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Recent results in High Energy Gamma-ray Astrophysics

G. Barbiellini([1])([2]) and F. Longo([1])([2])

([1]) *Dipartimento di Fisica, Università di Trieste - Trieste, Italy*
([2]) *INFN, Sezione di Trieste - Trieste, Italy*

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Summary. — Since June 2008 two gamma-ray satellite experiments, AGILE and *Fermi*-LAT, have been in contemporaneous operation. Their results allow the study of gamma-ray astrophysics from space to enter in a new era. Starting from the heritage of the EGRET experiment, the science objectives of these two experiments are reviewed. The role of the technological improvement in such achievements is also briefly introduced.

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1. – Introduction to High Energy Gamma-ray Astrophysics main questions

The study of the sky in the energy band $E > 10\,\mathrm{MeV}$ to $E \sim 100\,\mathrm{GeV}$ is commonly called High Energy Gamma-ray Astrophysics. In this energy band, some of the most energetic phenomena of the Universe happen. The processes at play in the high energy sources are characterized by a wide-band non-thermal emission. Observing the sources from radio to gamma-rays helps to clarify their nature and their environments. Moreover fundamental physics questions could be answered using the information provided by distant high energy sources. The two approaches are indeed complementary in the sense the second one needs the first to avoid potential source issues, while the first one needs the second one to address potential implications of the observations. In this sense the study of high energy astrophysics will clarify questions such as the origin of Cosmic Rays in Supernova Remnants, the composition and the velocity of the Extragalactic Jets in powerful Active Galactic Nuclei, the behaviour of elecromagnetic fields in strong gravitation field typical of Pulsars, the magnetic reconnection process in Solar Flares or the nature of the misterious Gamma-ray Bursts. Furthermore fundamental questions as the possible evidence of dark matter annihilation in the center of the Galaxy or the violation of Lorentz invariance. The same complementary approach is reflected on the collaborations behind the current generation of high energy gamma-ray experiments. The main experiments are built and managed by researchers sharing both high energy particle physics and astrophysics expertise [1].

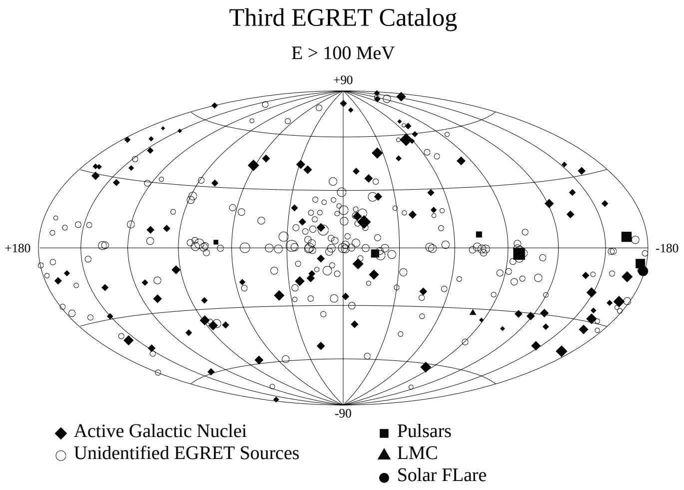

Fig. 1. – Map of source locations for the third EGRET catalogue [6], shown in Galactic coordinates.

2. – The EGRET heritage

The actual study of the high-energy sky relies on the great discoveries of the Energetic Gamma Ray Experiment Telescope (EGRET) (for a recent review see [2]). EGRET was the high-energy instrument on the Compton Observatory, covering the energy range 20 MeV to 30 GeV [3]. EGRET was built as a typical pair production telescope. A system able to identify the gamma-ray interaction in the presence of a huge background of charged particles and measure the gamma-ray arrival time, arrival direction, and energy. This was done by means of multidetector system, composed of an Anticoincidence System, a Spark chamber tracker system with 28 thin tantalum sheets, a scintillator-based Time-Of-Flight detector and Sodium Iodine Calorimeter [2].

