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Large-scale anisotropy of EGRET gamma ray sources

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In the course of its operation, the EGRET experiment detected high-energy γ-ray sources at energies above 100 MeV over the whole sky. In this communication, we search for large-scale anisotropy patterns among the catalogued EGRET sources using an expansion in spherical harmonics, accounting for EGRET's highly non-uniform exposure. We find significant excess in the quadrupole and octopole moments. This is consistent with the hypothesis that, in addition to the galactic plane, a second mid-latitude ($5^\circ < |b| < 30^\circ$) population, perhaps associated with the Gould belt, contributes to the γ-ray flux above 100 MeV.

1. Introduction

Our rudimentary understanding of the GeV γ-ray sky was greatly advanced in 1991 with the launch of the Energetic Gamma Ray Experiment Telescope (EGRET) on board the Compton Gamma Ray Observatory (CGRO). The science returns from EGRET observations have exceeded pre-launch expectations, increasing the number of known γ-ray sources from 1–2 dozen to the 271 listed in the third EGRET (3EG) catalog [1]. However, of this multitude of sources, only about half have been *definitively* associated with known astrophysical objects. One reason so few sources have been uniquely identified is due to a typical location uncertainty of up to 1° for an EGRET detected gamma-ray source, an area typically containing several potential candidate astrophysical objects. Consequently most of the γ-ray sky, as we currently understand it, consists of unidentified sources.

The EGRET sources appear to arise from several distinct populations. There is an almost isotropic distribution of $\sim$ 100 low/high variability objects, nearly all of which have now been plausibly associated with flaring blazars, a radio bright sub-class of active galactic nuclei [2, 3]. The remaining sources are believed to be within the Milky Way, and there is some speculation that they may comprise two distinct classes. The first class consists of bright sources with generally hard spectra with galactic latitude $|b| < 5^\circ$ of the Galactic Plane, and are thought to be bright objects up to approximately 10 kpc away. There is some evidence of a second population at mid-Galactic latitudes ($5^\circ < |b| < 30^\circ$) consisting of fainter objects with generally steeper spectra. It has been hypothesized that this population is associated with the Gould belt [4, 5], an asymmetric structure in a great circle on the sky tilted 20° to the Galactic Plane. The Gould belt comprises massive O and B stars as well as clusters of molecular clouds and expanding interstellar gas at distance of around 200 pc from earth. The observation of spatial coincidence [6, 7, 8] of low-latitude ($|b| < 10^\circ$) EGRET sources with massive OB stars and supernova remnants provides additional indication that the mid-latitude sources originate in the Gould belt.

Figure 1 shows the intensity map of EGRET sources. Though the correlation with the Galactic Plane is obvious, the hypothesized Gould belt population is not easy to extract using an eyeball fit. In this communication, we apply a power spectrum analysis [9] in an attempt to tease this component out of the bright Galactic Plane sources.

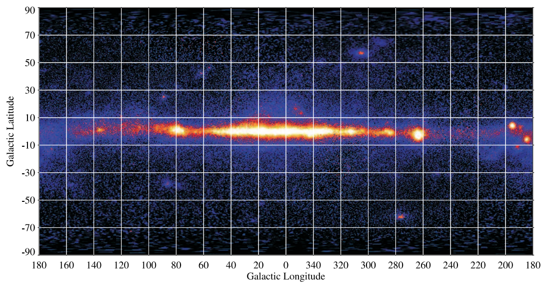

Figure 1. Intensity map of EGRET γ-ray sources with energies above 100 MeV.

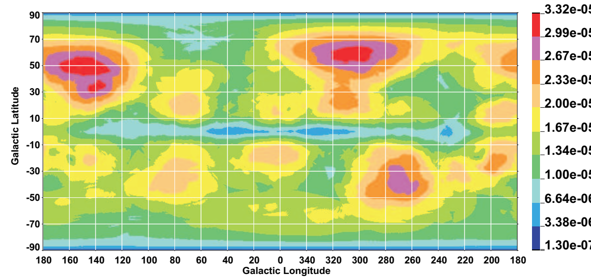

Figure 2. Two-dimensional EGRET detectability map for γ-ray sources (in units of cm^2 s).

2. EGRET Source Detectability

For $E_\gamma > 100$ MeV, the significance for a detection of an isolated point source with EGRET scales as

$$\omega_j \propto F\sqrt{\mathcal{E}/\mathcal{B}} \ , \tag{1}$$

where F is the flux, $\mathcal{E}$ is the exposure, and $\mathcal{B}$ is the intensity of the diffuse γ-ray emission at the region of the source [10]. Following [11], we derive the detectability map considering these three ingredients in turn. First, the populations used in the Monte Carlo simulations are prepared such that they reproduce the observed distribution of the number of sources per flux bin, globally as well as locally. Second, it is necessary to account for the highly non-uniform exposure of the instrument. Thirdly, the diffuse γ-ray background is compensated using the EGRET diffuse model, corresponding to the commonly believed cosmic ray/gas distribution coupling (dynamic balance).

With these considerations in mind, we construct the EGRET detectability map by determining 95% CL limits for a grid on the sky. We determine the limits using the so-called P1234 time span [1], *i.e.*, we request that the maximally significant measurement of the EGRET source has been obtained in the P1234 joint viewing period. This tends to eliminate flaring sources from our sample. The map is shown in Figure 2. To obtain the detectability weights we normalize each angular bin to unity.

