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Science highlights of the Fermi-LAT(*)

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Summary. — The LAT (Large Area Telescope) experiment is a gamma-ray detector onboard the Fermi satellite, sensitive to energies from 20 MeV to over 300 GeV. Launched in 2008, the main goal of the experiment is to study the origin and nature of high-energy gamma rays in the universe through the search for particle acceleration mechanisms and electromagnetic radiation emission from sources such as active galactic nuclei (AGN), pulsars, and supernova remnants, the study of galactic and extra-galactic diffuse gamma ray emission, the search for unidentified gamma-ray sources, the indirect detection of dark matter through its decay or annihilation into photons as the final state, and the study of high-energy emission from transient sources such as solar flares and gamma-ray bursts (GRBs). This contribution will illustrate the main scientific results obtained by the experiment in recent years.

1. – Introduction

The *Fermi* Gamma-Ray Space Telescope (FGST) is an international space mission dedicated to the study of gamma rays of astrophysical origin. Launched on June 11, 2008, on a Delta II rocket, the Fermi satellite carries two key scientific payloads: the Gamma-ray Burst Monitor (GBM) and the Large Area Telescope (LAT). Positioned in an almost circular orbit at an altitude of 565 km and an inclination of 25.6° , it completes an orbit roughly every 90 minutes. Almost 15% of the observation time is spent in the South Atlantic Anomaly (SAA), a region containing geomagnetically trapped protons and electrons. *Fermi* celebrated 15 years of operations in 2023. This observatory is a collaborative international effort, with support from NASA in the USA, and contributions from France, Germany, Japan, Italy, and Sweden. The *Fermi*-LAT and *Fermi*-GBM Collaborations count over 400 members from over 90 universities and laboratories. This paper reports the highlights of the most relevant scientific results of the *Fermi*-LAT.

2. – The Large Area Telescope

The *Fermi*-LAT operates as a pair conversion telescope. The detection of the electrons and positrons allows the arrival directions and energies of individual photons to be

(*) IFAE 2023 - "Cosmology and Astroparticles" session measured [14]. Its sensitivity range extends nominally from 20 MeV to over 300 GeV. The instrument is composed of three key sub-systems: the tracker (TKR), the calorimeter (CAL), and the anticoincidence detector (ACD).

Pair conversion primarily occurs within the TKR, consisting of 18 X-Y layers of single-sided silicon strip detectors, with a pitch of 228 μm, interleaved with tungsten foils to enhance conversion probability. The modular TKR, organized into a 4×4 matrix of 16 towers, features over 8.8×10^5 strips (and readout channels). The on-axis thickness of the whole TKR is of about 1 X_0(1).

The CAL, responsible for measuring the incident gamma-ray energy, consists of 1536 CsI(Tl) scintillator crystal bars, of $2.7 \times 2.0 \times 32.6$ cm^3 size, with photodiode readout, arranged in a hodoscopic configuration across 8 X-Y layers within 16 towers, corresponding to the TKR ones.

A system of 89 plastic scintillator tiles, with photomultiplier tube (PMT) readout covering five sides of the TKR is used to discriminate gamma rays from the charged cosmic-ray background.

The LAT's overall dimensions are $0.72 \times 1.8 \times 1.8$ m^3, with a 2.4 sr field of view, ensuring approximately $\sim 20\%$ coverage of the entire sky at any given time.

The LAT typically operates in science mode, performing sky scans by rocking the satellite pointing direction north and south of the orbital plane during alternating 96-minute orbits. This strategy enables the LAT to survey the entire sky approximately every 3 hours. While the standard observation mode involves regular scans, the spacecraft can adjust its orientation for Target of Opportunity (ToO) observations, focusing on specific targets like gamma-ray bursts (GRBs). Unfortunately, since March 16, 2018, the repointing mode has been inactive due to the failure of one solar panel drive motor, preventing that panel from tracking the Sun.

Despite this limitation, an adjustment in the observation approach allows Fermi's solar array to still deliver full power. Instead of the previous 3-hour routine, the LAT now occasionally takes several weeks to complete an all-sky image. This adaptation allows for more extensive short-term exposures of the current observation region.

Fermi was designed for adaptability as an extended mission. Regular updates to instrument settings and software, as well as modifications to the rocking pattern, have been implemented to manage temperature variations and enhance spacecraft battery longevity. The spacecraft also features a propulsion system initially intended only for controlled de-orbiting, but it has been effectively used to avoid potential collisions. In 2023, with the mission extension in mind, plans are being studied for raising the orbit altitude of *Fermi*.

