Fermi LAT measurements of diffuse \(\gamma\)-ray emission: results at the first-year milestone

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Abstract.
For more than one year the Fermi Large Area Telescope has been surveying the \(\gamma\)-ray sky from 20 MeV to more than 300 GeV with unprecedented statistics and angular resolution. One of the key science targets of the Fermi mission is diffuse \(\gamma\)-ray emission. Galactic interstellar \(\gamma\)-ray emission is produced by interactions of high-energy cosmic rays with the interstellar gas and radiation field. We review the most important results on the subject obtained so far: the non-confirmation of the excess of diffuse GeV emission seen by EGRET, the measurement of the \(\gamma\)-ray emissivity spectrum of local interstellar gas, the study of the gradient of cosmic-ray densities and of the \(X_{\text{CO}} = N(\text{H}_2)/W_{\text{CO}}\) ratio in the outer Galaxy. We also catch a glimpse at diffuse \(\gamma\)-ray emission in the Large Magellanic Cloud. These results allow the improvement of large-scale models of Galactic diffuse \(\gamma\)-ray emission and new measurements of the extragalactic \(\gamma\)-ray background.

Keywords: diffuse gamma rays, cosmic rays, interstellar medium, Large Magellanic Cloud
PACS: 98.70.Vc, 98.70.Sa, 98.38.Dq, 98.56.Si

INTRODUCTION

Since the dawn of \(\gamma\)-ray astronomy the \(\gamma\)-ray sky above a few tens MeV has been known to be dominated by diffuse emission [1], giving more than 80\% of the observed photons:

- a bright component is correlated with the Milky Way structures, and thus is interpreted to be Galactic in origin, arising from interactions of high-energy cosmic rays (CRs) with the gas in the interstellar medium (ISM) and the interstellar radiation field (ISRF);
- a weaker component is observed with almost isotropic distribution over the sky, and thus is thought to be extragalactic in origin and usually referred to as the extragalactic \(\gamma\)-ray background (EGB).

Unresolved point sources also contribute to what we call diffuse emission, remarkably for the EGB, which might be, according to current estimates, made up in large part by populations of unresolved extragalactic \(\gamma\)-ray sources like blazars and external galaxies [2].

Galactic interstellar \(\gamma\)-ray emission is produced in different interaction processes:

- CR nucleons interact with gas nuclei in the ISM leading to \(\gamma\)-ray production through \(\pi^0\) production and decay;
• CR leptons interact with gas nuclei in the ISM producing $\gamma$-rays via Bremsstrahlung;
• CR leptons interact with low-energy photons of the ISRF producing $\gamma$-rays via inverse Compton (IC) scattering.

Therefore, the interstellar $\gamma$-ray emission is a tracer of CR densities in the Galaxy, suitable to study CRs in distant locations that we cannot access with direct measurements, as well as of the total ISM column densities, complementary to studies at other wavelengths. Additionally, modeling the Galactic diffuse emission is fundamental for $\gamma$-ray astrophysics, since it provides a bright and structured foreground for source detection and characterization, the study of the EGB and the search for signals from exotic processes, like annihilation of dark matter (DM) particles. Our models of the interstellar emission result from the combination of a wide range of available information, including CR spectra and composition at Earth, theoretical description of the propagation processes, multiwavelength studies of the ISM/ISRF, measurements of the relevant interaction processes and estimates of the Galactic magnetic field.

Several studies on the EGB have been performed [3, 4], but its nature is still mysterious. Apart from the contribution by unresolved sources mentioned above, many processes which might produce truly diffuse extragalactic emission have been proposed [2], for example large-scale structure formation, interactions of ultra-high-energy CRs with the extragalactic low-energy background radiation, annihilation or decay of cosmological dark matter. On the other hand, interactions of CRs with nearby matter, like solar system bodies [5] or debris at its outer frontier [6], might contribute to the EGB derived in the aforementioned studies. Therefore, the extragalactic origin of this diffuse component is still not clear, even though we keep referring to it as EGB.

A wealth of new information on high-energy diffuse $\gamma$-ray emission has been provided during the last year by the Large Area Telescope (LAT) on board the Fermi observatory [7, 8], thanks to its large acceptance, more than one order of magnitude larger than the predecessor EGRET, and the improved angular resolution (e.g. at 1 GeV the single event 68% containment reaches $\sim 0.6^\circ$ for the LAT compared with $\sim 1.7^\circ$ for EGRET). In this contribution we review the most important results obtained in the first year of LAT science operations, which shed light on many open questions of the EGRET era.

