Fermi LAT Study of Galactic Cosmic-Rays by Observing Diffuse γ-Rays from Mid-Latitude Regions

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Abstract

The diffuse γ-ray emission is produced through the interaction of cosmic-rays (CRs) with the interstellar medium and the interstellar radiation field, and thus can be used as an indirect probe to study the CR spectral and spatial distribution in distant locations. Here we report the observations of diffuse γ-rays in two intermediate Galactic latitude regions by the Large Area Telescope (LAT) on the *Fermi* mission. The LAT spectrum in a mid/low-latitude region (Galactic latitudes $|b|$ from 10° to 20°) does not confirm a so-called EGRET GeV-excess. The γ-ray spectrum in a mid/high-latitude region in the third quadrant (Galactic longitude l from 200° to 260° and $22° \le |b| \le 60°$) agrees with the model based on directly measured CR spectra. These results indicate that CR nuclei spectra in the vicinity of the solar system are close to the local interstellar spectra, providing a solid basis for further studies of diffuse γ-rays and the CR distribution in our Galaxy.

Key words: cosmic rays – diffuse radiation – gamma rays: observations

1. Introduction

The diffuse high energy γ-ray emission ($E \ge 30$ MeV) has been interpreted to be a superposition of γ-rays produced via interactions between cosmic rays (CRs) and interstellar matter, inverse Compton (IC) scattering of interstellar soft photons off CR electrons, and the extragalactic diffuse γ-ray emission. The first component, if distinguished from the others, will enable using high-energy γ-ray observations for the study of the distribution of CRs and the interstellar medium. The distribution of neutral atomic hydrogen (H I) is traced by 21 cm line surveys and the molecular hydrogen distribution is derived indirectly using 2.6 mm line observations of carbon monoxide (CO). The total gas column density can also be traced indirectly from extinction and reddening by dust. Thus the spectrum and the flux of CRs can be obtained from sufficiently sensitive observations of high energy γ-rays (e.g., Fichtel et al. 1978; Lebrun et al. 1982).

One of the outstanding questions in the γ-ray astrophysics since the last century is a so-called "GeV-excess", the excess diffuse emission above 1 GeV seen in the EGRET data (e.g., Hunter et al. 1997; Strong et al. 2000) relative to that expected from the diffuse γ-ray model based on the directly measured CR spectra. This phenomenon led to the proposals such as that this emission was the long-awaited signature of dark matter annihilation (e.g., de Boer et al. 2005). More conservative interpretations include the unexpectedly large variations of CR spectra in the Galaxy (e.g., Strong et al. 2004) and the instrumental effects (e.g., Hunter et al. 1997).

In this paper, we report the analysis of the diffuse γ-ray emission seen by the *Fermi* LAT (Large Area Telescope) in a mid/low-latitude region (Galactic latitude $|b|$ from 10° to 20°) and that in a mid/high-latitude region in the third quadrant ($22° \le |b| \le 60°$ and Galactic longitude l from 200° to 260°). The former compares the LAT data in detail with that of the EGRET obtained from the same region of the sky and does not confirm the excess. The latter correlates the γ-ray intensity with the distribution of the interstellar medium to evaluate the local CR flux and the spectrum. These two studies provide a solid basis for future work to understand the diffuse γ-rays and the CR distribution in larger scale.

2. Diffuse γ-rays in the Mid/Low-Latitude Region

The LAT is the main instrument of the *Fermi* Gamma-ray Space Telescope. It consists of 4×4 modules (towers) built with tungsten foils and silicon microstrip detectors to measure the arrival directions of incoming γ-rays, and a hodoscopic cesium iodide calorimeter to determine the photon energies. They are surrounded by 89 segmented plastic scintillators serving as an anticoincidence detector to reject charged particle events. Details of the LAT instrument and pre-launch expectations of the performance can be found in Atwood et al. (2009).

Routine science operations with the LAT began on 2008 August 4. During this time interval the LAT was operated in sky survey mode nearly all of the time; in this observing mode the LAT scans the sky, obtaining complete sky coverage every two orbits and relatively uniform exposures over time. We have accumulated events for about five months to the end of December 2008. We used the standard LAT analysis software, ScienceTools. Events having the highest probability of being photons (so-called diffuse class events; see Atwood et al. 2009) are used in our analysis. In order to reduce the contamination from Earth albedo γ-rays, zenith-angle cut is also applied. A post-launch response function P6_V3_DIFFUSE, which was developed to account for the γ-ray detection inefficiencies that are correlated with trigger rate, was used in the analysis.

The photon counts and exposure were processed using the *GaRDiAn* package (Ackermann et al. 2008), part of a suite of tools we have developed to analyze the diffuse γ-ray emission. γ-ray skymaps with 5 bins per decade in energy from 100 MeV to 10 GeV were generated, and the intensity was obtained for each bin by dividing the in-bin counts by the exposure over the bin.