In its nine-year lifetime EGRET observed the entire high-energy gamma-ray sky. The brightest source is the Milky Way, particularly toward the inner part of the Galaxy, as a result of the interactions of high-energy cosmic rays with the interstellar matter and radiation fields. Individual gamma-ray sources appear as excesses above the modeled diffuse emission [4]. The EGRET analysis process used a maximum likelihood method to compare probabilities of fitting a given region of the sky with and without a source [5]. The most complete analysis of the sky by the EGRET team was the third EGRET catalogue [6]. Figure 1 shows the 3EG results on gamma-ray sources, with the source locations shown in Galactic coordinates. Among the 271 3EG gamma-ray sources, EGRET detected 94 sources with probable or possible association with the class of Active Galactic Nuclei known as blazars, 5 pulsars, the Large Magellanic Cloud detected as an extended gamma-ray source, one solar flare and 170 sources, well over half the total, with no identification with known astrophysical objects [2].

EGRET detected also few gamma-ray bursts (GRBs) above 30 MeV. The EGRET photons from GRBs were seen coincident with low-energy gamma-ray emission for at least 4 bursts among the brightest GRBS seen by BATSE [7]. In addition to the prompt high-energy emission, delayed emission from some GRBs was detected by EGRET [8].

In another remarkable event [9], the EGRET calorimeter detected an additional delayed spectral component.

The main EGRET results and the challenges left to the current generation could be summarized in the following main four topics.

- The brightest persistent sources detected in high energy gamma-rays are pulsars, rapidly rotating neutron stars in high magnetic fields. Definetely more exposure and more precise timing with respect to EGRET is needed to detect in gamma-rays more known radio pulsars and to discover new pulsars.
- Many of the bright sources away from the Galactic plane are highly variable types of Active Galactic Nuclei in the so-called blazar class. To understand the process at play in these sources a simultaneous mutiwavelength observation campaign might be useful. A larger field of view with respect to EGRET will let the new gamma-ray experiments to detect more flaring blazars.
- Most of the EGRET sources are not associated with known objects. A better angular resolution is definetely needed to clearly associate the gamma-ray excess with sources known at other wavelengths.
- A larger field of view, a wider energy coverage and a better timing will be useful to understand the nature of the high energy emission from GRBs.

The new generation of high-energy space missions has to address some of the fundamental issues that were left open (or unresolved) by EGRET. It is important to make substantial progress in the instrumentation and mission concept to achieve the following goals: 1) improving the gamma-ray angular resolution near 100 MeV by at least a factor of 2-3 compared to EGRET; 2) obtaining the largest possible field of view (FOV) at 100 MeV reaching 2.5-3 sr; 3) drastically reducing the deadtime for gamma-ray detection from the EGRET value of 100 ms; 4) obtaining broad-band spectral information possibly including a simultaneous detection capability in the MeV and X-ray energy ranges; 5) carrying out a rapid quicklook analysis of the gamma-ray data and a fast dissemination of results and alerts; 6) stimulating efficient multifrequency programs [10].

3. – AGILE

The AGILE scientific payload is made of three detectors surrounded by an Anticoincidence system, all combined into one integrated instrument with broad-band detection and imaging capabilities [10]. In particular the Gamma-Ray Imaging Detector (GRID) is sensitive in the energy range $\sim$ 30 MeV–50 GeV, and consists of a Silicon-Tungsten Tracker, a Cesium Iodide Calorimeter, and an Anticoincidence system. The GRID is designed to achieve an optimal angular resolution, a very large field-of-view, and a sensitivity comparable to that of EGRET for sources within 10-20 degree from the main axis direction.

The map of the high significant AGILE sources is shown in fig. 2. This map is the result of the significance-limited catalog that includes only sources above 4 σ extracted from the sample of AGILE detections obtained with a conservative data analysis approach [11].

AGILE fullfilled in its 2 years of operation most of the challenges that EGRET left open. Here we report some of the most important results made by the AGILE team.