THE EGRET GEV EXCESS AND LAT MEASUREMENTS AT INTERMEDIATE GALACTIC LATITUDES

One of the most intriguing legacies of the EGRET era was the so-called GeV excess. Data by EGRET showed an excess of diffuse emission with respect to conventional models based on the locally measured CR spectra, first reported on the Galactic plane by Hunter et al. [9]. It was then confirmed as a $\sim 50\%$ excess over all directions in the sky, which led to a number of possible interpretations, including instrumental effects, discrepancies between locally measured CR spectra and local interstellar space and possible signals of dark matter annihilation [9, 10, 11, 12].

In order to investigate this issue, the first target of LAT studies has been the emission at intermediate Galactic latitudes, $10^\circ \leq |b| \leq 20^\circ$, where most of the emission is thought
to be produced by interactions of CRs with local interstellar matter (∼ 1 kpc from the Sun). This region is well suited to verify if the observed γ-ray emission is consistent with locally measured CR spectra.

LAT data have been compared with physical expectations using GALPROP, a code for CR propagation in the Galaxy by Strong and Moskalenko [13], Strong et al. [14]. The GALPROP model used for this work is a revised version of the “conventional” model described in Strong et al. [10], based on the locally measured CR spectra, including updated formalism to treat p-p interactions, recent radio surveys of the ISM, improved routines for line-of-sight integration and a complete recalculation of the ISRF [for details see 15]. The results are shown in Fig. 1 and 2.

The LAT spectrum is softer than the EGRET one, showing significant lower intensities for energies > 1 GeV (Fig. 1). The LAT spectrum is approximately reproduced by the GALPROP model of the Galactic interstellar emission, plus the contribution from point sources in the LAT 3-month source list and an unidentified isotropic component derived from fitting LAT data with the same Galactic model fixed (Fig. 2). LAT measurements at intermediate Galactic latitudes are thus inconsistent with the EGRET GeV excess and suggest that the local diffuse emission is explicable in terms of interactions with interstellar matter of CRs with spectra similar to those measured at Earth.

![FIGURE 1.](image.png) [15] Spectrum of the γ-ray emission measured by the LAT for energies between 100 MeV and 10 GeV, averaged over all longitudes in the region with Galactic latitude 10° ≤ |b| ≤ 20° (circles), compared with the same spectrum as measured by EGRET (crosses). Shaded bands represent the systematic errors, which are the dominant source of uncertainty for both instruments.
FIGURE 2. [15] The spectrum by the LAT, as already shown in Fig. 1, is compared with the a priori GALPROP model, plus the contribution by resolved point sources and the unidentified isotropic component (see text).

THE EMISSIVITY OF LOCAL INTERSTELLAR ATOMIC HYDROGEN

To quantitatively compare the local diffuse emission with in situ CR spectra, we studied the emissivity spectrum of local interstellar atomic hydrogen, H\textsubscript{I}, based on measurements of the column densities $N(\text{H}_\text{I})$ across the sky derived from radio surveys of its 21 cm line.

For this purpose we selected a region of the sky at intermediate Galactic latitudes, at $200^\circ \leq l \leq 260^\circ$ and $22^\circ \leq |b| \leq 60^\circ$, where most of the gas along the line of sight is nearby (once again $\lesssim 1$ kpc from the solar system) and no known complexes of molecular gas are present. The $\gamma$-ray intensity maps, after subtraction of the components due to point sources and IC emission, were correlated with the distribution of $N(\text{H}_\text{I})$, derived from the LAB survey by Kalberla et al. [16]. For details on the analysis see Abdo et al. [17].

The obtained spectrum of H\textsubscript{I} emissivity is shown in Fig. 3. The emissivity measured by the LAT is compared with the results of a calculation based on the locally measured CR spectra. The Bremsstrahlung component is derived using GALPROP. In the energy range considered the dominant contribution is the $\pi^0$-decay emission. Using the locally measured proton spectrum we calculated the $p$-H $\gamma$-ray emissivity using the inclusive
parametrization by Kamae et al. [18]. The obtained emissivity spectrum is then multiplied by a factor $\varepsilon_M$ which accounts for interactions involving heavier nuclei in both CRs and the ISM. This factor, often called nuclear enhancement factor, is the subject of a long-standing debate in the literature, where values spanning from 1.45 [19] to 1.84 [20] are found. The two extreme values are considered in Fig. 3 for comparison. The results show that $\gamma$-ray emission from local gas is consistent with CR spectra measured at Earth.

