Space-based observations of gamma-rays

Philippe Bruel
Laboratoire Leprince-Ringuet, École polytechnique, CNRS/IN2P3, Palaiseau, France
E-mail: Philippe.Bruel@llr.in2p3.fr

Abstract. The γ-ray space telescopes AGILE and Fermi have been successfully launched on April 2007 and June 2008. Thanks to better capabilities than their predecessor EGRET, and in particular to their considerably improved angular resolution, they are able to provide a much more detailed view of the γ-ray sky above ~20 MeV. They have already reported on a wide variety of astrophysical phenomena and sources such as diffuse galactic emission, pulsars and other galactic sources, active galactic nuclei, gamma-ray bursts, and cosmic-ray electrons.

1. Introduction
After the EGRET experiment [1] on CGRO ended in June 2000, there was no space based experiment able to look at the γ-ray sky above 100 MeV, until the AGILE and the Fermi satellites were launched, in April 2007 and June 2008 respectively. Since their designs and performance are significantly advanced compared to their predecessor, these two experiments reach an unprecedented sensitivity and allow a better and deeper understanding of the γ-ray sky.

2. From EGRET to AGILE and Fermi
The EGRET mission was very successful, with 271 sources reported in the Third EGRET Catalog, far more than the 25 sources detected by its predecessor COS-B. Among these sources, 6 were pulsars, 90 were blazars and 170 were unidentified. These numbers show the limitations of EGRET: 6 pulsars are not enough to perform a real population study, and it is nearly impossible to have a complete understanding of the sky when almost two thirds of the sources are unidentified. The relatively small number of detected sources and the lack of identification was due to the limited sensitivity of the detector, arising from a rather poor angular resolution (5.8° at 100 MeV and 0.5° at 10 GeV) and a relatively small field of view. The successors of EGRET had to overcome these limitations in order to reach a higher sensitivity.

In order to detect γ-rays and measure their directions and energies, a space-based detector needs three sub-detectors: a tracker, in which γ-rays pair-convert, to measure their directions, a calorimeter to measure their energies and an anti-coincidence detector (ACD) to reject charged particles. EGRET used a spark chamber to track e+e- pairs. By using the silicon strip technique with tungsten convertors, AGILE and Fermi are able to achieve a finer precision in the measurement of the direction of the incoming γ-ray. This technique also leads to a better aspect ratio: the height of the tracker is reduced and thus the field of view is greatly enhanced. The ACD of EGRET was a monolithic dome, which caused problems above ~10 GeV: electromagnetic showers in the calorimeter produced backsplash which made a signal in the ACD, thus tagging high energy γ-rays incorrectly as charged particles. To overcome this vetoing problem, the ACDs of AGILE and Fermi are segmented. Another limitation of
EGRET was its large deadtime, which was a serious drawback for measurement of gamma-ray bursts (GRBs). Thanks to fast electronics, AGILE and Fermi have a very small deadtime.

3. AGILE and Fermi

3.1. AGILE

AGILE [2] is an Italian Space Agency (ASI) mission launched on April 23 2007 and capable of observing cosmic sources simultaneously in X-ray (18–60 keV) and γ-ray (30 MeV–30 GeV) bands with the coded-mask hard X-ray imager (SuperAGILE) and the Gamma-Ray Imaging Detector (GRID), respectively. The GRID instrument is the core of the AGILE mission. It is a pair conversion telescope composed of a tungsten-silicon tracker (12 (x,y) planes) and a CsI(Tl) calorimeter (30 CsI(Tl) scintillator bars arranged in two orthogonal layers, 1.5 X₀). AGILE is a small and light instrument: its weight is 100 kg and its sensitive surface is 38x38cm².

3.2. Fermi

The Fermi Gamma-ray Space Telescope (formerly known as Gamma-ray Large Area Space Telescope, GLAST) was successfully launched on June 11 2008. It consists of two instruments: The Large Area Telescope (LAT) [3] and the Gamma-ray Burst Monitor (GBM) [4]. The GBM covers the energy range from 8 keV to 40 MeV and is largely devoted to the detection of GRBs. The LAT is the main instrument of Fermi and was made by an international collaboration (USA, Italy, Japan, France, Sweden) of scientists and engineers. It detects γ-rays from ~20 MeV to above 300 GeV. It is a pair-conversion telescope with 16 identical towers (tracker+calorimeter), covered by an ACD made of 89 plastic scintillator tiles and 8 flexible scintillator ribbons. The tracker consists of 18 tungsten-silicon (x,y) planes. The hodoscopic calorimeter is an array of 1536 CsI(Tl) crystals, arranged in 8 alternating orthogonal layers, which allows the measurement of the position and the shape of the showers. On axis, the thickness of the LAT is 1.5 X₀(tracker)+8.8 X₀(calorimeter).

