermi LAT data are characterized by a complex background contamination which leads to unstable results.
- Possible extensions of this work will include the background intensity model discussed in [1].

References

[1] Acero, F., et al. "Development of the model of galactic interstellar emission for standard point-source analysis of Fermi Large Area Telescope data." The Astrophysical Journal Supplement Series 223.2 (2016): 26.

[2] Jones, David E., Vinay L. Kashyap, and David A. Van Dyk. "Disentangling Overlapping Astronomical Sources using Spatial and Spectral Information." The Astrophysical Journal 808.2 (2015): 137.

[3] Mattox, James R., et al. "The likelihood analysis of EGRET data." The Astrophysical Journal 461 (1996): 396.

Andrea Sottosanti sottosanti@stat.unipd.it