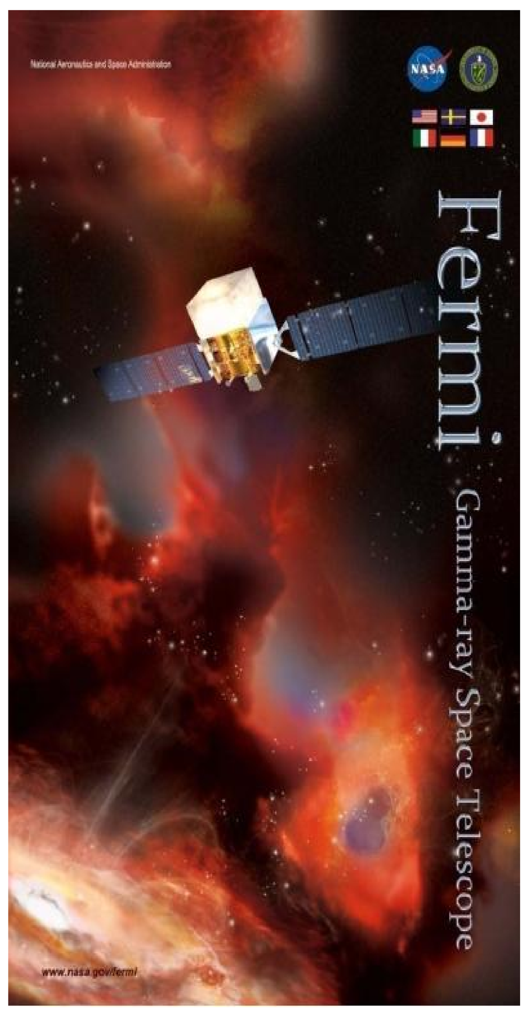

Searches for Cosmic-Ray Electron Anisotropies with the *Fermi*-LAT

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The Fermi Large Area Telescope (*Fermi*-LAT) provides unique high statistics for high-energy cosmic-ray electrons (CREs), with excellent angular resolution. Any anisotropies in the arrival directions of these CRE could potentially be a signature of electrons originating in a nearby source (for energies high enough to avoid heliospheric effects and also depending on the properties of the Galactic magnetic field between us and the source) and could provide information not only on the source parameters and location but also on the solar and Galactic magnetic-field structures. We present methods to search for small to large scale (up to several tens of degrees) anisotropies in high-energy CRE events detected by the *Fermi*-LAT.

Cosmic-Ray Anisotropies

Cosmic Rays (CRs) of GeV-TeV energies are produced in our own galaxy. During their transport from their source of origin to our solar system, CRs scatter on random and irregular components of the Galactic Magnetic Field (GMF) that tend to perfectly isotropize their direction distribution. However, various effects can still generate anisotropies:

- The Compton-Getting effect[1] predicts anisotropies arising from the relative motion of the observer with respect to the local CR plasma. Such anisotropies may arise from the motion of the earth around the sun or the motion of the solar system through the local interstellar medium (the latter not having been detected yet).
- At energies below ~100–200GeV, anisotropies can be created by effects of the magnetic-field inside the heliosphere, that can also show annual variations.
- At higher energies, solar effects become negligible and the observed direction distribution reflects the distribution of CR sources and the propagation of CRs through the GMF. In such a case, large-scale coherent structures in the GMF can cause anisotropies. Also if the observed CR population is produced locally (as in the case of high-energy CREs described below), anisotropies might also arise from the fact that the initial CR direction distribution is highly anisotropic since it is set by the directions of a few local sources.

Cosmic-Ray Electron Anisotropies

The case of Cosmic-Ray Electrons is particularly interesting because, contrary to hadronic CRs, CREs lose their energy rapidly and therefore have a considerably shorter range.

