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Fermi Space Telescope highlights

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Summary. — The *Fermi* Space Mission has had a remarkable first two years of operation in low-Earth orbit, collecting over 380 million events, and revealing unprecedented details of the gamma-ray sky. The Large Area Telescope (LAT) has lived up to expectations. Being the first all-sky monitor in almost real time has revealed a wealth of transient phenomena. Some highlights of the discoveries made by the *Fermi*-LAT in the past two years are presented. Possible future directions for this highly successful mission will be discussed.

PACS `95.30.Cq` – Elementary particle processes.
PACS `95.35.+d` – Dark matter (stellar, interstellar, galactic, and cosmological).
PACS `95.45.+i` – Observatories and site testing.
PACS `95.55.Ka` – X- and γ-ray telescopes and instrumentation.

1. – Introduction

The Gamma-ray Large Area Space Telescope (GLAST) was launched on June 11, 2008. After an initial 60-day period to check out the space craft and flight instruments, GLAST was renamed to the *Fermi* Large Area Telescope (*Fermi*-LAT) and began officially taking science data on August 4, 2008 [1]. The main operating mode is "All-Sky scanning", which allows for full sky coverage after two orbits (on successive orbits the bore sight of the LAT is rocked first towards the north pole of the orbit plane alternating with rocking to the south pole). This began a new era both for high-energy gamma-ray astronomy and astronomy as a whole: for the first time a near-real time imaging all-sky monitor is operational.

For the first year data, the instrument team was given proprietary access. With the anniversary of the commencement of data taking, the first year and the subsequent data stream are public. This enables other researchers that are not members of the LAT Collaboration to also mine the data. The *Fermi*-LAT Collaboration remains strong. The original instrument team included institutions from the US, Italy, Japan, Sweden, and France, and now has some 313 members plus many students. There are over 100 LAT papers accepted for publication and over 2300 citations of the combined LAT publications to date. Science Magazine selected the Fermi mission as the no. 2 science "breakthrough" for 2009 (no. 1 was the reconstruction of the 4.4 million-year-old Ardipithecus ramidus

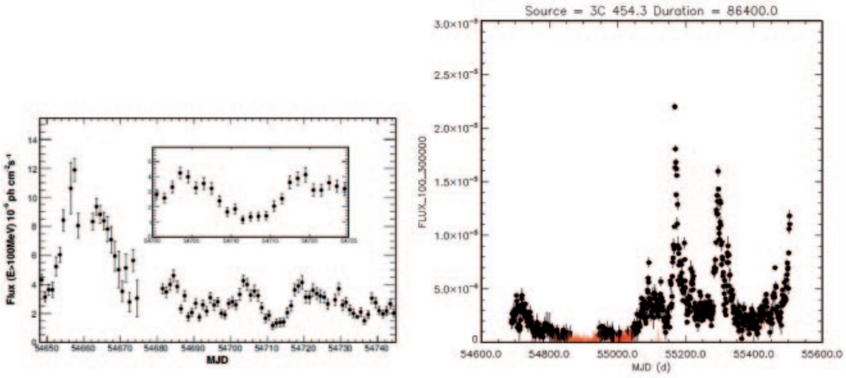

Fig. 1. – Activity of 3C454.3 seen by the *Fermi*-LAT during its checkout period. These figures illustrate the new era of AGN monitoring enabled by the *Fermi*-LAT. The frequency, duration, and magnitude of flares are now measured, which will lead to a better understanding of their origin and significance.

skeleton—the oldest fossil on the human branch of evolution) [2]. The *Fermi*-LAT was also used as the cover for the Science Magazine issue reporting many of the LAT pulsar results [3-5]. The *Fermi*-LAT has already had a large impact on the field of high-energy gamma-ray astrophysics, as illustrated by the participation at this conference: SciNeGHE 2010 has more than 20 talks on the *Fermi*-LAT results (out of 70 total).

The science reported on and published by the LAT Collaboration covers many more topics and results than is possible to present in an overview. Necessarily I will restrict this paper to a few topics. These are inline with some of my individual interests and do not necessarily reflect those of others, or the *Fermi*-LAT Collaboration at large.

