

Studies of gamma-ray sources with the Fermi Large Area Telescope

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Summary. — With its excellent sensitivity, large field of view, broad energy coverage, and good per-photon angular resolution, the Large Area Telescope aboard the *Fermi Gamma-ray Space Telescope* satellite provides us with an unprecedented view of the high-energy Universe, revealing a large diversity of cosmic particle accelerators that are active at various scales. We present in this paper a selection of science highlights of the *Fermi* mission, with particular emphasis on results that are relevant for cosmic-ray physics. We cover observations of supernova remnants and studies of interstellar gamma-ray emission, reaching from the vicinity of the solar system out to the more distant starburst galaxies.

PACS 95.85.Pw – Gamma ray.

PACS 98.70.Sa – Cosmic rays (including sources, origin, acceleration, and interactions).

1. – Introduction

The *Fermi Gamma-ray Space Telescope* has been successfully launched on 2008 June 11, and since 2008 August it routinely surveys the sky with the Large Area Telescope (LAT). Compared to its predecessor, the EGRET telescope that operated aboard *CGRO* from 1991 to 2000, the LAT brings a sensitivity improvement of more than a factor of 10, provides a wide field of view (2.4 sr at 1 GeV), and covers a wide energy range from 20 MeV to > 300 GeV [1]. In its regular surveying mode, the entire sky is observed every 3 hours, providing information on flux variability for any source in the sky.

We present in this paper a selection of the science highlights of the *Fermi* mission, with particular emphasis on results that are relevant for cosmic-ray physics. While we focus here on observations of gamma-rays, an accompanying paper will present results on direct cosmic-ray measurements *Fermi* (Latronico, these proceedings). We start with an overview of the types of (steady) gamma-ray sources that are observed by *Fermi*/LAT, and summarize results that were obtained on observations of Galactic

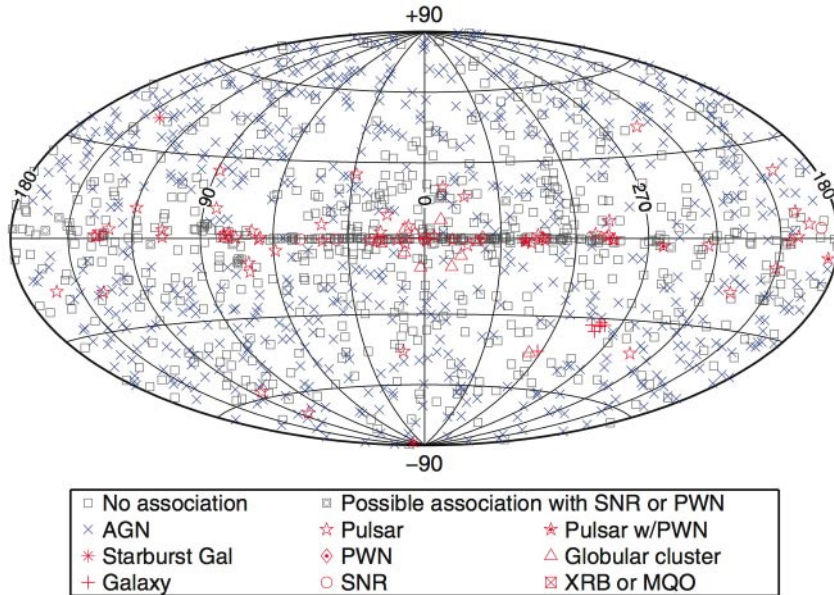


Fig. 1. – (Colour on-line) 1451 1FGL catalogue sources, showing locations on the sky (in Galactic coordinates with Aitoff projection) and associated source class, coded according to the legend. The colour is chosen simply to enhance the visibility of the associated and non-blazar sources (from [2]).

supernova remnants. The remainder of the paper is dedicated to the observation of interstellar gamma-ray emission, and results are presented by gradually moving away from the local interstellar medium to the extragalactic space.