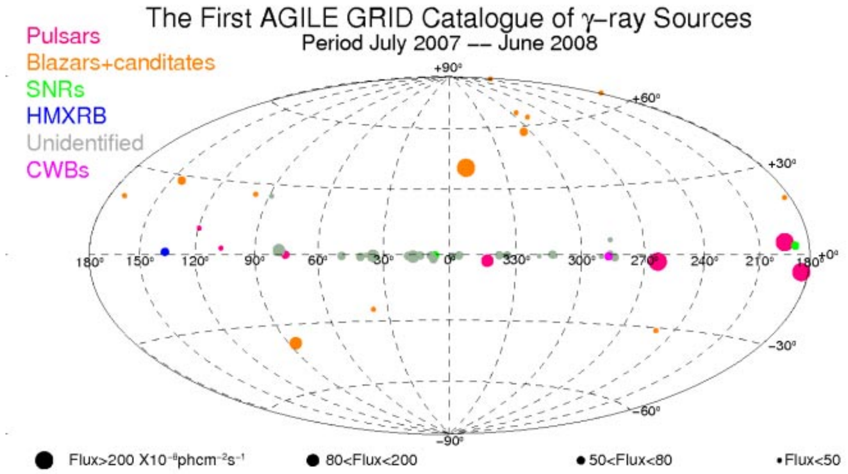

Fig. 2. – The First AGILE-GRID Catalog of high-confidence sources [11].

– Searching for pulsed signals from 35 potentially interesting radio pulsars, ordered according to $F_\gamma \propto \sqrt{\dot{E}d^{-2}}$ and for which contemporary or recent radio data were available, AGILE detected three new top-ranking nearby and Vela-like pulsars with good confidence both through timing and spatial analysis. Among them the remarkable PSR B1509-58 with a magnetic field in excess of 10^{13} Gauss, PSR J2229+6114 providing a reliable identification for the previously unidentified EGRET source 3EG 2227+6122 and the powerful millisecond pulsar B1821-24, in the globular cluster M28 [12].

– AGILE made several multiwavelength campaigns. One of the most interesting objects studied by this means by AGILE is the blazar 3C 454.3. One simultaneous campaign was carried out in November 2007 with AGILE, INTEGRAL, Swift, the WEBT Consortium, and the optical-NIR telescope REM. AGILE detect significant day-by-day variability of the gamma-ray emission. A correlation analysis based on the entire data set is consistent with no time-lags between the gamma-ray and the optical flux variations [13].

– AGILE performed an extensive observation campaign on the Galactic region hosting the Carina nebula and the remarkable colliding wind binary Eta Carinae (Eta Car) during the period 2007 July to 2009 January. AGILE detected a gamma-ray source consistent with the position of Eta Car, providing the long sought first detection above 100 MeV of a colliding wind binary [14].

– GRB 080514B was the first gamma-ray burst (GRB), since the time of EGRET, for which individual photons of energy above several tens of MeV have been detected with a pair-conversion tracker telescope. The hard X-ray emission observed by the X-imager of AGILE lasted about 7 s, while there is evidence that the emission above 30 MeV extends for a longer duration (at least 13 s) [15].

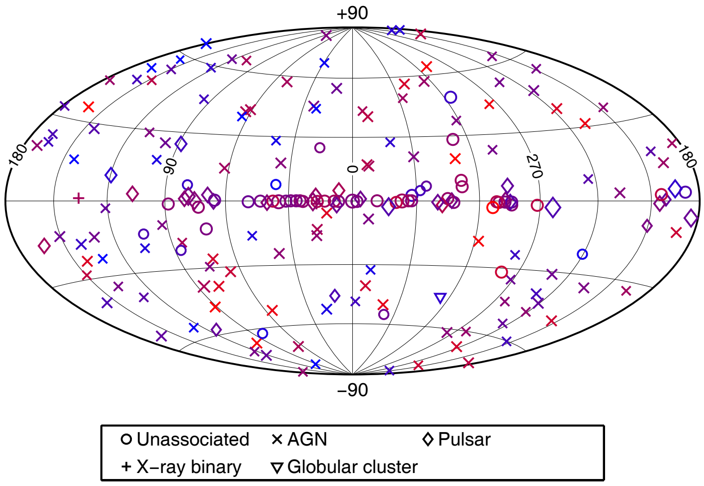

Fig. 3. – Location of the LAT Bright Sources [17].