2. – All-sky monitoring and operations

The first highlight is meant to underscore the scientific benefit of continuous “all-sky” monitoring. Shortly after launch (in fact during the instrument check-out phase) the Active Galactic Nucleus (AGN) 3C454.3 was observed to be in a high emission state (“flaring”). It has long been known that AGN have out-bursts: periods of dramatically increased luminosity often appearing simultaneously in different wavelength bands. This particular AGN had been observed by EGRET to exhibit flaring but, due to the pointed observation data plan of the CGRO mission, and hence non-continous monitoring of the source, details as to frequency, rapidity of onset, duration, etc., were not captured during the almost 9-year mission. Figure 1 shows the early LAT observations of 3C454.3, illustrating the detailed measurements of the time evolution of the light curve afforded by the almost continuous monitoring in the all-sky survey mode [6].

Another example of where the scientific return was enhanced by the all-sky monitoring was the observation of the nova in V407-Cygni [7]. This event was first observed by a pair of optical astronomers, F. Kabashima and K. Nishiyama, on March 10, 2010 [8]. The *Fermi*-LAT observed this nova in gamma-rays (!) peaking a few days later on March 13-14, 2010 [9] (see fig. 2). V407-Cygni is in a binary system with a Red Giant (RG) and the observed gamma-ray emission is consistent with Fermi-accelerated electrons and protons in the outgoing nova shock expanding into the RG wind.

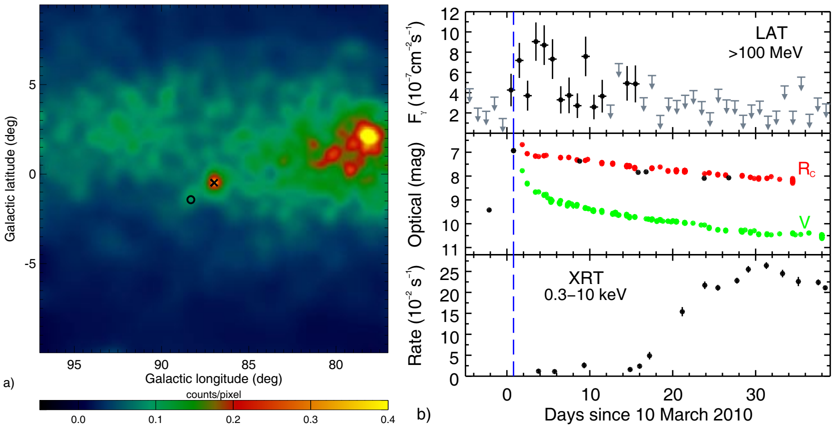

Fig. 2. – (a) Counts map for energies $> 100\,\mathrm{MeV}$ for the V407-Cygni region during the nova. (b) Light curves for the *Fermi*-LAT optical and X-ray bands during the nova.

3. – Pulsars

Another early discovery was made during the *Fermi*-LAT check-out period: a new gamma-ray pulsar in the supernova remnant CTA-1 [10]. In the EGRET era, 7 gamma-ray pulsars were discovered. However, none were found based solely on gamma-ray data. Establishing the period and period derivative of a pulsar, in a dataset where an event is recorded by the detector every several thousands-to-millions of revolutions of the neutron star, required re-thinking of the search algorithms previously employed. This approach was needed in the LAT era considering the data are dispersed in time even more due to the scanning mode. The reward for the pre-launch effort to develop a time-differencing technique [11, 12] was the detection of this pulsar.

By using the EGRET catalog and the first *Fermi*-LAT source catalog, other pulsar candidates were identified and analyzed for pulsation [13]. In addition to the "blind search", gamma-ray emission from the many radio-loud pulsars was searched for using their known ephemerides. The radio timing solutions were provided by a consortium of radio telescopes organized to support the discovery of new gamma-ray pulsars prior to the *Fermi* launch. The return of these efforts has been remarkable. To date, the LAT has found over 26 pulsars with the blind search method. The search using the radio timing information has yielded over 25 gamma-ray emitting pulsars. In addition to these, the radio community has used the list of the *Fermi*-LAT unidentified sources and found 24 new millisecond pulsars (MSP). All of these are in addition to the 6 pulsars detected in gamma-rays by EGRET. The detection of MSPs is a big boost to such projects as "Nano-Grav" [14], which aims to use MSPs as precision clocks to search for the passage of gravitational waves. The contribution to pulsar science of these new detections is to help identify the actual physics of how the pulsar is transforming its rotational energy into the beamed radiation patterns observed. It is already obvious from the data that the gamma-ray antenna pattern is much broader than that in the radio, and this has already ruled out the so-called "polar-cap" model in favor of "slot-gap" and "outer-gap" models.