Figure 1 shows the LAT data averaged over all Galactic longitudes and latitude range $10^\circ \leq |b| \leq 20^\circ$. Also shown are the EGRET data for the same region of the sky derived from count maps and exposure maps available from the *CGRO* Science Support Center [1]. The hatched bands surrounding the LAT and EGRET represent the systematic uncertainties of these instruments. Although the contribution by point sources has not been subtracted for both data sets, the effect on the diffuse emission is minor.

As shown by the Figure, the LAT-measured spectrum is significantly softer than the EGRET measurement with an integrated intensity $J_{\rm LAT}(\geq 1~{\rm GeV}) = (2.35 \pm 0.01) \times 10^{-6}~{\rm cm^{-2}~s^{-1}~sr^{-1}}$ compared to the EGRET integrated intensity $J_{\rm EGRET}(\geq 1~{\rm GeV}) = (3.16 \pm 0.05) \times 10^{-6}~{\rm cm^{-2}~s^{-1}~sr^{-1}}$ where the errors are statistical only. Even if we take account of the systematic uncertainties of two instruments, the LAT spectrum is lower and softer than that measured by the EGRET above 1 GeV. We thus do not confirm the EGRET GeV-excess in this region of the sky and give strong constraints on the dark matter interpretations proposed to explain the EGRET data. On the other hand, the LAT spectrum agrees reasonably with the spectra of an *a priori* diffuse γ-ray model based on the pre-Fermi CR measurements. For detail, see Porter et al. (2009) and Abdo et al. (2009a).

*1 http://fermi.gsfc.nasa.gov/ssc/

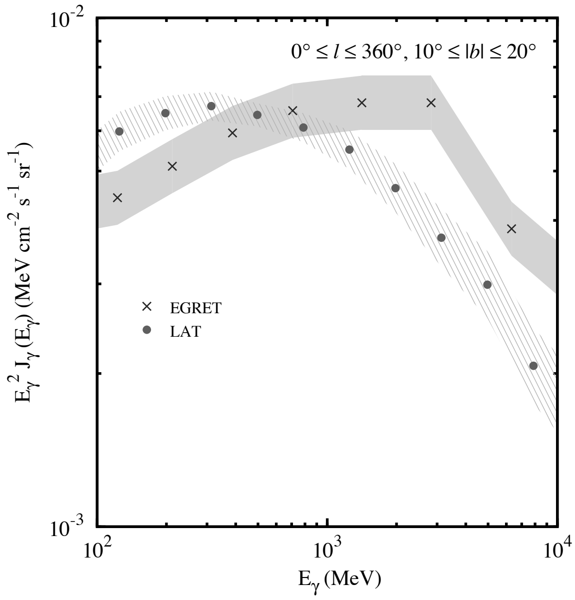

Fig. 1. Diffuse emission spectra averaged over all Galactic longitudes for latitude range $10^\circ \leq |b| \leq 20^\circ$ obtained by the *Fermi* LAT and the EGRET. Systematic uncertainties are shown by hatched areas.

3. *Fermi* LAT View of the Mid/High-Latitude Region

To discuss the CR spectrum close to the solar system in further detail, we also analyzed the diffuse γ-rays in a mid/high-latitude region in the third quadrant ($200^\circ \leq l \leq 260^\circ$ and $22^\circ \leq |b| \leq 60^\circ$). The region contains no known large molecular cloud and thus is suitable for correlating the γ-ray intensities with the local atomic-gas column densities.

To distinguish γ-rays produced in the interstellar medium from others, we referred to the GALPROP (e.g., Strong et al. 1998) prediction of the IC emission and an LAT source list for six month data which is internally available to the LAT team. We therefore used the six-month LAT data to extract the diffuse γ-ray emission. We masked the point sources with circular region of 1° radius, and confirmed that the estimated IC and residual point source contributions are small (less than 15% of the total diffuse emission) above 100 MeV. Hereafter we analyze the diffuse γ-rays after masking point sources and subtracting IC emission and the residual contributions from point sources. The LAT counts are divided in 13 logarithmically sliced energy bins from 100 MeV to 9.05 GeV and divided by the exposure of each bin to calculate the γ-ray intensity.

The γ-ray intensities, after masking point sources and subtracting the IC emission and the residual point source contributions, are correlated with the H I column densities in each energy band. The H I column densities are obtained from the Leiden/Argentine/Bonn (LAB) survey (Hartmann et al. 1997; Arnal et al.2000; Bajaja et al. 2005) under the assumption of a uniform spin temperature of 125 K. The maps are then convolved with the LAT point-spread function for each of our energy bins using the GaDGET package (Ackermann et al. 2008). We found a linear relationship between $N(\mathrm{H\,I})$ and residual γ-ray intensities for energies from 100 MeV to 10 GeV as exemplified by Figure 2. The linear correlation indicates that point source contributions are successfully subtracted and residual γ-rays mostly originate from interstellar atomic gas through interactions with CRs, plus isotropic diffuse component which includes the residual particle background in addition to the extragalactic diffuse γ-ray emission.