2. – Gamma-ray sources

2.1. Source catalogue. – The combination of deep and fairly uniform exposure, good per-photon angular resolution, and stable response of the LAT has made for the most sensitive, best-resolved survey of the sky to date in the 100 MeV to 100 GeV energy range. During the first 11 months of operations, 1451 gamma-ray sources have been significantly detected in this energy range by the LAT, making up the First *Fermi*-LAT catalogue (1FGL) [2] that provides a significant enhancement over the catalogue of 271 sources that have been by detected the EGRET telescope over its entire mission lifetime [3].

About 56% of the 1FGL sources have been associated to counterparts at other wavelengths based on positional coincidence at the 80% confidence level (cf. fig. 1). The large majority of these associations are with Blazars, *i.e.* active galactic nuclei (AGN) that presumably host supermassive black holes creating relativistic jets that are pointing in the general direction of the Earth and that are the sites of particle acceleration. The second most important source class are pulsars (56 sources) which are firmly identified by the high-confidence detection of periodicity in the arrival times of the gamma-ray photons that is caused by the rotation of the neutron star. While most of the pulsars are young and energetic, an increasingly large number of millisecond pulsars has also been detected by the LAT [4]. Populations of millisecond pulsars are also believed to

account for the gamma-ray emission that is seen towards globular clusters [5] of which 8 are associated with gamma-ray sources in the 1FGL catalogue. Young and energetic pulsars are often associated to pulsar wind nebulae (PWN) and the remnants of their natal supernova explosions (SNR), and consequently there is some ambiguity in associating gamma-ray sources to these 3 source classes. Excluding 1FGL sources that are associated with pulsars, we find 6 1FGL sources associated to PWN and 41 1FGL sources associated to SNRs. Dedicated follow-up studies that investigate the spectral energy distributions and spatial morphologies of the sources may help to clarify the underlying natures of these sources (cf. subsect. 2.2). Finally, 3 1FGL sources are firmly identified as high-mass X-ray binaries based on their orbital variability (LS I + 61°303 [6], LS 5039 [7] and Cyg X-3 [8]), and 2 1FGL sources are associated to the starburst galaxies M 82 and NGC 253 [9]. Furthermore, gamma-ray emission is detected from the LMC [10] and SMC [11] and several 1FGL sources are associated to local emission maxima in these dwarf galaxies.

2.2. *Supernova remnants.* – Supernova remnants have long been considered the primary candidates for the origin of Galactic cosmic rays (CRs). Specifically, diffusive shock acceleration [12, 13] is widely accepted as the mechanism by which charged particles can be accelerated to very high energies at collisionless shocks driven by supernova explosions. However, it has not yet been confirmed whether strong shocks in SNRs are indeed capable of efficiently transferring kinetic energy into the acceleration of CR ions, and the definite proof for cosmic-ray acceleration in SNRs is still missing.

Gamma-ray observations may probe for ion acceleration in SNRs by revealing the characteristic decay signature from π^0 mesons that are produced by collisions between relativistic nuclei with ambient gas. Recent ground-based gamma-ray observations in the TeV domain have revealed several spatially resolved young SNRs (age ~ 1 ky) in our Galaxy, showing a morphology that correlates well with that observed in non-thermal X-rays. The TeV observations, however, cover only the high-energy part of the source spectra, and thus discriminate only poorly between leptonic (inverse Compton and/or Bremsstrahlung) and hadronic (π^0 decay) emission scenarios. Clearly, an improved low-energy coverage of these sources is needed to better constrain the underlying emission mechanism [14].

Fermi has now provided this low-energy coverage for several galactic SNRs (cf. fig. 2). Among those are Cas A [15] and RX J1713.7-3946 that both have been detected also at TeV gamma-rays. Both objects are young SNRs that exhibit broad-band emission spectra ranging from $\lesssim 1$ GeV up to ~ 10 TeV and beyond. The spectra of these sources impose so far only little constraints on the underlying emission mechanism and are satisfactorily modelled by either leptonic or hadronic emission models. Interestingly, regardless of the origin(s) of the observed gamma-rays, the total amount of CRs accelerated in Cas A constitutes only a minor fraction ($\leq 2\%$) of the total kinetic energy of the supernova [15].