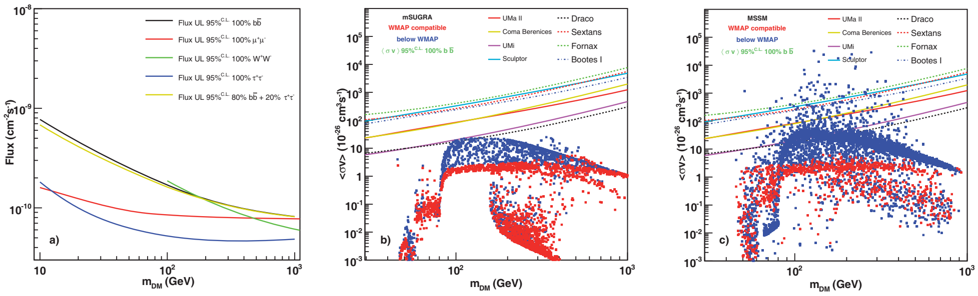

Fig. 3. – (Colour online) (a) Flux limit from Ursa Minor, one of the most promising dSphs for DM searches; (b) mSUGRA-type models shown with (red—lower bands of points in plots) and without (blue—upper bands of points in plots) the WMAP constraint for several dSphs; and (c) the same for MSSM models.

4. – Dark Matter

For decades the nature of the "Dark Matter" (DM) has been an enigma. Its existence has so far been ascertained solely by observing its gravitational effects: galaxy rotation curves, the motion of galaxies within clusters, gravitational lensing effects, and so on. From particle physics comes the tantalizing possibility that DM is an elementary particle, of the type thought necessary to complete aspects of the so-called "Standard Model". Currently, particle physicists are trying to produce directly such particles at the newly commissioned Large Hadron Accelerator (LHC), in Geneva, Switzerland. If the DM is an elementary particle, perhaps a relic of the early Universe, then potentially it can either self-annihilate or decay into the particles we already know about, and a gamma-ray signal can be the result.

The search for DM as part of the *Fermi*-LAT mission was a major reason for its support from the US Department of Energy. Prior to launch, several different places to look for a DM signal were identified and analyses were developed. These include satellite galaxies, DM halo clumps, DM lines searches, the galactic center and Milky Way Halo, and the extra-galactic diffuse emission. Of these the satellite galaxy search and the diffuse emission perhaps reveal the depth of the non-detection dilemma.

Dwarf Spheroidal Galaxies (dSphs) are ideal locations to search for a DM signal. There are now more than a dozen detections of these small satellite galaxies associated with the Milky Way. By observing the motion of the stars within each, an estimate of the gravitational mass holding the ensemble together can be derived. By simply counting the stars, the luminous mass is also apparent. Many of these dSphs have gravitational mass-to-light (ML) ratios exceeding ~ 100 (some are even estimated to have a ML ratio > 1000!). The most recent *Fermi*-LAT analysis of the dSphs uses 14 such candidates [15]. At each of their locations in the sky a gamma-ray signal was searched for. In addition, a "stacked" analysis was also performed in which the various sky regions were simultaneously summed over. None of the analyses have so far found a gamma-ray signal from these objects. Figure 3 shows the flux limits for the most sensitive of the dSphs, Ursa Minor. The limits have some model dependence in that a specific flux model must be used to set a limit. These can be translated into limits on the specific models used, which are shown in fig. 3 in the annihilation cross-section *vs.* DM mass plot. The limits certainly are not constraining to most DM models provided there

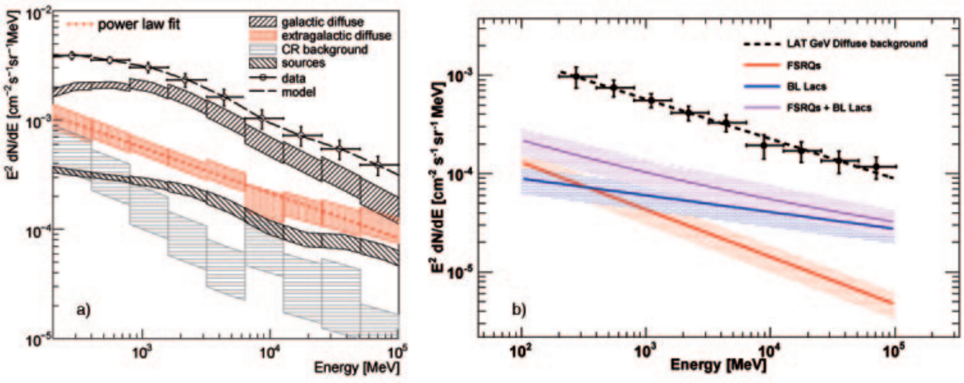

Fig. 4. – (a) Complete gamma-ray intensity and spectrum for Galactic latitudes $|b| > 10°$ together with the derived EGB intensity and spectrum and various foreground signals, from [17]. (b) Estimation of the portion of the diffuse signal accounted for by unresolved AGN and the residual signal, from [18].

