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Galactic science with *Fermi*-LAT

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Summary. — High energy γ-rays reveal extreme, non-thermal processes in the Universe. The *Fermi* Large Area Telescope (LAT) has been exploring the γ-ray sky for almost eight years, enabling the observation of many powerful events happening in our Galaxy. The wide energy range and field of view make the LAT a unique instrument to monitor the sky and study both powerful transient events and long-term phenomena. We present a review of the latest results obtained by the *Fermi*-LAT observation of Galactic objects.

1. – Introduction

The Large Area Telescope (LAT) onboard the *Fermi* satellite is an imaging, wide-field of view, pair-conversion telescope, which detects photons from few tens of MeV to few hundreds of GeV. It consists of an array of 4×4 identical towers, each made of a converter-tracker module and a calorimeter module. The converter-tracker is made of 16 tungsten planes, in order to convert the incoming photon in an e^+e^- pair, interleaved with silicon strip detector planes, which track the particles resulting from the pair conversion and allow the reconstruction of the direction of the incoming photon. The electromagnetic calorimeter below the tracker-converter module measures the energy of the incoming photon. A segmented anti-coincidence module encloses the instrument, allowing the background rejection, mostly due to charged cosmic rays [1]. In recent years, the *Fermi*-LAT collaboration has developed a new version of the reconstruction method, known as Pass 8, allowing a sensible increase in the performance of the instrument, especially in the effective area and in the Point Spread Function (PSF). Furthermore, a new type of data selection has been introduced, allowing the selection of data with better angular resolution (PSF class) or energy dispersion (EDISP class), which is very useful to increase the sensitivity in some types of analysis.

In the first eight years of operation, *Fermi*-LAT has collected a huge amount of data, observing the entire sky in survey mode for most of its observing time and detecting many different types of sources and phenomena. The detection of γ-rays is a clear signature that non-thermal processes are happening at the source, eventually accelerating particles. Since photons are not deflected by magnetic fields (the Galaxy magnetic field and the interstellar magnetic field for Galactic and extragalactic phenomena, respectively), they provide key information to study these phenomena.

The observation of our Galaxy in the γ-ray energy range shows different types of emissions, such as a diffuse dominant emission along the Galactic plane, mainly due to Galactic Cosmic Rays interacting with the Interstellar Medium. More localized emissions are also visible both along the Galactic plane and outside the Galaxy, associated to different γ-ray emitting objects, such as Supernova Remnants (SNRs), Pulsars, Pulsar Wind Nebulae (PWNe), which are mostly distributed along the Galactic plane.

In the next paragraphs, an overview of how the γ-ray emission originates in these objects and how it is seen by *Fermi*-LAT will be given.

2. – Supernova Remnants

A Supernova Remnant (SNR) is an object resulting from the death of a massive star, mainly constituted by the shock wave and the expanding ejected material originating from a Supernova explosion. SNRs are very interesting and very well studied Galactic objects in different energy ranges, since they are the best candidates to explain the origin of Galactic Cosmic Rays (CRs). In particular, the Diffusive Shock Acceleration (DSA) theory predicts that in the presence of a strong shock wave, such as the one originating from a Supernova explosion, particles are accelerated, producing a power-law spectrum. A generalization of this theory, known as Non-linear Diffusive Shock Acceleration (NLDSA) theory, which accounts for the interaction of accelerated particles with the shock, predicts values for the spectral index of the accelerated particle spectrum compatible with the observations [2].

The spectrum of CRs observed at the Earth is a combination of the spectrum of particles at the source with effects of propagation through the Galaxy. For protons, which are the most abundant particles in CRs, the spectrum at the Earth can be expressed as

$$N(E) = Q(E)\tau_e(E), \tag{1}$$

where $Q(E)$ is the source term representing the number of particles injected in the Galaxy with energy E and τ_e is the confinement time in the Galaxy of CRs with energy E and is due to the propagation of CRs through the Galaxy.

Observations of the carbon-to-boron ratio in CRs provides a measurement of the energy dependence of the propagating term τ_e, which is proportional to $E^{-\delta}$, with $\delta \in [0.3, 0.6]$. The observed spectrum of CRs for energies up to the "knee" of CRs ($\approx 10^{15}$ eV) is well described by a simple power-law with spectral index -2.7. As a consequence the expected spectrum at the source is a power-law $Q(E) \propto E^{-\alpha}$, with $\alpha \in [2.1, 2.4]$, compatible with the NLDSA predictions.

2˙1. *Fermi-LAT detection of "pion bump"*. – The clear signature of cosmic ray acceleration in SNRs is provided by the detection of the so-called *pion bump*. The interaction of accelerated protons with the target gas produces many hadrons, especially neutral pions, which decay in γ-rays. The γ-ray spectrum produced by this decay is characterized by a cut-off around 100 MeV, due to the kinematic constraints of the π^0 decay process.