3. – The most important scientific results of the *Fermi*-LAT

The LAT has achieved a wide range of scientific goals, including the exploration of the high-energy gamma-ray sky and the investigation of the origin of isotropic diffuse emissions. Moreover, the LAT has probed particle acceleration mechanisms in various astrophysical sources, including active galactic nuclei (AGNs), pulsars, and supernova remnants. Its focus extends to studying the high-energy emissions of GRBs and other transient sources, while also contributing significantly to using high-energy gamma rays for studying the early Universe and the origin of Dark Matter (DM).

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(1) X_0 is a radiation length unit.

A prominent outcome of LAT's efforts is the production of source catalogs. Over the years, the *Fermi*-LAT Collaboration has released many catalogs, both general and class-specific, each iteration providing a deeper view of the gamma-ray sky. These catalogs serve as base resources for various analyses, providing information for modeling the sky regions under investigation.

3·1. *The 4th* Fermi-*LAT Source Catalog (4FGL).* – The Fermi-LAT Collaboration has released multiple iterations of the general gamma-ray source catalog, with a significant milestone being the publication of the Fourth *Fermi*-LAT catalog of gamma-ray sources (4FGL) in 2020 [2]. Improvements in this catalog are attributed to enhancements in the background diffuse emission model, crucial for accurate source detection. Additionally, the catalog benefits from the third reprocessed version of the Pass 8 data reconstruction algorithm [13], resulting in a substantial increase in angular resolution above 3 GeV and approximately 20% greater sensitivity across all energy levels. A minor correction has also been applied to address energy dispersion effects.

The most recent release, 4FGL-DR4 (Data Release 4) [3, 15], extends observations from 8 to 14 years. It retains existing sources from previous releases and introduces new ones, with a total of 7194 sources covering an energy range from 50 MeV to 1 TeV. Approximately 51% of the sources exhibit curved spectral shapes, indicating complexity beyond a simple power-law model. About 6% are classified as identified due to pulsations, correlated variability, or matching angular sizes with observations in other wavelength bands. Lower-energy counterparts for about 62% of the sources have been identified, while the remaining 32% remain unassociated.

The catalog includes a wide range of galactic and extragalactic sources. Among galactic sources, pulsars, including young pulsars and millisecond gamma-ray pulsars, are the most abundant ones. Extragalactic sources, on the other hand, are predominantly represented by blazars.

3·2. *The 4th* Fermi-*LAT AGN Catalog (4LAC).* – Blazars constitute a subset of AGNs characterized by the alignment of their relativistic jets with the observer's line of sight. Within the *Fermi*-LAT source catalog, blazars form the largest group among extragalactic sources. The catalog undergoes continuous updates with dedicated catalogs periodically introduced for specific source classes. One such catalog is the Fourth *Fermi*-LAT catalog of AGN (4LAC), spanning over 8 years of LAT observations. It contains 2863 sources, including 23% Flat Spectrum Radio Quasars (FSRQs), 37% BL Lac objects, and 38% blazar candidates of unknown types. The latest release, 4LAC-DR3 [11], aligns with 4FGL-DR3 and covers 14 years of LAT observations.

At high Galactic latitudes, blazar-type AGNs are the prevalent sources. The extensive data from both 4LAC releases have enabled investigations into the division between the two blazar subclasses, FSRQs and BL Lacs [18]. The catalog has also contributed to examining connections between gamma-ray intensity, brightness, and polarization across different energy ranges [12]. Furthermore, it has played a role in exploring potential links between AGN-originated gamma rays and Ultra High Energy Cosmic Rays (UHECR) [19], as well as high-energy neutrinos [21].

3·3. *Pulsars with the* Fermi-*LAT*. – LAT observations have proven that pulsars constitute a substantial portion of previously unexplained gamma-ray sources at low galactic latitudes, a discovery initially found by [22]. Pulsars, characterized as swiftly rotating and highly magnetized neutron stars surrounded by plasma-filled magnetospheres, have been an important focus of LAT investigations. The LAT has discovered numerous radio-quiet gamma-ray pulsars and millisecond pulsars, establishing pulsars as the predominant class of GeV gamma-ray sources within the Milky Way [1]. The Third Pulsar catalog (3PC) [23] reports a compilation of 294 pulsars identified by the LAT.

