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Observations of high-energy gamma-rays with the *Fermi* Observatory

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Summary. — The *Fermi* Gamma-Ray Space Telescope is a satellite-based observatory that explores the gamma-ray sky in a wide energy range from a few keV to more than 300 GeV, allowing the investigation of many fields of gamma-ray astrophysics. Fermi will open a new and important window on a wide variety of phenomena, including black holes and active galactic nuclei, gamma-ray bursts, the origin of cosmic rays and supernova remnants and searches for hypothetical new phenomena such as supersymmetric dark matter annihilations. The primary instrument is the Large Area Telescope (LAT), which measures gamma-ray flux and spectra from 20 MeV to > 300 GeV and is a successor to the highly successful EGRET experiment on CGRO. The LAT has better angular resolution, greater effective area, wider field of view and broader energy coverage than any previous experiment in this energy range. The detectors were integrated with the spacecraft in December 2006 and Fermi has been launched on June, 11 2008 from Kennedy Space Flight Centre (NASA). In an early phase of the operations, a series of calibrations and performance measurements and monitoring were performed and the first sky images were collected. This paper will present a short review of the Fermi observatory physics and the first sky images collected during the first 6 months of the science phase of the mission.

PACS 95.85.Pw – γ-ray.
PACS 97.60.Gb – Pulsars.
PACS 98.54.Cm – Active and peculiar galaxies and related systems.
PACS 98.70.Sa – Cosmic rays.

1. – Introduction

Fermi was successfully launched from Cape Canaveral on the 11th of June 2008. It is currently in an almost circular orbit around the Earth at an altitude of 565 km having an inclination of 25.6° and an orbital period of 96 minutes. After an initial period of engineering data taking and on-orbit calibration [1], the observatory was put into a sky-survey mode. The observatory has two instruments onboard, the Large Area Telescope [2, 3] (LAT), a pair-conversion gamma-ray detector and tracker and a Gamma

TABLE I. – *Summary of Large Area Telescope Instrument parameters and estimated performance.*

Parameter	Value or range
Energy range	20 MeV–300 GeV
Effective area at normal incidence	
(peak typically is in the 1–10 GeV range)	9500 cm^2
Energy resolution (equivalent Gaussian 1σ):	
100 MeV–1 GeV (on axis)	9%–15%
1 GeV–10 GeV (on axis)	8%–9%
10 GeV–300 GeV (on-axis)	8.5%–18%
> 10 GeV ($> 60°$ incidence)	$\leq 6\%$
Single photon angular resolution (space angle)	
on-axis, 68% containment radius:	
> 10 GeV	$\leq 0.15°$
1 GeV	0.6°
100 MeV	3.5°
Field of View (FoV)	2.4 sr
Timing accuracy	$< 10\,\mu$s
Event readout time (dead time)	26.5 μs

Ray Burst Monitor (GBM), dedicated to the detection of gamma-ray bursts. The instruments on *Fermi* jointly provide coverage over the energy range from a few keV to several hundreds of GeV. With respect to previous gamma-ray missions, *Fermi*-LAT has a very large field of view that allows monitoring 20% of the sky at any instant and a very wide energy range from 20 MeV to > 300 GeV.

2. – The Large Area Telescope

The Large Area Telescope has good angular resolution for source localization and multi-wavelength studies, high sensitivity over a broad field-of-view to monitor variability and detect transients, good calorimetry over an extended energy band to study spectral breaks and cut-offs, and good calibration and stability for absolute, long-term flux measurement. The LAT measures the tracks of the electron (e^-) and positron (e^+) that result when an incident γ-ray undergoes pair-conversion, preferentially in a thin, high-Z foil, and measures the energy of the subsequent electromagnetic shower that develops in the telescope's calorimeter. Table I summarizes the scientific performance capabilities of the LAT [2]. To take full advantage of the LAT's large FoV, the primary observing mode of *Fermi* is the so-called "scanning" mode in which the normal to the front of the instrument (z-axis) on alternate orbits is pointed to +35° above and below the orbital plane on alternate orbits. In this way, after 2 orbits, about 3 hours for *Fermi*'s orbit, the sky exposure is almost uniform. For particularly interesting targets of opportunity, the observatory can be inertially pointed. Details of the LAT design and performance are presented in [2].