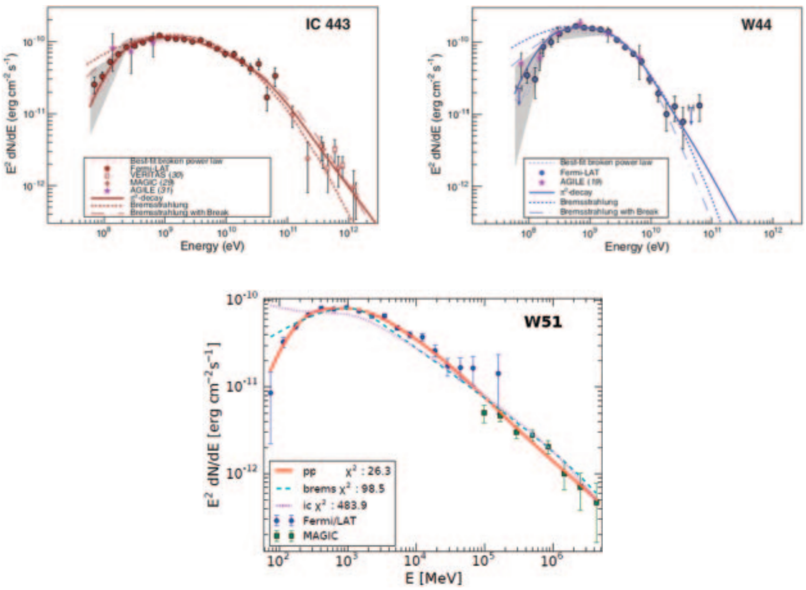

Fig. 1. – Spectral Energy Distribution of three SNRs, overlaid with theoretical models based on a hadronic interpretation of γ-ray emission. Top left: IC443 [3]. Top right: W44 [3]. Bottom: W51 [4].

Fermi-LAT has successfully detected this signature in many Supernova Remnants. The first clear detection occurred in the observation of IC443 and W44 SNRs [3]. They are middle-aged SNRs, which are interacting with a molecular cloud, *i.e.* with a dense cloud of target gas, allowing the production of a strong γ-ray flux. W51 provides another example of interacting SNR, with the detection of the *pion bump* [4]. Figure 1 shows the Spectral Energy Distributions (SEDs) of these three SNRs, compared to the emission coming from an accelerated proton population interacting with the cloud.

However, the spectra of this type of SNRs often show some features especially at energies above 1 GeV, which are probably due to effects of escaping of high energy cosmic rays. For this reason, younger SNRs ($\approx$ few thousand years old) are often preferred to test directly the acceleration theory. *Fermi*-LAT has detected many of these objects, providing key information for the interpretation of their γ-ray emission. For example Cassiopeia A [5] and Tycho [6] SNRs, have shown spectra which can be interpreted with hadronic models, *i.e.* based on the pion decay. On the other hand, other SNRs, such as RX J1713.7-3946 [7] and RCW 86 [8], show different shapes, which can be interpreted much more easily with leptonic models, based on the production of γ-ray via Inverse Compton scattering of accelerated electrons on the radiation field around the SNR, mostly made of the Cosmic Microwave Background and the infrared dust emission.

A more systematic study of SNRs has been recently developed by the *Fermi*-LAT collaboration, producing the first Supernova Remnant catalog [9]. Three years of data above 1 GeV have been analyzed to study the SNRs already detected in other energy ranges, resulting in the observation of 36 SNRs, with the detection of 14 new objects. This work has shown that studies of an entire population of SNRs is necessary to correctly understand the mechanisms at the basis of their γ-ray emission.

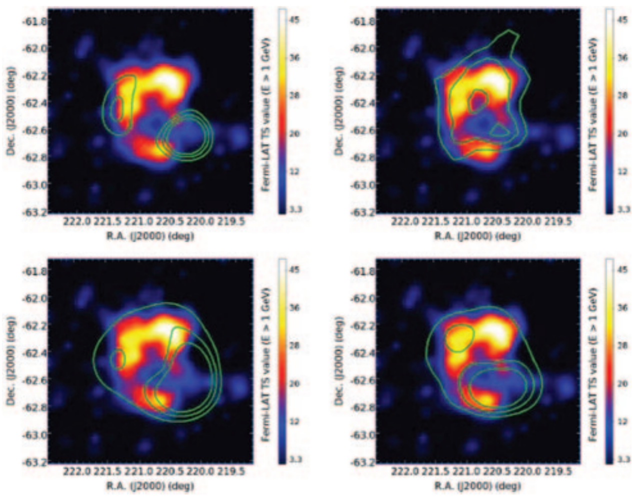

Fig. 2. – Test statistic maps of RCW 86 SNR seen by *Fermi*. The map is overlaid to the contours of the same source observed in other energy ranges: radio (top left), HESS (top right), soft X-ray (bottom left), hard X-ray (bottom right) [8].