On April 15, 2020, the LAT achieved an extraordinary discovery by detecting high-energy gamma rays emitted during a massive flare from a magnetar located in the Sculptor Galaxy [10]. Magnetars, a distinctive subclass of neutron stars, feature exceptionally powerful magnetic fields and a relatively slower rotation compared to standard neutron stars. A magnetar giant flare, characterized by brief yet intense emissions of hard X-rays and gamma rays, is an infrequent occurrence. The LAT detection of the initially misclassified event, GRB 200415A [20], represents a groundbreaking accomplishment, marking the first detection of gamma rays above 100 MeV originating from a magnetar giant flare.

3˙4. *Gamma-Ray Bursts with the* Fermi-*LAT*. – Gamma-Ray Bursts (GRBs) are the most luminous and energetic events in the known Universe, with their emission lasting from fractions of seconds to several minutes (or hours). They are thought to originate from catastrophic events giving birth to a compact object as, *e.g.*, collapse of massive stars or neutron star binary mergers. The LAT regularly detects high-energy emissions from GRBs. The Second Catalog of LAT-detected GRBs, spans the initial 10 years of operations [9]. A total of 186 GRBs are identified; among these, 91 exhibit emissions in the 30–100 MeV range (including 17 exclusively in this band), and 169 are detected above 100 MeV. Many of these sources were initially discovered by other instruments (*e.g.*, *Fermi*-GBM or *Swift*-BAT), or reported by the Interplanetary Network (IPN), while the LAT independently triggered on four GRBs.

The catalog reports the analysis of the GRBs, detailing their onset, duration, and spectral characteristics in the 100 MeV–100 GeV energy range, with a focus on high-energy photons. Compared to the first catalog [5], the detection rate has significantly improved. The findings confirm that the LAT primarily detects the brightest *Fermi*-GBM bursts, exhibiting delayed onset and prolonged duration. In particular, delays exceeding 1 ks and durations larger than 10 ks are observed. Many properties and models are probed, but no single theoretical model currently explains all findings, emphasizing the crucial role of LAT observations in advancing the understanding of these gamma-ray sources.

3˙5. *Dark Matter searches*. – Multiple experimental findings strongly suggest that the majority of the mass in our Universe is composed of non-baryonic DM [25]. Among the various DM candidates emerging from theories beyond the Standard Model (SM), Weakly Interacting Massive Particles (WIMPs) stand out as promising candidates compatible with observational constraints. In the indirect DM detection approach, the products of potential annihilations or decays of DM particles into Standard Model (SM) particles are expected to be found in regions where DM is potentially abundant. If the considered processes foresee gamma rays in the final state, these can be identified by the *Fermi*-LAT, offering indirect evidence for the existence of DM particles.

Satellite galaxies of the Milky Way, dwarf spheroidal galaxies (dSphs), are the cleanest targets for indirect DM searches with gamma rays, due to their high mass-to-light ratio, the low number of sources and the low gas content [17]. None of the dSphs are significantly detected in gamma rays, as reported in [6], where a combined analysis of 15 dSphs with Pass 8 data was also performed. This analysis yields constraints on the velocity-averaged

DM annihilation cross section which lie below the thermal limit for several channels in a DM particle mass interval below 100 GeV.

Another interesting research target is the region around the Galactic Center (GC), where an excess at a few GeV with respect to the expected contributions from conventional models of diffuse gamma-ray emission and catalogs of known sources, has been reported over the years [8]. However, due to the large uncertainties in the modeling of the astrophysical background, the GC excess cannot be clearly ascribed to a possible DM signal.

Finally, gamma-ray lines are expected to be observed from annihilations or decays of DM particles in the Milky Way halo. Over the years several searches have been carried out, increasing the statistics when more data became available and yielding more stringent constraints. A potential line signal at 133 GeV was reported in 2012 [16, 24]. The *Fermi*-LAT detected this feature, although with low global significance [4]. A more recent analysis, performed using a 5.8 years Pass 8 data sample, showed that the feature is not significant [7].

4. – Conclusions

As summarized in this article, the *Fermi*-LAT is playing a key role in the study of many different astrophysical sources. The relevance of its observations and scientific results is outstanding, embracing a wide range of topics and its findings are of crucial importance for the whole scientific community.

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