- E>10GeV electrons lose their energy mostly through Synchrotron emission and Inverse Compton scattering. CREs of energies 200GeV (1 TeV) arrive at the earth from relatively nearby locations <1kpc (<0.5kpc) away [2].
- This means that such higher-energy CREs originated from a highly anisotropic collection of few nearby sources (most likely pulsars and SNRs).
- Therefore, depending on the properties of the GMF, ***the detection of excess CREs, with energies high enough to minimize heliospheric effects (i.e. E>100–200GeV), might reveal the presence of such nearby CRE sources.***
- Calculations of the expected CRE anisotropy from the presence of local sources (in this case the Vela SNR) predict an energy-dependent fractional anisotropy of magnitude about 10^{-3} (10^{-1}) at an energy 0.1 (1) TeV towards the direction of the source [2]. As will be shown, anisotropies of such magnitudes are detectable with the *Fermi*-LAT CRE dataset.

From the above, it can be seen that studies of the arrival directions of CRs can be used to probe the properties of the heliospheric and galactic magnetic fields, the transport of CRs through the GMF, and most importantly in the case of CREs reveal any local CRE sources.

References

[1] A.H. Compton and I. A. Getting, Phys. Rev. Vol. 47, No. 11 (1935) 817
[2] Yoshida, K., Advances in Space Research 2008, (42) 377-485
[3] M. Ambrosio et al. (MACRO Collaboration), Phys. Rev. D 67 (2003) 042002

Examining CRE Anisotropy with the LAT

The dataset of the *Fermi*-LAT provides unique high statistics for Cosmic-Ray proton and electron anisotropy studies.

Here we present a progress report on the methods to be used to perform such studies, applied to the LAT CRE dataset. Take note that by "electrons" here we mean both e^- and e^+.

- To avoid any geomagnetic field effects (such as the east-west effect) only events with energies greater than 60GeV were included in this analysis.
- In the first year of normal operations, the LAT has detected over one million CREs with energies over 60GeV. Using such a dataset, ***anisotropies with magnitudes at least ~10^{-2} (~10^{-3}) can be detected for an angular half-size of 10º (60º).***
- We plan to perform analyses using various energy ranges to search for anisotropies generated by different effects (e.g. heliospheric vs galactic).

Method

Our CRE-anisotropy studies begin with the construction of the skymap that corresponds to the case of no CRE anisotropy, to be used as the null hypothesis of the absence of any effect. The comparison of the no-CRE-anisotropy skymap (see for example Figures 1 or 2) to the actual skymap (Figure 3) can reveal the presence of any anisotropies in the actual data.

- An easy and straight-forward way to accomplish that is by a direct bin to bin comparison between these two independent-bin skymaps. However, in this case because a potential anisotropic signal will be probably distributed among adjacent bins it might become too weak to be significantly detectable.
- A more robust method involves smoothing the skymaps so that the content of each bin becomes the integrated number of events detected at some larger-than-the-bin radius around it. The smoothing radius is chosen to be equal to the size of the anisotropy under search. An anisotropy with angular size close to the smoothing radius will be contained in at least one bin of such a smoothed map. This will ameliorate any spillover effects (such as in the previous case of independent bins) and will maximize the sensitivity.

Caveats

This is a search of very small effects (<1%). Because of that, we are continuously checking for systematics or other problems that can manifest as a real signal:

- Varying CRE detection efficiencies due to instrument configurational or other changes (e.g. varying background noise rates).
- Contamination of the CRE sample with other species such as photons or protons, or earth-albedo events.

Two Methods for Creating the no-CRE-Anisotropy Skymaps

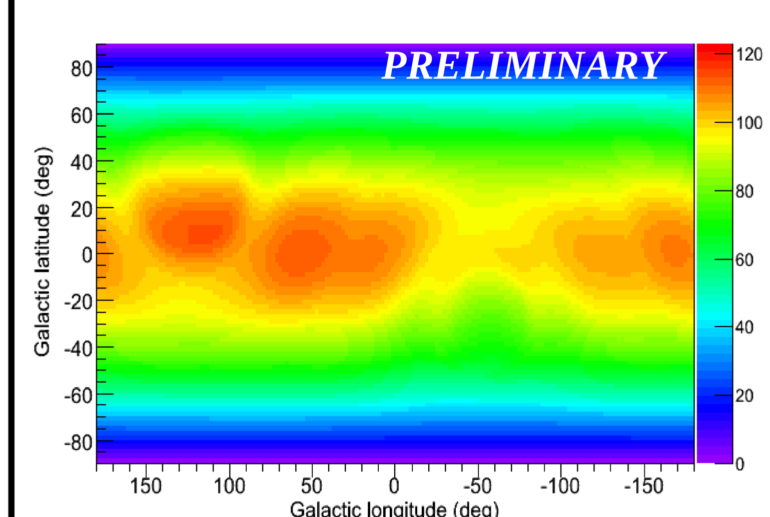
Direct Integration Method *(by V. Vasileiou)*