3.3. Event reconstruction and selection for the LAT

The reconstruction of the direction of the incoming γ-ray is based on the tracker information. Knowing the direction, the energy of the γ-ray can be reconstructed. Below ~1 GeV, a large fraction of the energy is deposited in the tracker, so the energy reconstruction relies on the tracker and the calorimeter information and their correlation. Above ~1 GeV, a large fraction of the energy escapes the calorimeter, so the energy is reconstructed from the longitudinal profile of the shower, which is measured thanks to the longitudinal segmentation of the calorimeter. The direction information is used to extrapolate the trajectory of the particle back to the ACD in order to determine whether the particle is charged. This information, in addition to the topology of the shower in the tracker and in the calorimeter, is used for the selection of the γ-ray candidates. The reconstruction and selection are based on classification trees and have been optimized using a detailed GEANT4 simulation. The performance of the instrument has been carefully checked during beam tests and is monitored on orbit.

3.4. Orbit characteristics and observation mode

AGILE and Fermi both have an almost 1.5 hour orbit period, but do not have the same inclination. With a 2.5° inclination, AGILE does not pass through the South-Atlantic anomaly (SAA). In contrast, with a 25.6° inclination, Fermi loses 14% of its time in the SAA. AGILE operates exclusively in pointing mode, while Fermi’s main observation mode optimized to survey the full sky: the vertical axis of the instrument is pointed to 35° above and below the orbital plane on alternate orbits. In this mode, Fermi can see the whole sky in 2 orbits and the exposure is almost uniform over the full sky. In special cases, particularly for follow-up observations of GRBs, the observatory can be inertially pointed.
3.5. Performance comparison
The improvement of sensitivity from EGRET to AGILE and Fermi is mainly due to the improvement of the angular resolution and the increase of the field of view. The angular resolution at 100 MeV improves from 5.8° for EGRET to 3.5° for AGILE and Fermi. At 10 GeV, the improvement is much more important: from 0.5° to 0.1°. The product of the effective area times the field of view improves from 750 cm² sr to 1500 cm² sr for AGILE and 20000 cm² sr for Fermi. Fig. 1 shows the same portion of the sky as seen by EGRET (left), AGILE (center) and Fermi (right). One can see that after 9 months AGILE, with a much smaller sensitive surface, does almost as well as EGRET in 9 years. Fermi, with a larger sensitive surface and observing efficiency, reveals the γ-ray sky above 100 MeV with an unprecedented precision.

4. AGILE and Fermi bright source lists
With one year of data and a conservative analysis, AGILE [5] detected 40 sources above 4σ significance: 21 pulsars, 13 AGNs, and 8 remained unassociated. Using 3 months of data, Fermi [6] detected 206 sources above 10σ: 30 pulsars, 119 AGNs, and 37 remained unassociated. Compared to the results of EGRET after 9 years of operation (6 pulsars, ~90 AGNs and 170 unidentified), the differences are striking. Thanks to their better sensitivity, AGILE and Fermi are able to detect far more sources with much less non-identification (from ~60% for EGRET to 20% for AGILE and Fermi). The fraction of sources being pulsars jumped from 2% for EGRET to 15% for Fermi, enabling population studies of this important class of γ-ray sources.

![Figure 1](image1.png)
Figure 1. The same part of the sky seen by EGRET, AGILE and Fermi.

![Figure 2](image2.png)
Figure 2. Comparison of Fermi DGE measurement with model prediction [7].