3. – Fermi physics opportunities

Since *Fermi*-LAT scans the entire sky in few hours, a dramatic change of the catalog of high-energy gamma-ray sources and an increment by an order of magnitude of the number of point sources is underway. Additionally, the timing resolution for variable phenomena (gamma-ray burst, pulsars, AGNs. . .) and the spatial localization of known sources are being greatly improved. The scientific objectives that *Fermi*-LAT will address include:

1) resolving the high-energy gamma-ray sky and determining the nature of the unidentified gamma-ray sources seen by EGRET and the origin of the apparently isotropic diffuse emission;

2) understanding the mechanisms of particle acceleration in celestial sources, including active galactic nuclei, pulsars, and supernovae remnants;

3) studying the high-energy behavior of gamma-ray bursts and transients;

4) using high-energy gamma-rays to probe the early universe to $z \geq 6$;

5) probing the nature of dark matter.

Fermi-LAT should help us determine how much energy extreme astrophysical sources produce, and therefore tell us about the acceleration mechanisms that produce such high-energy particles.

4. – Fermi first 6 month results

The first two months of data taking were mainly dedicated to calibrations and alignments [2]. Therefore the first results are related to the discovery of new sources and to the measurements of known objects, with the intent to verify both the pointing and the observatory features. Since Vela is the brightest source in the GeV sky, we have used this pulsar to verify spatial and temporal alignments of the *Fermi* observatory. During Launch and Early Orbit operations (L&EO), *Fermi* targeted Vela pulsar for several pointed observations added to the data taking in survey mode, and as a result established the position of Vela in gamma-rays within $0.5'$ of the the radio pulsar position [4]. *Fermi* timing validation and verification has been obtained using data collected during first period of data taking and using the known radio ephemeris measurements to verify the absolute timing of photons observed by *Fermi*, after correcting photon arrival time to the Solar System barycenter [5]. At the end of the on-orbit calibrations [1], the observatory was put into a sky-survey mode, and here we summarize most relevant results observed in the first 6 months. The EGRET era left us some unresolved problems that FERMI has started to explore:

– the nature and characteristics of GRBs;

– the identification of the unresolved sources, *i.e.* not associated to known sources from other catalogues;

– the problem of the GeV excess;

– the number of γ-ray pulsars and the γ-ray emission mechanisms.

5. – Gamma Ray Burst studies

The two instruments on *Fermi* will also provide us with the complete high-energy spectra of gamma-ray bursts, from a few keV to hundreds of GeV. These bright and distant flashes of gamma-rays, which take place at a rate of about one per day, briefly shine as the most luminous objects in the universe—yet the total energy released and their energy range has yet to be measured. The standard picture that has emerged of GRB physics is that an initial fireball powers a collimated, super-relativistic blast wave with initial Lorentz factor $\sim 10^2$–10^3. Prompt γ-ray and X-ray emission from this "central engine" may continue for few $\times 10^3$ s. Then external shocks arising from interaction of the ejecta with the circumstellar environment at lower Lorentz factors give rise to afterglows in the X-ray and lower-energy bands that are detected for hours to months. The physical details—primary energy source and energy transport, degree of blast wave collimation, and emission mechanisms—remain for debate [6]. GBM and LAT onboard *Fermi* Observatory together, record GRBs over a broad energy range spanning about 7 decades of gamma-ray energy. During the first 6 months, *Fermi* has detected several GRBs, mostly on GBM detector and others with joint observations between GBM and LAT. In September 2008, Fermi observed the exceptionally luminous GRB 080916C [7], 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 costraints on the quantum gravity mass. The increasing number of detections of GRBs by the LAT will help constrain many uncertainties in these areas.