THE DISTRIBUTION OF CR SOURCES AND THE X$_{\text{CO}}$ RATIO IN THE OUTER GALAXY

Since the local interstellar $\gamma$-ray emission is consistent with models based on locally measured CR spectra, we are confident that we have understood its basic mechanisms, and, as explained in the introduction, we can use diffuse emission as a tracer of CR densities and of ISM column densities throughout the Galaxy. The first target was the outer Galaxy, in selected regions where the velocity gradient with galactocentric radius is very steep, and so the Doppler shift of the radio/microwave lines observed for interstellar gas provides a good separation of the different structures along each line of sight.

As told above, the 21 cm line of H$\text{I}$ allows us to directly trace its column densities. Molecular hydrogen, H$_2$, which is the most abundant constituent of the molecular phase of the ISM, does not have observable lines. The integrated intensity $W_{\text{CO}}$ of the 2.6 mm line of CO is usually adopted as a surrogate tracer of molecular masses, assuming that...
\(N(H_2) = X_{CO} \cdot W_{CO}\). However, the \(X_{CO}\) ratio is still uncertain, and in particular there are many evidences that it might increase in the outer Galaxy with respect to local clouds, as explained in Strong et al. [21] and references therein. The increase still needs to be verified in \(\gamma\)-rays, because of the limited performances of previous-generation telescopes [22, 23].

On the other hand for many years supernova remnants (SNRs) have been considered the best candidates as CR sources in the Galaxy. However, the origin of CRs is still mysterious and the distribution of SNRs is very poorly determined [24], leading to large uncertainties in the models of diffuse \(\gamma\)-ray emission.

Since the Doppler shift of the radio/microwave lines allows us the to separate different structures along a line of sight these issues can be investigated directly in \(\gamma\)-rays:

- the emissivity of the diffuse H\(I\) gas can be used to trace the CR densities in distant locations;
- the emissivity per \(W_{CO}\) unit, compared with that per H\(I\) atom, can be used to evaluate the \(X_{CO}\) ratio in each molecular complex.

The first region studied with this method was the region of Cassiopeia and Cepheus in the second Galactic quadrant. For details on the analysis see Abdo et al. [25]. The main results are shown in Fig. 4 and 5.

![Figure 4](image-url)

**FIGURE 4.** [25] Emissivity of atomic gas integrated above 200 MeV, \(q_{H I}\), as a function of Galactocentric radius: points are LAT measurements (the shaded area represents systematic uncertainties in the event selection efficiency), the dashed line is the prediction by a GALPROP model based on a CR source distribution derived from pulsars [26].

Fig. 4 shows that the gradient of H\(I\) emissivity measured by the LAT is flatter than the predictions by a GALPROP model based on a CR source distribution peaking in the inner Galaxy as suggested by pulsars. This might point to CR sources extending further in the outer Galaxy, but might also hint to diffusion parameters different from those derived from local CR isotopic abundances used by GALPROP. However, systematic effects might be at the origin of this effect, e.g. contamination by populations of
FIGURE 5. [25] $X_{\text{CO}}$ as a function of Galactocentric radius: black points are LAT measurements in the second quadrant, gray points EGRET measurements in the same region. The dashed step function represents the model used in GALPROP by Strong et al. [21] and the solid line is the conversion law based on virial masses by Nakanishi and Sofue [27].

unresolved sources or large errors in the determination of $N(\text{H}I)$ (because of the approximations applied to handle the radiative transfer of $\text{H}I$ radio emission or self-absorption phenomena).

Fig. 5 confirms a significant but moderate increase of $X_{\text{CO}}$ from the solar circle to the outer Galaxy. The large gradient proposed by Strong et al. [21] to interpret EGRET data is not supported by our results. This large gradient was introduced on the basis of non-$\gamma$-ray data to accommodate the problem of the flat emissivity profile, but this solution is disfavored by the LAT. On the other hand the values are systematically lower than the conversion law by Nakanishi and Sofue [27], mostly based on virial masses. The $\gamma$-ray estimates might be biased by the limited resolution of the data, but on the other side the virial masses are based on the rather crude assumption of clouds with simple spherical shapes and a velocity dispersion due only to balancing gravitational forces.

Further investigation is undergoing by the LAT team to extend the analysis to the segment of the outer Galaxy seen in the third quadrant and to explore the origin of the flat gradient of $\text{H}I$ emissivities [28].