The amount of CRE events detected from some direction in the sky *(Theta,Phi)* (where Theta and Phi are the off-axis and azimuthal angles in local instrument coordinates) at some instant *t* is equal to the all-sky CRE rate at that instant ($R_{CRE\_allsky}(t)$) times the probability that a generic CRE event will be reconstructed at that direction (P(Theta,Phi)).

Any CRE anisotropies would create fluctuations in $R_{CRE\_allsky}(t)$ and P(Theta,Phi), as these anisotropies pass through the LAT's field of view. For observations consisting of at least few orbits, any such CRE anisotropy effects will be averaged out and these functions will correspond to the case of no CRE anisotropy. Then, for an observation of a duration short enough that the LAT's pointing can be approximated as constant, a skymap that corresponds to the case of no CRE anisotropy can be constructed from the averaged-over-multiple-orbits values of these functions. Splitting the one-year CRE LAT dataset in such short quasi-constant pointing observations, and adding the individual skymaps for each segment, a no-CRE-anisotropy skymap for the whole dataset can be created (see Fig. 1).

By Randomizing the Directions of Detected Events *(by N. Mazziotta)*

Another way of generating a no-CRE-anisotropy map is by randomizing the reconstructed directions of the detected events [3]. Assuming that the arrival directions and the arrival time of the detected events are uncorrelated variables, sets of simulated events can be constructed by randomly coupling the times and the directions of each event in local instrument coordinates. This process is repeated multiple times, and at the end an averaged no-CRE-anisotropy map is produced. Figure 2 shows such a skymap produced by averaging 25 randomized realizations of the data, that is to compared to the actual skymap in Figure 3.



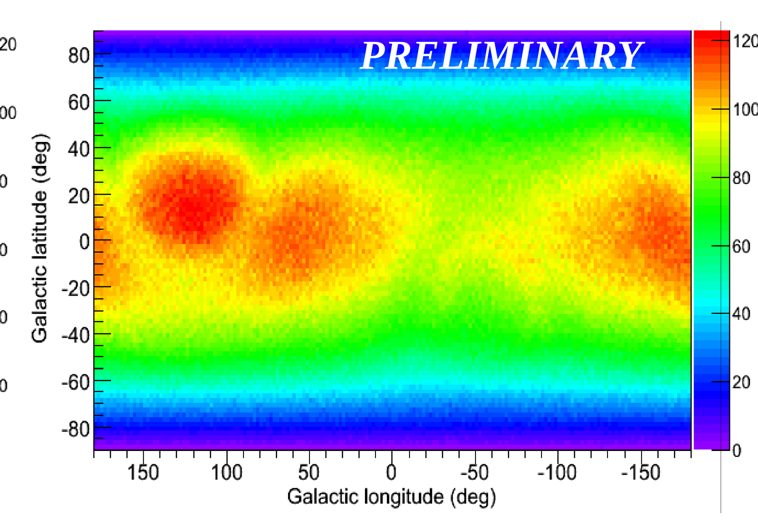


Figure 1. (top left): A no-CRE-anisotropy skymap produced by the "Direct-Integration method".

Figure 2. (top right): A no-CRE-anisotropy map produced by randomizing the reconstructed directions of detected events.

Figure 3. (right): A skymap showing the events in the actual one year CRE LAT dataset.

All maps have 2º bins, are for E>60GeV, and a maximum off-axis angle Theta<60º.

By comparing the calculated no-CRE-anisotropy maps (Figures 1 or 2) to the actual signal map (Figure 3) we can search for CRE anisotropies in the real data.