By fitting the correlation in each energy band with a linear function, we obtained the intensity of the isotropic diffuse component and the emissivity of atomic gas as the offset and the slope, respectively. The emissivity spectrum is summarized in Figure 3 with the systematic uncertainty indicated by the shaded area. The integral emissivity above 100 MeV and 300 MeV is $(1.63\pm0.05)\times 10^{-26}$ photons s^{-1} sr^{-1} H-atom^{-1} and $(0.66 \pm 0.02) \times 10^{-26}$ photons s^{-1} sr^{-1} H-atom^{-1}, respectively, with an additional systematic uncertainty of $\sim$ 10 %. While the early measurements such as Lebrun et al. (1982) and Digel et al. (2001) are consistent with the LAT data, the emissivity obtained by the LAT is much improved in photon statistics and energy range.

We can give constraints on the local CR spectrum by comparing the obtained emissivity with the model calculation of interactions between CRs and interstellar matter, as shown by solid lines in the same figure. Here we adopted the proton local interstellar spectrum (LIS) from the GALPROP model with 54_5gXvarh7S and calculated the γ-ray spectrum from nucleon-nucleon interactions using formulae given by Kamae et al. (2006) under the assumption of a so-called nuclear enhancement factor to be 1.84 as a representative value of those by Mori (2009). In order to calculate the electron bremsstrahlung, we fully utilized GALPROP.

As shown by Figure 3, the emissivity measured by the LAT agrees with the prediction from the assumed LIS and the recent estimate of the nuclear enhancement factor at the 10 % level. Although the true LIS is somewhat uncertain due to solar activity, the effect on our calculation is small, as discussed in Abdo et al. (2009b). We thus conclude that CR nuclei in the vicinity of the solar system in regions observed have spectral distributions and intensities close to those of the LIS inferred from measurements at the Earth within $\sim$ 10 %.

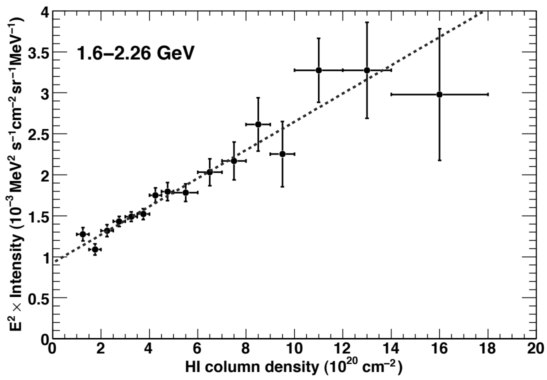

Fig. 2. Correlation of the (IC and point-sources subtracted) γ-ray intensities and the H I column densities at about 2 GeV. The map of $N(\mathrm{H\,I})$ is convolved with the LAT point-spread function of the corresponding energy range.

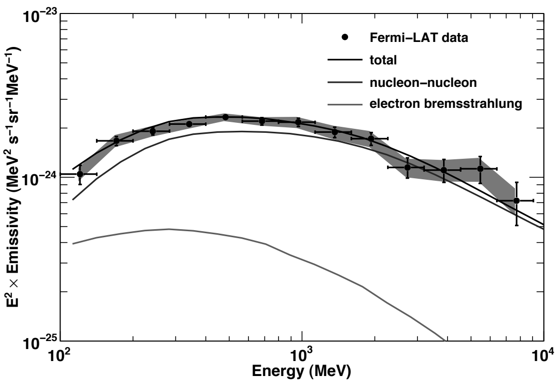

Fig. 3. Differential γ-ray emissivity from the local atomic hydrogen gas compared with the calculated γ-ray production. Estimated systematic errors of the LAT data are indicated by the shaded area. A nucleus enhancement factor of 1.84 is assumed for the calculation of the γ-rays from nucleon-nucleon interactions.

4. Summary and Conclusions

We report two observations of diffuse γ-rays in mid-latitude regions using data from *Fermi* LAT science observations. The *Fermi* LAT data in the mid/low-latitude region ($10^\circ \le |b| \le 20^\circ$) are compared with the EGRET data in the same region of the sky and does not confirm the EGRET GeV excess. It also shows a reasonable agreement with the spectra of an *a priori* diffuse γ-ray model. We also analyzed the mid/high-latitude region in the third quadrant ($200^\circ \le l \le 260^\circ$ and $22^\circ \le |b| \le 60^\circ$) to further constrain the CR spectra in the vicinity of the solar system. The measured emissivity spectrum of local atomic hydrogen agrees with the prediction from CR spectra assumed, indicating that the CR nuclei spectra in the vicinity of the solar system in regions analyzed are close to the LIS inferred from direct measurements at the Earth within $\sim$ 10 %. More details of the analysis and discussions of these studies can be found in Porter et al. (2009), Abdo et al. (2009a) and Abdo et al. (2009b).

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