6. – Galactic sources

Pulsars are fast-rotating magnetic neutron stars that probably emit beams of radio waves from their poles. Taking into account radio observations, the gamma-ray energy distributions from these ultra-dense objects will tell us about the geometry of the magnetic fields present and about the location of the acceleration sites. Since the large magnetic field of a pulsar can cause gamma-ray photons to convert into e^+-e^- pairs, *Fermi*-LAT may allow us to study a process in quantum electrodynamics that is not observable anywhere else. Gamma-rays may also tell us about far high-energy particle-acceleration mechanisms more powerful than anything seen on Earth. Observations of supernova remnants suggest that particles can be accelerated to enormous energies by shocks produced as the blast from an exploding star ploughs into the interstellar medium. While the existence of such shocks is well established, the way in which particles are accelerated to extreme relativistic energies is not fully understood. Most of the Galactic point sources identified by EGRET were pulsars. There were five young radio pulsars detected with high significance, along with the radio-quiet pulsar Geminga and one likely millisecond pulsar [8]. A number of other pulsars had lower significance pulse detections and many of the bright, unidentified γ-ray sources are coincident with known radio pulsars. Surrounding young pulsars are bright non-thermal pulsar wind nebulae (PWNe). Rotation-induced electric fields in charge-depleted regions of pulsar magnetospheres ("gaps") accelerate charges to ten's of TeV and produce non-thermal emission across the electromagnetic spectrum. The coherent radio emission, through which most pulsars are discovered, is however a side-show, representing a tiny fraction of the spin-down power. In contrast the $\sim$ GeV peak in the pulsed power can represent as much as 20–30% of the total spin-down. Many central questions remain unanswered about the pulsar emission. A basic issue is whether the high-energy emission arises near the surface, close to the classical radio emission ("polar cap" model [9]) or at a significant fraction of the light cylinder distance ("outer gap" models [10, 11]). In addition to geometrical (beam-shape) differences, the two scenarios predict that different physics dominates the pair production. Near the surface $\gamma + B \rightarrow e^+ + e^-$ is important, while in the outer magnetosphere $\gamma + \gamma \rightarrow e^+ + e^-$ dominates; these result in substantially different predictions for the high-energy pulsar spectrum. *Fermi* observations on the most intense pulsar, *i.e.* Vela, let us to conclude [4] that at least for this object, the emission seen is more compatible with outer gap [10, 11] rather than polar cap emission [9]. Moreover *Fermi* discovered several radio-quiet gamma-ray only pulsars. The first one discovered was CTA1 [12] but during these first months, the total sample includes a dozen of objects in this category. Moreover we identify several candidates as millisecond pulsars [13-15].

7. – Active Galactic Nuclei

One of the major scientific goals of the *Fermi* is to provide new data about γ-ray activity of AGNs. Rapidly varying fluxes and large luminosities of extragalactic γ-ray sources are best explained if the γ-rays are emitted from collimated jets of charged particles moving at relativistic speeds [16, 17]. *Fermi*-LAT observations [18] will help determine how these particles are accelerated, where the gamma-rays are emitted, what the energy and power budgets of the supermassive black-hole engines are, what this says for the fueling and growth of black holes, and the reasons for the differences between radio-loud and radio-quiet AGNs, and FSRQs and BL Lac objects. These are just a few of the questions that γ-ray AGN studies with the *Fermi*-LAT are helping to answer [19, 20]. Source variability is one of the most impressive features that *Fermi* has observed in the first months of observations. Most of the variable sources are AGNs. Some of these were particularly intense, in particular on 4 September 2008, a strong gamma-ray emission was detected from PKS 1454–354 with flux peaking on the time scale of a few hours then decaying on the time scale of days [21].

8. – Diffuse emission

The diffuse emission of the Milky Way is an intense celestial signal that dominates the γ-ray sky. The diffuse emission traces energetic particle interactions in the ISM, primarily protons and electrons, thus providing information about cosmic-ray spectra and intensities in distant locations [22]. This information is important for studies of cosmic-ray acceleration and propagation in the Galaxy [23]. Gamma-rays can be used to trace the interstellar gas independently of other astronomical methods, *e.g.*, the relation of molecular H_2 gas to the CO molecule [24] and hydrogen overlooked by other methods [25]. The diffuse emission may also contain signatures of new physics, such as dark matter, or may be used to put restrictions on the parameter space of supersymmetrical particle models and on cosmological models. The Galactic diffuse emission also must be modeled in detail in order to determine the Galactic and extragalactic γ-ray backgrounds and hence to build a reliable source catalog. Accounting for the diffuse emission requires first a calculation of the cosmic-ray (CR) spectra throughout the Galaxy [26, 27]. A realistic calculation that solves the transport equations for CR species must include gas

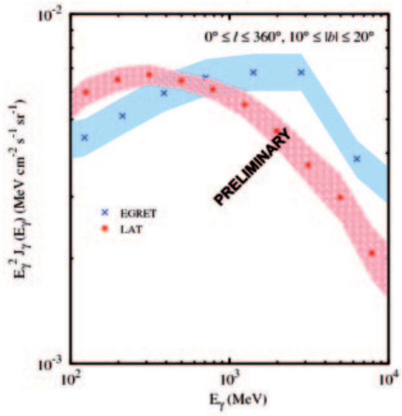

Fig. 1. – (Colour on-line) LAT spectrum averaged over all Galactic longitudes and latitude range $10° \leq |b| \leq 20°$. Also shown are the EGRET data for the same region of the sky. Data points: LAT, red dots; EGRET blue crosses. Systematic uncertainties: LAT red hatched regions, EGRET blue regions.