2˙2. *Extended source studies.* – Most of the sources detected by the LAT are considered point-like, meaning that their size is not detectable due to the large PSF of the instrument. The improvement in PSF and effective area introduced by the Pass 8 reconstruction method has allowed the study of the spatial extension of some sources.

RCW 86 is an example of SNR which has been recently detected as extended. Figure 2 shows a test statistic map of this source observed by the LAT, compared with the contours of the same sources observed in other energy ranges. The shape observed is in very good agreement with template provided by the HESS experiment, which detected the source in the energy range above 1 TeV, as demonstrated in [8].

3. – Pulsars

Pulsars constitute another very well studied class of Galactic objects in the γ-ray energy range. A pulsar is a rotating neutron star, originating from the gravitational collapse of a massive Supernova and characterized by a strong rotating magnetic field. Particles are accelerated to relativistic energies along their curved field lines, emitting curvature radiation from radio to γ-ray wavelengths. Furthermore, the high electric fields allow the e^+e^- pair creation and generate electromagnetic cascades. This emission is much more intense along the rotating axis of the magnetic field. Hence, the object seems to be *pulsating* when the magnetic field axis points towards the Earth.

In the first eight years of operation, *Fermi*-LAT has shown its outstanding capabilities in detecting γ-ray pulsars, as is shown in fig. 3([1]). In most cases, for known radio or X-ray pulsars, data analysis is performed using given timing models, which allow the reconstruction of the flux of the source as a function of the phase. A blind search of

([1]) A public list of *Fermi* detected pulsars is available at `https://confluence.slac.stanford.edu/x/5Jl6Bg`.

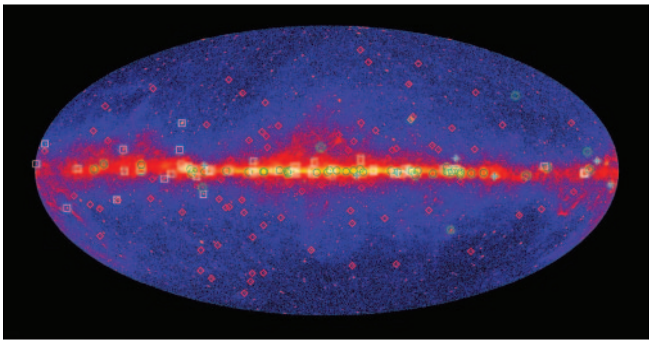

Fig. 3. – γ-ray sky observed by *Fermi* with the positions of the 205 pulsars detected by *Fermi*. White: young γ-ray selected "normal" pulsars; green: radio and X-ray selected "normal" pulsars; cyan: CGRO pulsars; red: radio selected millisecond pulsars; yellow: γ-ray selected millisecond pulsar.

pulsation is computationally intense, since it requires a scan of the entire sky position and of the pulsar parameter space, constituted of its period P and its spin-down rate $\dot{P}$, caused by the energy lost by the pulsar and carried out by radiation and accelerated particles. This search is currently being performed with the Einstein@Home project, which is a volunteer distributed computing project that takes advantage of CPU time made available all over the world. At present, the incredible amount of more than 10000 years of CPU time has been reached, allowing the detection of 14 new γ-ray pulsars. A detailed review of the detection and study γ-ray pulsars is given in [10].

3˙1. *Pulsar Wind Nebulae*. – The relativistic particles ejected by the pulsar and expanding towards the outer shock wave often produce a non-thermal emission from radio to X-ray and γ-ray wavelengths. This emission is broader than the central pulsating emission and often results in the detection of an extended source. This wind takes away most of the pulsar rotation power and is responsible for the pulsar spin-down.

The Crab Nebula is one of the most studied object in our Galaxy and has been used as an astronomical standard candle and deeply observed also by the *Fermi*-LAT [11], even though has recently shown a γ-ray flaring activity.

4. – Conclusions

Fermi-LAT has proved to be a very powerful instrument to study non-thermal phenomena in our Universe. In particular, many different objects in our Galaxy have been discovered and studied, in the energy range from one hundred MeV to few hundreds GeV, which is a crucial range to understand the origin of many phenomena. Besides the objects described in this work, there are γ-ray binaries and γ-ray Novae, which have also opened new scenarios.

Obviously, many other studies are conducted in our Galaxy, such as the diffuse emission, dark matter searches, Solar System objects, and outside our Galaxy, with the study of extragalactic sources (mainly Active Galactic Nuclei) and Gamma-ray Bursts.

Furthermore, the improved performances introduced with Pass 8 are allowing also different studies, such as a more precise study of the morphology of the brightest sources. Hence, new results have to be expected from *Fermi* in the next years.

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