A second class of SNRs detected by *Fermi* consists of mid-aged (3–50 ky) remnants that generally are known to be interacting with molecular clouds that might act as target material for π^0 production. These SNRs (W51C [16], W44 [17], IC 433 [18], W28 [19]) are all characterized by spatially extended emission in the GeV domain with spectral breaks near ~ 1 GeV and a spectral steepening towards the TeV domain. Consequently, many of these SNRs are only barely detected at TeV energies with current Cerenkov telescopes. The gamma-ray spectra of these objects can be fitted with either leptonic and hadronic models, yet in general, leptonic models require rather extreme conditions to be met to explain the observations (such as unusually large ratios of injected electrons

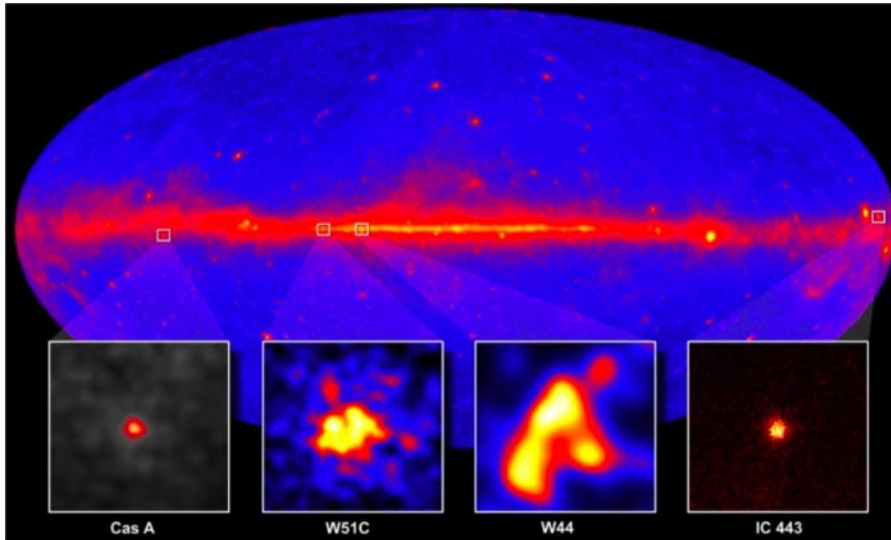


Fig. 2. – *Fermi*/LAT allsky map of the gamma-ray sky with enlarged images of four SNRs superimposed.

to protons, strong magnetic fields, *ad hoc* breaks in the particle spectra, excessively large ambient photon densities or electron energy contents; *e.g.* [16-19]). Consequently, hadronic models provide a more plausible explanation of the observed emissions. The increasing amount of SNRs that are detected by *Fermi* together with a continuously growing database at TeV energies opens up the possibility to study now how particle acceleration responds to environmental effects such as shock propagation in dense clouds and how accelerated particles are released into interstellar space.

3. – Interstellar gamma-ray emission

3.1. Galactic cosmic rays. – Once accelerated, CRs diffuse away from their acceleration sites into the interstellar space of our Galaxy where in encounters with the interstellar gas and radiation fields they produce a diffuse glow of gamma-rays through π^0 decay, inverse Compton scattering and non-thermal Bremsstrahlung processes. This diffuse Galactic glow is in fact the first source of high-energy gamma-rays that was discovered by observations with the OSO-3 satellite in 1968 [20]. Similar to observations of SNRs, the study of the diffuse Galactic gamma-ray emission provides important insights into CR acceleration and propagation within our Galaxy.