4. – *Fermi*-LAT

The Large Area Telescope (LAT) [16] on board the Fermi Mission is a pair-conversion telescope with a precision tracker and calorimeter, each consisting of a 4×4 array of 16 modules, a segmented anticoincidence detector that covers the tracker array, and a programmable trigger and data acquisition system. Each tracker module has a vertical stack of 18 x, y tracking planes, including two layers (x and y) of single-sided silicon strip detectors and high-Z converter material (tungsten) per tray. Every calorimeter module has 96 CsI(Tl) crystals, arranged in an 8 layer hodoscopic configuration with a total depth of 8.6 radiation lengths, giving both longitudinal and transverse information about the energy deposition pattern. The calorimeter's depth and segmentation enable the high-energy reach of the LAT and contribute significantly to background rejection. The aspect ratio of the tracker (height/width) is 0.4, allowing a large field-of-view (2.4 sr) and ensuring that most pair-conversion showers initiated in the tracker will pass into the calorimeter for energy measurement [16].

Figure 3 reports the initial results for energies above 100 MeV for the 205 most significant (statistical significance greater than $\sim$ 10-σ) γ-ray sources in the early mission LAT data. These are the best-characterized and best-localized point-like (*i.e.*, spatially unresolved) γ-ray sources [17].

During its first months of operation the LAT team made several important discoveries not only fullfilling EGRET challenges, but opening really a new era in gamma-ray astrophysics. Here we report only some of them.

- Although there are more than 1800 known radio pulsars, until recently, only seven were observed to pulse in gamma-rays and these were all discovered at other wavelengths. The Fermi Large Area Telescope made it possible to pinpoint neutron stars through their gamma-ray pulsations. LAT reported the detection of 16 gamma-ray pulsars in blind frequency searches. Most of these pulsars are coincident with previously unidentified gamma-ray sources, and many are associated with supernova remnants. Direct detection of gamma-ray pulsars enables studies of emission mechanisms, population statistics, and the energetics of pulsar wind nebulae and supernova remnants [18].

- LAT made the first simultaneous observations that cover the optical, X-ray, and high-energy gamma-ray bands of the BL Lac object PKS 2155-304. The gamma-ray bands were observed for 11 days, between 2008 August 25 and 2008 September 6, jointly with the Fermi Gamma-ray Space Telescope and the HESS atmospheric Cherenkov array, providing the first simultaneous MeV-TeV spectral energy distribution (SED) with the new generation of gamma-ray telescopes. The ATOM telescope and the RXTE and Swift observatories provided optical and X-ray coverage of the low-energy component over the same time period. The object was close to the lowest archival X-ray and very high energy (VHE; $> 100\,\text{GeV}$) state, whereas the optical flux was much higher. The light curves show relatively little (30%) variability overall when compared to past flaring episodes, but this campaign found a clear optical/VHE correlation and evidence for a correlation of the X-rays with the high-energy spectral index [19].

- Energetic young pulsars and expanding Supernova remnants (SNR) are the most visible remains after massive stars, ending their lives, explode in core-collapse supernovae. The Fermi Gamma-Ray Space Telescope has unveiled a radio quiet pulsar located near the center of the compact synchrotron nebula inside the supernova remnant CTA 1. The pulsar, discovered through its gamma-ray pulsations, has a period of 316.86 milliseconds and a period derivative of 3.614×10^{-13} seconds per second. Its characteristic age of 10^4 years is comparable to that estimated for the SNR [20].

- Gamma-ray bursts (GRBs) are highly energetic explosions signaling the death of massive stars in distant galaxies. The Gamma-ray Burst Monitor and Large Area Telescope onboard the Fermi Observatory together record GRBs over a broad energy range spanning about 7 decades of gamma-ray energy. In September 2008, Fermi observed the exceptionally luminous GRB 080916C, with the largest apparent energy release yet measured. The high-energy gamma-rays are observed to start later and persist longer than the lower energy photons. A simple spectral form fits the entire GRB spectrum, providing strong constraints on emission models. The known distance of the burst enables placing lower limits on the bulk Lorentz factor of the outflow and on the quantum gravity mass [21].

5. – Conclusions: the importance of the technological development

Both AGILE and *Fermi*-LAT, unlike the previous generation instruments, such as EGRET, do not require high voltages nor gas operations. Both instruments contain as the central detector a Silicon-Tungsten Tracker characterized by a very fine spatial resolution (obtained by a special arrangement of Silicon microstrip detectors and analog signal storage and processing), a very small deadtime for gamma-ray detection, and the capability of self-triggering allowing the achievement of a large field of view crucial for the detection of the variable gamma-ray sky.

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