and source distributions, interstellar radiation field (ISRF), nuclear and particle cross-sections and nuclear reaction network, γ-ray production processes, and energy losses. Finally, the spectrum and spatial distribution of the diffuse γ-rays are the products of CR particle interactions with matter and the ISRF. One of the critical issues for diffuse emission remaining from the EGRET era is the so-called "GeV excess". This puzzling excess emission above 1 GeV relative to that expected [22, 26] has shown up in all models that are tuned to be consistent with directly measured cosmic-ray nucleon and electron spectra [28]. The excess has shown up in all directions, not only in the Galactic plane. The origin of the excess is intensively debated in the literature since its discovery by [22]. The excess can be the result of an error in the determination of the EGRET effective area or energy response or could be the result of yet unknown physics (see [23]). Recent studies of the EGRET data have concluded that the EGRET sensitivity above 1 GeV has been overestimated [29] or underestimated [30] or imply different cosmic-ray energy spectra in other parts of the Galaxy compared to the local values [28, 31]. If these possibilities are eliminated with high confidence, then it may be possible to attribute the excess to exotic processes, *e.g.*, dark matter annihilation products [32].

We have started a preliminary analysis of the diffuse emission using middle-latitude regions respect to the Galactic plane [33]. These regions contain a significant Galactic diffuse emission, but at the same time fewer point-like sources, respect to direct usage of central Galactic plane regions. To select events from this region a $10° \leq |b| \leq 20°$ selection has been applied on data. Figure 1 shows the spectrum of diffuse emission seen by *Fermi* and a comparison with EGRET data [34] and a model of the diffuse component (see [33] for more details). The EGRET data, available from the CGRO science support centre, were processed following the procedure in [28]. The LAT systematic error is $10\% \leq 100\,\text{MeV}$, 5% at $10^{2.75}$ MeV, 20% for $E \geq 10\,\text{GeV}$ (and linearly interpolated in $\log E$ between those points). Therefore the first months of LAT science data shown in fig. 1 do not confirm the GeV excess seen by EGRET in the latitude range $10° \leq |b| \leq 20°$. The spectral shape is reasonably explained with a cosmic-ray propagation model.

9. – High-energy electron observations

The on-board filter [2] is configured to accept all events that deposit at least 20 GeV in the calorimeter(CAL); thus we ensure that the rare high-energy events, including electrons, are available for thorough analysis on the ground. We developed [35] a dedicated event selection for high-energy electrons that provides a large geometry factor with a residual hadron contamination less than 20% at the highest energy. As for the analysis developed for extracting LAT photon data [2], the electron selection essentially relies on the LAT capability to discriminate EM and hadronic showers based on their longitudinal and lateral development, as measured by both the TKR and CAL detectors. The background rejection power for photon science is optimized up to 300 GeV. The electron selection criteria are instead tuned in the multi-100 GeV range, where the much steeper electron spectrum requires an overall hadron rejection power of $1 : 10^4$. Events considered for the electron analysis are required to fail the ACD vetoes developed to select photon events [2]. This removes the vast majority of the potential gamma-ray contamination. The overall gamma contamination in the final electron sample is estimated as always less than 2%. *Fermi* measurements of the electron spectrum [35] do not confirm balloon observations [36] of electron excessess on the expected spectrum due to cosmic-ray propagation in our Galaxy. These new observations together with the recent observation of positron excess [37] make the complex problem of electron and positron production puzzling and these observations may put some constraints about possible dark matter signals in these channels or suggest nearby astrophysical sources as the most reasonable candidates for their production.

10. – Conclusions

The first *Fermi*-LAT results confirm the excellent quality of the instrument and confirm the capability of the observatory to start a new gamma-ray era. Among the first observations Fermi has observed several GRB, detected new pulsars, in particular several radio-quiet gamma-ray only pulsars and a new class of milli-seconds pulsars, several AGNs are monitored, the Moon and Sun emissions were detected [38,39]. Moreover, first observations of the diffuse Galactic emission from intermediate latitude regions do not confirm the previously observed by EGRET “GeV excess” and some more recent observations on the electron spectrum observed by *Fermi* [35] may complete the picture of the cosmic-ray propagation in the galaxy. During the first year of data taking therefore we expect an impressive improvement in the knowledge of all the physics topics previously indicated and a substantial increment of known sources.

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