3. Angular Power Spectrum

The spherical harmonics form a useful set for expansions of the intensity over the celestial sphere. For a uniform sky coverage,

$$I(\mathbf{n}) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m}\, Y_{\ell m}(\mathbf{n}) \ , \tag{2}$$

where $\mathbf{n}$ is a unit vector that denotes the direction in the sky of each source in the survey.[1] To account for the nonuniform EGRET exposure, we define a weighted intensity

$$I(\mathbf{n}) = \frac{1}{\mathcal{N}} \sum_{j=1}^{N} \frac{1}{\omega_j}\, \delta(\mathbf{n}, \mathbf{n}_j) \ , \tag{3}$$

[1] Throughout this work we use real-valued spherical harmonics, which are obtained from the complex ones by substituting, $e^{i\,m\,\phi} \to \sqrt{2}\sin(m\phi)$, if $m < 0$, $e^{i\,m\,\phi} \to \sqrt{2}\cos(m\phi)$, if $m > 0$, and $e^{i\,m\,\phi} \to 1$ if $m = 0$.

where ω_j is the relative detectability at sky direction $\mathbf{n}_j$, $\mathcal{N}$ is the sum of the weights ω_j^{-1}, and N is the number of sources. Since the eigenvalues of the $Y_{\ell m}$ expansion are uniquely defined

$$a_{\ell m} = \int I(\mathbf{n})\ Y_{\ell m}(\mathbf{n})\ d^2\mathbf{n}\ , \tag{4}$$

the replacement of Eq. (3) into Eq. (4) leads to the explicit form of the coefficients for our set of $N = 124$ EGRET sources

$$a_{\ell m} = \frac{1}{\mathcal{N}} \sum_{j=1}^{N} \frac{1}{\omega_j}\ Y_{\ell m}(\mathbf{n}_j)\ . \tag{5}$$

The coordinate independent angular power spectrum of fluctuations,

$$C(\ell) = \frac{1}{(2\ell+1)} \sum_{m=-\ell}^{\ell} a_{\ell m}^2\ , \tag{6}$$

provides a gross summary of the features present in the celestial distribution together with the characteristic angular scales. The power in mode ℓ is sensitive to variation over angular scales of ℓ^{-1} radians.

If the steady EGRET sources in fact originate from two overlapping great circles associated with the Galactic Plane and the Gould belt, one would expect a strong signal in the quadrupole ($\ell = 2$) moment describing the main component, and a fainter signal in the octopole ($\ell = 4$) moment indicating the spread from a perfect quadrupole. Note that the Gould belt is tilted 20° relative to the Galactic Plane, so one would expect its presence to be manifest in the octopole term which is sensitive to angular scales of about 15°.

For $\ell \geq 1$, the expectation for an isotropic distribution observed with uniform exposure is $\overline{\mathcal{C}}_\ell = (4\pi N)^{-1}$, and the RMS fluctuations are [12]

$$\overline{\Delta\mathcal{C}}_\ell = \sqrt{2/(2\ell+1)}\ \overline{\mathcal{C}}_\ell\ . \tag{7}$$

Figure 3 shows a comparison of the distributions of angular power spectra for isotropically distributed sources observed with uniform exposure ($\overline{\mathcal{C}}_\ell$) and with the EGRET exposure ($\overline{C}_l$). It can be seen that for the four multipole moments of interest, the spread of the distributions corresponding to uniform and non-uniform exposures are similar.

Figure 4 compares the observed angular power spectrum of EGRET to the spectrum expected for an isotropic distribution. Clear excesses are seen for the quadrupole and octopole moments. The probability of the excess for either moment to be consistent with isotropy is estimated (from a fit to the distributions shown in Fig. 3) to be less than $\mathcal{O}(10^{-10})$. This supports the hypothesis that, in addition to the Galactic Plane, a mid-latitude population of sources, associated with the Gould belt, contributes to the observed γ-ray flux above 100 MeV.

Acknowledgements

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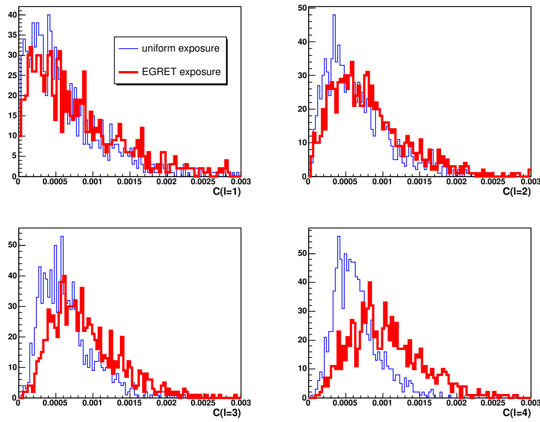

Figure 3. Comparison of the distributions of angular power spectra for isotropically distributed sources observed with uniform exposure and with the EGRET exposure.

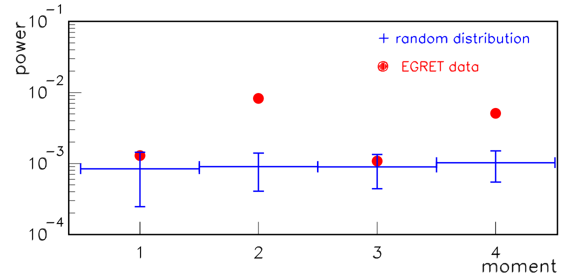

Figure 4. The angular power spectrum of the EGRET four-year observations is indicated by circles. The lines with error bars show the RMS of $\overline{C}_\ell$. The RMS values are obtained from 1000 sets of Monte Carlo simulations of 124 events each, including corrections for ω_j.

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