Figure 3 shows the differential gamma-ray emissivity of hydrogen in the local interstellar medium (within 1 kpc of the solar system) as determined by *Fermi* from observations of diffuse gamma-ray emission at high Galactic latitudes [21]. The differential emissivity spectrum agrees remarkably well with calculations based on CR spectra that are consistent with those measured directly at Earth, at the 10% level. This indicates that the CR nuclei spectra within 1 kpc from the solar system are comparable to those measured near Earth.

Going further away from the Sun, observations of the gamma-ray emission towards the Cassiopeia and Cepheus constellations allow studying CR density variations in the outer

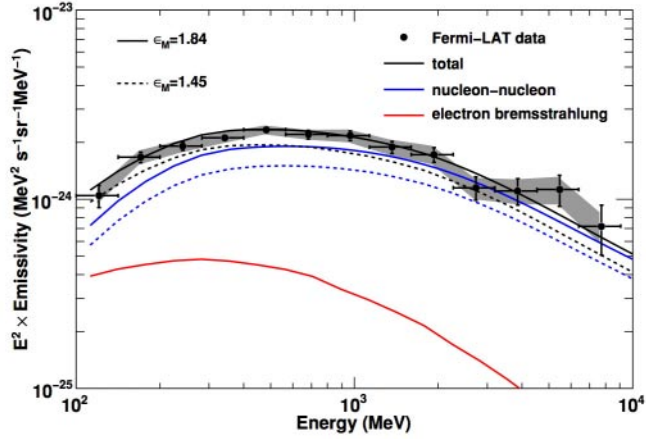


Fig. 3. – Differential gamma-ray emissivity from the local atomic hydrogen gas compared with the calculated gamma-ray production (from [21]).

Galaxy, covering Galactocentric distances from ~ 9 kpc to ~ 20 kpc. A recent *Fermi* study of this region revealed that the gamma-ray emissivity spectrum of the gas in the nearby Gould Belt (within 300 pc from the solar system) is consistent with expectations based on locally measured CR spectra [22]. The gamma-ray emissivity decreases from the Gould Belt to the distant Perseus arm, but the measured gradient is flatter than expectations based on current estimates of the distribution of sources of CRs in the Milky Way and of CR propagation parameters. In addition, the observations present evidence in the Gould Belt for the so-called dark gas, which is gas that is not properly traced by radio and microwave surveys, and of which the mass amounts to $\sim 50\%$ of the CO-traced molecular gas mass.

In the late nineties, measurements with the EGRET telescope indicated a global excess of diffuse emission $\gtrsim 1$ GeV relative to that expected from conventional diffuse galactic emission models [23] which led to speculations about a possible dark matter origin of this so-called “GeV excess” [24]. *Fermi* has measured the diffuse gamma-ray emission with improved sensitivity and resolution with respect to EGRET [25]. Figure 4 compares the LAT data (red) to the earlier EGRET data (blue) which reveals a significant discrepancy between both measurements. In particular, the LAT data do not show the excess reported by EGRET and are in fact well reproduced by a diffuse gamma-ray emission model that is consistent with local CR spectra. The knowledge about the LAT instrument response function comes from detailed simulations that were validated with beam tests of calibration units, and from post-launch refinements based on the actual particle background, and are considered as accurate [25]. It thus is plausible to attribute the “GeV excess” to an instrumental artefact of the earlier EGRET measurements.

3.2. Mapping cosmic-ray acceleration in the LMC. – Nearby galaxies have some advantages as targets for studies of CR physics as they are viewed from outside, and so line-of-sight confusion, which complicates studies of gamma-ray emission from our own Galaxy, is diminished. The Large Magellanic Cloud (LMC) is an excellent target for studying the link between CR acceleration and gamma-ray emission since the galaxy is nearby (~ 50 kpc), can be easily resolved (angular extent $\sim 8^\circ$), and is seen almost