5. The diffuse Galactic emission
The diffuse Galactic emission (DGE) dominates the γ-ray sky. It is produced by interactions of cosmic rays (CRs), mainly protons and electrons, with the interstellar gas (via π⁰ production and Bremsstrahlung) and radiation field (via inverse Compton scattering). It is a direct probe of CR fluxes in distant locations, and may contain signatures of physics beyond the Standard Model, such as dark matter annihilation or decay. Measurements by EGRET indicated an excess of γ-ray emission above 1 GeV relative to diffuse Galactic γ-ray emission models, which were constructed to be consistent with directly measured CR spectra. The excess emission was observed in all directions on the sky and has remained unexplained for a decade. Fermi reported on the DGE at intermediate Galactic latitudes [7], where most of the emission comes from interactions of CRs with the local gas. Fig. 2 shows that the Fermi spectrum is well described by the sum of three components: an a priori model for DGE emission, a point source contribution and an isotropic diffuse emission (extragalactic diffuse emission and residual background). Fermi does not detect the EGRET GeV excess.
6. Galactic sources

6.1. Pulsars

Among the wide variety of $\gamma$-ray sources, pulsars were the first objects identified in our Galaxy. EGRET detected only 6 pulsars with high confidence, despite the few thousand observed in radio. Five of them were normal radio pulsars, discovered using the ephemerides measured by radio astronomers, and the last one, Geminga, was a radio-quiet pulsar. AGILE has detected 21 pulsars [5] and Fermi has detected 46 pulsars [8].

Pulsars are fast-rotating magnetic neutron stars. They come with different flavors: radio loud and radio quiet pulsars, young and old recycled pulsars (millisecond pulsars). In addition to the 6 pulsars seen by EGRET, Fermi has detected 16 young radio pulsars, 16 new pulsars discovered in a blind search and 8 millisecond pulsars.

The light curves measured by AGILE and Fermi for all these different kinds of pulsars are very similar. As a consequence they seem to host the same $\gamma$-ray emission mechanism. An important question not answered by EGRET is whether the $\gamma$-ray emission arises near the surface of the neutron star, close to the classical radio emission (polar cap model), or at a significant fraction of the light cylinder distance (outer gap, slot gaps models). The peaks of the $\gamma$-ray light curve are appreciably offset from the radio peak, suggesting that the $\gamma$-rays arise at high altitude. This is confirmed by the spectral shape of the pulsars: all spectra are well modeled with a simple power law with an exponential cut-off, as shown in Fig. 3. Low altitude emission would imply an hyper-exponential cut-off because of pair attenuation with the strong magnetic field.

With much more $\gamma$-ray statistics for individual sources, Fermi is able to perform a phase-resolved spectral analysis. In [9] Fermi reported that in the light curve of Vela there is a third peak, evolving very clearly with energy as shown in Fig. 4.

![Figure 3](image1.png) **Figure 3.** Vela spectrum measured by Fermi fitted with a power law with an exponential cut-off [9].

![Figure 4](image2.png) **Figure 4.** Counts as function of pulsar phase for different energy bands for Vela, showing that the third peak P3 evolves with energy [9].

6.2. Other Galactic results

Related to these pulsars discoveries is the first detection at $\gamma$-ray energies of a globular cluster, 47 Tucanae, by Fermi [10]. Globular clusters contain from tens to several hundreds of millisecond pulsars (MSPs). Since Fermi had discovered a population of MSPs, it seemed possible to finally detect a globular cluster. So far 23 MSPs have been detected in 47-Tuc by radio and/or X-ray observations and the total population is estimated at 30-60. The spectrum measured by Fermi is well fitted by a power law with exponential cut-off, as are all pulsars seen by Fermi. The spectral index and cut-off are very similar to the mean spectral index and cut-off of the 8 MSPs detected by Fermi. Fermi reported an estimation of the total number of MSPs in 47 Tuc which is compatible with previous estimates.
Another result related to galaxy emission is the detection of the Large Magellanic Cloud by Fermi [11]. The LMC is an excellent target for studying the link between CR acceleration and γ-ray emission since it is nearby, has a large angular extent, and is seen at a small inclination angle that avoids source confusion along the lines of sight. In addition, the LMC is relatively active, housing many supernova remnants, bubbles and superbubbles and massive star forming regions that are all potential sites of CR acceleration. The close correlation found by Fermi between CR density and massive star tracers supports the idea that CRs are accelerated in massive star forming 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.