THE LARGE MAGELLANIC CLOUD

External galaxies are a promising target for diffuse emission studies, because the interpretation of the data is less affected by confusion along the line of sight than in the Milky Way. The only normal galaxy seen in high-energy $\gamma$-rays before the LAT era has been the Large Magellanic Cloud (LMC) [29]. It is an ideal object to map CR acceleration sites and study their propagation in the ISM because it is nearby ($\sim 50$ kpc), seen at a small inclination angle ($20^\circ - 35^\circ$) and it hosts many SNRs, bubbles and star-forming
regions. EGRET, due to its limited angular resolution, could not resolve the LMC, but the measured integral flux led to derive CR densities similar to those in the Milky Way. On the other hand, the non-detection by EGRET of the Small Magellanic Cloud (SMC), a similar external Galaxy, was a strong evidence supporting the idea that CRs up to energies of $\sim 10^{15}$ eV are galactic and not extragalactic in origin [30].

The LAT, thanks to its improved angular resolution, is now able to resolve the LMC, making it the first extragalactic object ever resolved in high-energy $\gamma$-rays.

FIGURE 6. Adaptively smoothed preliminary map of LAT counts (200 MeV – 100 GeV, from the first 200 days of the Science phase of the mission) in the region of the Large Magellanic Cloud. The starburst region 30 Doradus appears at $l \sim 279.5^\circ$ $b \sim -31.5^\circ$. Overlaid contours of ionized gas density in the LMC [32]. The cross in the north-east of the image corresponds to the location of the blazar CRATES J060106-703606.

In Fig. 6 we show a preliminary count map of the LMC. The starburst region of 30 Doradus is clearly visible together with a larger halo of diffuse emission, plausibly arising from interactions of CRs with the gas in the ISM. A detailed analysis of this object, investigating CR acceleration and propagation in the LMC, will be presented soon by the LAT team [33].
SUMMARY AND PERSPECTIVES

In the previous sections we have presented some results relevant for the understanding of diffuse $\gamma$-ray emission, obtained by the Fermi LAT during the first year of observations: the non-confirmation of the EGRET GeV excess in the local interstellar emission, the measurement of the $\gamma$-ray emissivity of local atomic gas, the study of the CR density and $X_{\text{CO}}$ gradient across the Galaxy and the first view of diffuse emission in an external Galaxy.

All these findings are being incorporated in a new large-scale model of diffuse $\gamma$-ray emission based on the previously introduced GALPROP code [34]. As we have seen, a priori GALPROP predictions are locally approximately consistent with LAT measurements of interstellar $\gamma$-ray emission, so reasonable adjustments of the CR spectra, CR source distribution, CR propagation parameters (e.g. the height of the propagation halo, the diffusion coefficients), ISM properties (e.g. $X_{\text{CO}}$) are expected to provide a large-scale agreement between observations and physical expectations [34]. At the same time the comparison will help to get a deeper understanding of the long-standing puzzle of CR acceleration and propagation, as well as about the census of the gas in the ISM.

The Galactic interstellar emission model will support a new estimate of the isotropic diffuse spectrum, and later on of the EGB spatial properties, based on LAT data. The new estimate of the isotropic diffuse spectrum is based on event selection criteria explicitly developed for the delicate task of separating the EGB from residual backgrounds due to CR interactions in the LAT misclassified as $\gamma$-rays. The isotropic spectrum is then derived from a fit to LAT data including the aforementioned model of Galactic interstellar emission, LAT resolved sources and the emission from the Sun. The analysis and results will be presented in detail in Abdo et al. [35]. These studies, together with source population syntheses, will provide insightful information on the nature of the EGB.

As LAT data accumulate we can expect many more results, which will make the next years very exciting for studies on diffuse $\gamma$-ray emission.

ACKNOWLEDGMENTS

The Fermi LAT Collaboration acknowledges support from a number of agencies and institutes for both development and the operation of the LAT as well as scientific data analysis. These include NASA and DOE in the United States, CEA/Irfu and IN2P3/CNRS in France, ASI and INFN in Italy, MEXT, KEK, and JAXA in Japan, and the K. A. Wallenberg Foundation, the Swedish Research Council and the National Space Board in Sweden. Additional support from INAF in Italy and CNES in France for science analysis during the operations phase is also gratefully acknowledged.

LT is partially supported by the International Doctorate on AstroParticle Physics (IDAPP) program.

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