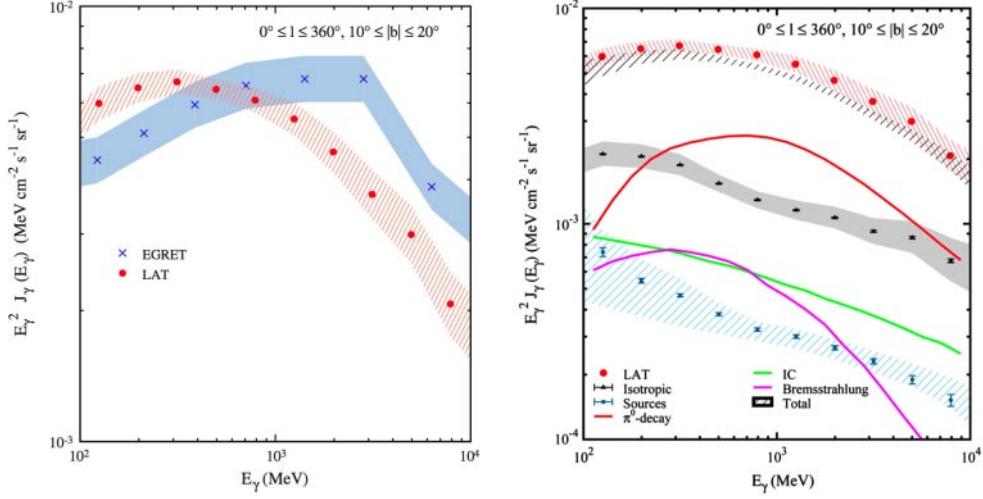


Fig. 4. – (Colour on-line) Diffuse emission intensity averaged over all galactic longitudes for latitude range $10^\circ \leq |b| \leq 20^\circ$. The left plot shows the comparison of LAT data (red) to EGRET data (blue), the right plot shows the comparison of LAT data with a model of Galactic diffuse emission (from [25]).

face-on. The LMC has been initially detected by the EGRET telescope [26], but *Fermi* now provides the instrumental capabilities to perform a detailed study of the galaxy.

The LMC is clearly detected with the LAT ($\gtrsim 33\sigma$) and for the first time the emission is spatially well resolved in gamma-rays [27]. The observations (cf. fig. 5) reveal the

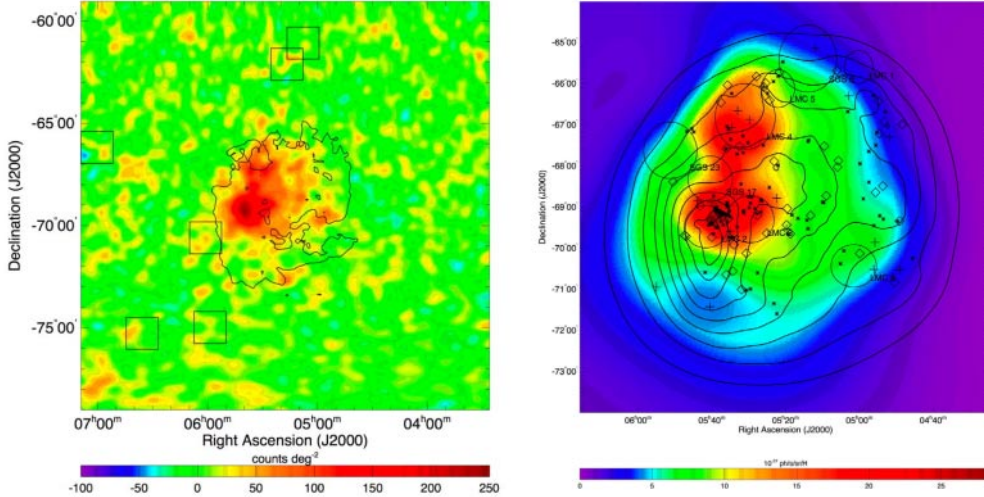


Fig. 5. – Left panel: Gaussian kernel ($\sigma = 0.2^\circ$) smoothed background subtracted counts map of the LMC region for the energy range 200 MeV–20 GeV. Right panel: adaptively smoothed integrated > 100 MeV emissivity map of the LMC revealing the cosmic-ray density distribution within the LMC. The contours indicate the gas density smoothed with the LAT instrumental point spread function (from [27]).