is no “boost” from further clumping of the DM within the dSphs themselves. The same type of analysis has also been performed using galaxy clusters with similar results [16]. So, the search for a signal from DM continues. A significant increase in sensitivity would come from a LHC discovery of a DM particle candidate. This would provide some of the specifics for spectral content as well as flux. Using such a template the LAT data could be searched for this signature and, if found, help understand the role the LHC discovered particle plays on the cosmic stage.

Another “natural” place to look for a DM signal is in the Extra-Galactic Diffuse Background (EGB) [17]. The *Fermi*-LAT Collaboration has derived this using data from Galactic latitudes $|b| \geq 10°$. The EGB is a small component of the total diffuse gamma-ray emission and even though the strong emission from the plane was excluded from the analysis, significant foreground signals must still be accounted for and subtracted. The largest of these remains the diffuse gamma-ray emission from the Milky Way. This is mainly due to inverse Compton scattering by cosmic-ray electrons of the interstellar radiation field and cosmic-ray nuclei interacting with the relatively nearby gas ($\leq 1\,$kpc) for the region of sky used in the analysis. Contributions by sources and residual background events were also estimated and included in the analysis. The results for the derived EGB spectrum from 200 MeV to 100 GeV are shown in fig. 4.

The resulting spectrum is a featureless power law approximately $\propto E^{-2.4}$. This is a less intense spectrum with a steeper power law than previously derived from EGRET data. Some of the observed flux comes from unresolved AGN and a detailed estimate of that contribution has been made, which is also shown in fig. 4 [18]. However, it is clear that not all of this signal is accounted for by these source populations. Extension of this analysis up to 1 TeV is currently under way within the *Fermi*-LAT Collaboration.

5. – Gamma-Ray Bursts

The *Fermi* spacecraft, in addition to the LAT, has a Gamma-ray Burst Monitor (GBM) similar to BATSE flown on CGRO. The GBM Collaboration is separate from the LAT Collaboration, but there is a large overlap in the memberships [19]. The GBM is performing as expected and detects ~ 250 GRBs per year. When the onboard GBM

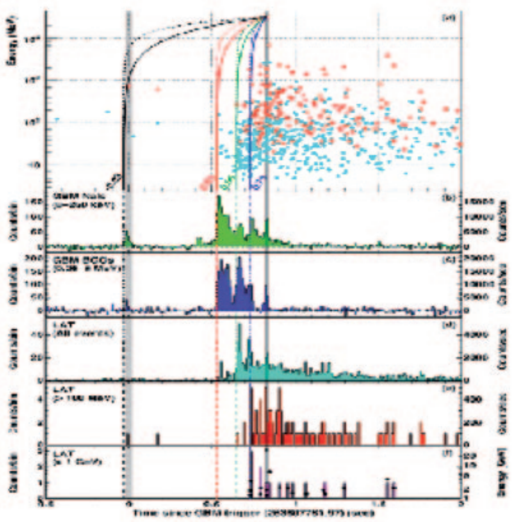

Fig. 5. – The light curves for various energy bands in the LAT and GBM for GRB 090510.

analysis detects a GRB, the satellite can autonomously re-point itself to place the event well within the field of view of the *Fermi*-LAT. So far, re-pointing events have occurred several times a year. The population of GRBs that the GBM has detected is compatible with those of BATSE and SWIFT. The disappointment, however, is how few of the GBM detected GRBs have a measureable signal in the LAT. To date, while the GBM has detected over 450 GRBs the LAT has detected only 17. Much of the disparity in numbers can be accounted for by the much larger field of view of the GBM, however even after taking that into account fewer than 10% of GRBs seem to have high energy emission (*i.e.* $> 100\,\mathrm{MeV}$).