7. Active Galactic Nuclei
About 1% of galactic centers are active and emit radio, optical, UV, X-ray and γ-ray radiation. Rapidly varying fluxes and large luminosities of AGN are best explained if the γ-rays are emitted from collimated jets of charged particles moving at relativistic speeds. Most of the AGN seen at γ-ray energies are blazars in which the jet points directly to us. Their spectra are usually well described by two broad humps. This is explained in purely leptonic models by an accelerated population of electrons in a magnetic field: the low energy peak is due to the synchrotron emission and the high energy peak is due to Inverse Compton scattering. There are two kinds of blazars: Flat Spectrum Radio Quasars (FSRQs), having strong emission lines and an intense radiation field due to the accretion disk and clouds, BLLacs (BLs), which have nearly featureless spectra and have a low radiation field. The synchrotron peaks of FSRQs lie at IR energies and their IC peak lies below 1 GeV. The IC emission is large because the intense radiation field provides a large density of IC targets. But this large density prevents the γ-rays from reaching very high energy, which explains why the IC peak does not reach higher energies. For BLs, the lower radiation field allows the IC peak to reach hundreds of GeV but the IC emission is less intense. BLs are subclassified into low/intermediate/high-frequency peaked BLs (LBLs/IBLs/HBLs), depending on the position of the synchrotron peak. With their broad energy ranges, AGILE and Fermi are very well suited to study AGN. AGILE [12] has detected 13 AGNs and Fermi [13] has detected 119 AGNs in 3 months.

Thanks to its good energy resolution, Fermi is able to perform a precise spectral measurement of AGN. The spectral index of an AGN as measured by Fermi is correlated with the position of the IC peak: Fermi measures the rising (falling) part of the IC peak of FSRQs (BLs), so the spectral index is greater (lower) than 2. Fermi has found that the spectral index changes continuously from FSRQs to HBLs. Since FSRQs show cosmic evolution but the BLs do not, it seems to indicate that the young FSRQs with standard accretion disk evolve to old BLs with radiatively inefficient accretion disk. Fermi also discovered that many AGN exhibit a spectral break around a few GeV. This is observed for essentially all FSRQs and some LBLs, but not for HBLs.

AGN are strongly variable. Thanks to their sensitivity, AGILE and Fermi are able to perform much better variability measurements than EGRET, as shown in Fig. 5 and 6, which is essential in order to understand the emission mechanism in AGN.

**Figure 5.** AGILE γ-ray light curve above 100 MeV of PKS 1510-089 during March 2009 [14].

**Figure 6.** Fermi γ-ray light curve above 100 MeV of 3C454.3 [15].
8. Gamma-Ray Bursts
GRBs are bright and distant flashes of γ-rays, taking place at a rate of about one per day, briefly shining as the most luminous objects in the Universe. EGRET detected 4 GRBs in its spark chamber. As of May 2009, AGILE has localized 21 GRBs with SuperAGILE (X-rays), has detected 103 GRBs using only its calorimeter (350 keV-100 MeV) and 3 GRBs with the full detector [16]. The Fermi-GBM (<40 MeV) has detected 192 GRBs and the Fermi-LAT (>20 MeV) has detected 8 GRBs. The latter are the ones with the highest measured γ-ray energies. For instance, the highest energy event in GRB 080916C [17] (z=4.35) had 13.2 GeV and arrived 16.5s after the start of the burst. In some quantum gravity models, high-energy photons travel more slowly through the Universe and therefore arrive later than low-energy photons, so this GRB was used to set a lower limit on the quantum gravity mass, M_{QG} > 1.3 \times 10^{18} \text{ GeV/c}^2. Using both the GBM and the LAT, Fermi covers a large energy range: from 8 keV to 300 GeV. So far, Fermi has not detected any departure from the Band function. That is to say, as of May 2009, no new high energy component has been seen in GRBs.

9. Cosmic-ray electrons
Prior to Fermi, available data on high energy electrons were obtained mainly in balloon-borne experiments (except AMS-01) and had limited statistics. Since the only important difference between e^+ e^- and γ-rays in the Fermi-LAT instrument is a signal detected by the ACD, the Fermi team carefully investigated the capability of the LAT to measure cosmic-ray electrons. As a result, a high statistics spectrum of electrons for the energy range 20 GeV - 1 TeV was obtained [18]. This spectrum and the recent PAMELA positron fraction result suggests that there is one or several nearby sources of e^+ e^- (believed to be pulsars or SNRs) responsible for the excess with respect to the conventional model (based on contribution from quasi-uniformly distributed distant sources).

10. Conclusions
Thanks to their performance, AGILE and Fermi have opened a new era of space-based observation of γ-rays. Compared to EGRET, they have a much better angular resolution, which allows a better source identification, and they have a better sensitivity, which allows them to detect more sources and to study the brightest ones with much more precision. The detection and identification of more sources allows population studies that were not conceivable a decade ago. AGILE and Fermi will certainly continue to improve our understanding of the high energy sky in the forthcoming years.

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