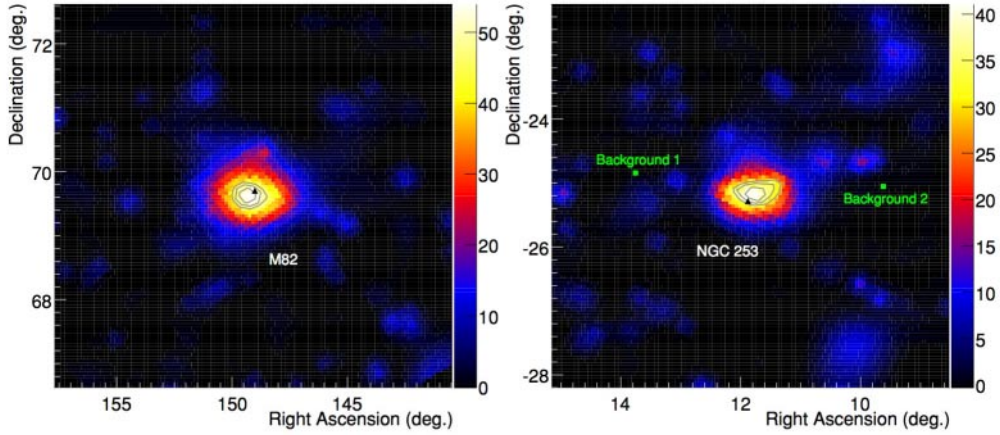


Fig. 6. – (Colour on-line) Test statistic maps obtained from photons above 200 MeV showing the 6° by 6° large regions around M 82 and NGC 253. Aside from the source associated with each galaxy, all other *Fermi*-detected sources (green squares) within a 10° radius of the best-fit position have been included in the background model as well as components describing the diffuse Galactic and isotropic gamma-ray emission. Black triangles denote the centres of M 82 and NGC 253 at optical wavelengths (from [28]).

massive star forming region 30 Doradus as a bright source of gamma-ray emission, in addition to a fainter glow that spreads out over large areas of the galaxy. Surprisingly, the observations reveal little correlation of the gamma-ray emission with gas density, as it would have been expected if CRs propagate throughout the entire galaxy. The gamma-ray emission correlates more with tracers of massive star forming regions, supporting the idea that CRs are accelerated in these regions as a result of the large amounts of kinetic energy that are input by the stellar winds and supernova explosions of massive stars into the interstellar medium.

3.3. Starburst galaxies. – Probing galactic cosmic-ray acceleration even well beyond the local group of galaxies has now become possible thanks to *Fermi*. For the first time, steady GeV gamma-ray emission has been detected significantly by the LAT from sources positionally coincident with locations of the starburst galaxies M 82 and NGC 253 [28]. Test statistic maps obtained with LAT for photons ≥ 200 MeV for regions around both galaxies are shown in fig. 6. Both starburst galaxies have also been detected at TeV energies by VERITAS [29] and H.E.S.S. [30], and the emission is well explained by the interaction of CRs with local interstellar gas and radiation fields. M 82 and NGC 253, though having less gas than the Milky Way, have factors of 2–4 greater gamma-ray luminosity, suggesting a connection between active star formation and enhanced CR energy densities in star-forming galaxies. In particular, the H.E.S.S. observations of NGC 253 localise the gamma-ray emission towards the starbursting core of the galaxy, which is very much like the situation in the LMC where the gamma-ray emission is brightest towards 30 Doradus, a region that is considered as a “mini-starburst” [31]. Star-forming and starburst galaxies are thus a new class of prominent gamma-ray emitters in the Universe, and thanks to their large number, they have the potential to make a significant, $\gtrsim 10\%$ contribution to the extragalactic gamma-ray background at high-energy gamma-rays [28].

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