Nevertheless the detection of the 17 *Fermi*-LAT GRBs has enabled some excellent science. In particular, the observation that high energy photons arrive on short time scales with respect to the GBM X-rays has resulted in limits on possible Lorentz Invariance violations [20]. If it is posited that space-time has a linear velocity dispersion with photon energy, the mass scales necessary to explain the data exceed the Planck mass. The light curve for GRB 090510, which sets the most stringent limit, is shown in fig. 5. The onset of the X-ray emission is somewhat open to interpretation, and so all reasonable choices were tested with respect to the arrival of the highest energy gamma-ray event. All of these time intervals result in an energy scale exceeding the Planck mass for a linear velocity dispersion with energy.

6. – Conclusions

Over the past 2 years, the *Fermi*-LAT data-taking fraction of the mission has been very high: a 98% duty cycle with the balance being devoted to calibration with only the occasional mission interruption. This has already provided a database of over 380 million gamma-ray event candidates available for science analysis. Data is taken constantly and available for science analysis, typically with less than a 10 hour delay. The instrument performance is very stable with only minor drifts and degradations, a direct result of the selection of an all-solid-state core instrument package. (Note: the one exception is the anti-coincidence veto system (ACD), which uses photomultiplier tubes to readout plastic scintillators.) In the pair conversion section of the instrument, the Tracker, only 0.038% of the nearly 1 million channels are masked off due to noise or shorts in the electronics, and approximately half of these were bad or dead at launch.

Many results have been published and the expectation that the *Fermi*-LAT mission would establish large samples of the various high-energy gamma-ray sources has been met. However, the *Fermi*-LAT mission is still in the early stages. There has been a large effort put into cataloging and quantifying the ~ 2000 sources detected so far. In some sense this is the "low hanging fruit": "source" physics is comparatively easy and does not push the modeling and understanding of the instrument to its limits. In the coming years, the understanding and analysis of the image resolution will be improved, and perhaps provide the first reliable measurement of pair halos around AGN. The energy reach of the instrument will be extended up to 1 TeV and down to 10 MeV. Improvements identifying backgrounds and their elimination will result in more efficient signal capture (effective area) and thus increased sensitivity. Furthermore, the all-sky scanning can be interrupted occasionally for extended pointed observations, greatly increasing the sensitivity for transient phenomena that have characteristic time scales of $\sim 10^3$–10^4 seconds.

There are many science topics left out of this "highlights" talk: limits on the extragalactic background light, observations of Galactic Binaries, the Galactic Center, etc. Limitations on time and space do not allow for a more complete exposition of the scientific outcomes so far from the *Fermi*-LAT mission. (However, see the many other *Fermi*-LAT talks at this conference.) The technology and their implementations in the LAT have resulted in a stable and extremely productive observatory that should easily last the duration of the current 5-year mission, and afford an extension to 10, or even 20, years if the science benefits continue. The *Fermi*-LAT Collaboration is committed to pushing the instrument to the limits of its design and looks forward to the science that will result.

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REFERENCES

[1] Atwood W. B. *et al.*, *Astrophys. J.*, **697** (2009) 1071.
[2] *Science*, **326** (2009) 1600.
[3] Abdo A. A. *et al.*, *Science*, **325** (2009) 840.
[4] Abdo A. A. *et al.*, *Science*, **325** (2009) 848.
[5] Abdo A. A. *et al.*, *Science*, **325** (2009) 845.
[6] Escande L., this conference.

[7] Cheung C. C., this conference.
[8] Nishiyama K. and Kabashima F., *IAUC 2199* (2010).
[9] Abdo A. A. *et al.*, *Science*, **329** (2010) 817.
[10] Abdo A. A. *et al.*, *Science*, **322** (2008) 1218.
[11] Atwood W. B. *et al.*, *Astrophys. J. Lett.*, **652** (2006) 49.
[12] Ziegler M. *et al.*, *Astrophys. J.*, **680** (2008) 620.
[13] Saz-Parkinson P., this conference, and references therein.
[14] *Nature*, **463** (2010) 147.
[15] Abdo A. A. *et al.*, *Astrophys. J.*, **712** (2010) 147.
[16] Ackermann M. *et al.*, *Astrophys. J. Lett.*, **717** (2010) 71.
[17] Abdo A. A. *et al.*, *Phys. Rev. Lett.*, **104** (2010) 101101.
[18] Abdo A. A. *et al.*, *Astrophys. J.*, **720** (2010) 435.
[19] Bissaldi E., this conference.
[20] Abdo A. A. *et al.*, *Nature*, **462** (2009) 331.