GEV telescopes: results and prospects for Fermi

R P Johnson\(^1\) and R Mukherjee\(^2,3\)

\(^1\) Santa Cruz Institute for Particle Physics and Department of Physics, University of California at Santa Cruz, Santa Cruz, CA 95064, USA
\(^2\) Physics & Astronomy, Barnard College, Columbia University, New York, NY 10027, USA
E-mail: muk@astro.columbia.edu

New Journal of Physics 11 (2009) 055008 (26pp)
Received 20 January 2009
Published 12 May 2009
Online at http://www.njp.org/
doi:10.1088/1367-2630/11/5/055008

Abstract. We present a review of the current status and future prospects of the field of high-energy gamma-ray astrophysics in the 30 MeV to 30 GeV regime. Scientific studies in this energy range are carried out by satellite-based gamma-ray instruments. We have now entered a new era in space-based gamma-ray astrophysics with the operation of AGILE and the Fermi Gamma Ray Space Telescope. We summarize here highlights from earlier experiments such as the EGRET on board the Compton Gamma Ray Observatory and describe some of the first results from AGILE and Fermi.

Contents

1. Introduction ................................................. 2
2. Instruments and detectors .................................... 3
   2.1. EGRET .................................................. 3
   2.2. AGILE .................................................. 4
   2.3. Fermi ................................................... 5
3. Science ......................................................... 8
   3.1. AGN ..................................................... 8
   3.2. GRBs ................................................... 12
   3.3. Pulsars, SNR, PWN and other galactic sources ......... 13
   3.4. Unidentified gamma-ray sources ......................... 17
   3.5. Diffuse emissions ....................................... 19
   3.6. Signals for new physics ................................ 20
4. Summary and future prospects ............................... 22
References ..................................................... 22

\(^3\) Author to whom any correspondence should be addressed.
1. Introduction

With the launch of the Fermi Gamma-Ray Space Telescope (néé GLAST) in June 2008, gamma-ray astrophysics entered a new era. Fermi offers a dramatic leap in the progress of space-based high energy astrophysics, and much is anticipated from it in the particle-astrophysics community. Gamma-ray telescopes provide the most direct view of high-energy non-thermal processes throughout the Universe, allowing us to study nature’s highest-energy accelerators. Cosmic sources of gamma rays include Galactic sources such as supernovae and pulsars, extragalactic blazars and radio galaxies, as well as the interstellar and intergalactic media. Gamma-ray bursts (GRBs) represent some of the most energetic phenomena in the Universe, and it remains to be seen whether most of them have high energy emission. High-energy gamma-rays also provide opportunities for exploring physics beyond the standard model, for example by searching for signatures of dark matter annihilation.

The first major thrust in the field of high-energy gamma-ray astronomy (above 30 MeV) came in the early 1990s from EGRET, one of the instruments on board the Compton Gamma-Ray Observatory (section 2.1). Although earlier experiments had made some pioneering explorations, including the first detection of an extragalactic source [1] and a map of the Galactic plane [2], it was not until the EGRET era that we had a first comprehensive gamma-ray catalog. The final EGRET (3EG) catalog lists 271 point sources of high-energy gamma-rays (one a solar flare), including details on source spectra and variability [3]. One of the unexpected results from EGRET was the detection of gamma-ray emission from a large number of active galaxies of the blazar class, the majority of which exhibited highly variable gamma-ray emission. A recent comprehensive review by Thompson [4] summarizes the observational results and describes some of the pioneering science from EGRET during its nine-year mission. EGRET was succeeded by AGILE (Astro-rivelatore Gamma Immagini Leggero; section 2.2), an Italian mission in orbit since 2007 [5], and more recently by the Fermi Gamma-Ray Space Telescope. Fermi has already begun to survey the gamma-ray sky with much more sensitivity than EGRET or AGILE and detect and catalog an order of magnitude more sources. Initial results from Fermi are already exciting, but this is surely only the tip of the iceberg.

Results from satellite-based experiments are complemented by those of ground-based imaging atmospheric Cherenkov telescopes (ACTs), operating at energies above 100 GeV (see the accompanying article by J Hinton). At those energies, space-based experiments are limited by their effective area and the steeply falling spectra of gamma-ray sources. ACTs, on the other hand, use the atmosphere as a detector and detect the gamma-rays indirectly by measuring the Cherenkov light produced in gamma-ray or cosmic-ray air showers. In the past few years, there has been a tremendous leap in sensitivities of imaging ACTs (IACTs), ushering in a new era in GeV/TeV astronomy. The ground-based TeV observatories HESS [6], MAGIC [7] and VERITAS [8] have now come online, producing exciting new results. Particularly noteworthy are the completion of a survey of the Galactic plane with unprecedented sensitivity by HESS, revealing at least 50 previously unknown sources of TeV gamma-ray emission [9], the detection of spatially resolved TeV emission from supernova remnants (SNRs) [10], the discovery of TeV emission from x-ray binary systems containing compact objects, such as LSI +61 303 observed by MAGIC [11] and VERITAS [12], and the microquasar LS 5039 observed by HESS [13] and the discovery of TeV emission for the first time from intermediate-frequency-peaked BL Lacs (IBL) [14]. Also notable is the detection by Milagro (not an IACT) of strong and extended TeV emission from the nearby and actively star-forming Cygnus region [15].
Figure 1. Schematic diagram of EGRET showing the various subsystems of the instrument [18].

Ground-based TeV instruments have gone beyond simply detecting high-energy gamma-ray sources and are carrying out detailed measurements of spectra and time variability of cosmic gamma-ray sources. This article focuses on gamma-ray astrophysics in the roughly 30 MeV to 30 GeV regime, and a detailed description of scientific results from TeV telescopes is beyond the scope of this review (see [16] for a recent review). Nevertheless, space-based experiments such as Fermi are complemented by the ground-based IACTs, and this ‘TeV connection’ is important for understanding the physical processes in high-energy sources.

In this paper, we review the current status of the field of satellite-based high-energy gamma-ray astrophysics above 30 MeV. We focus on the scientific results in the last decade from the EGRET and AGILE missions, summarize the first results from Fermi, and discuss some of the future possibilities for Fermi.

2. Instruments and detectors

2.1. EGRET

EGRET was one of four instruments onboard the Compton Gamma Ray Observatory (CGRO), the second in the sequence of NASA’s Great Observatories4. Together, the four instruments covered the unprecedented spectral energy range of 30 keV to 30 GeV for studying gamma-ray sources. EGRET was sensitive to the highest energy gamma-rays, measuring the spectral and timing information of galactic and extragalactic sources in the range of 30 MeV to 30 GeV. It was based on the pair-conversion telescope principal used in earlier pioneering satellite missions [17]. EGRET used a simple spark chamber interspersed with the high-Z material tantalum as the main tracking detector, to convert gamma-rays into electron–positron pairs and measure their trajectories. Figure 1 shows a schematic of the EGRET instrument, including

4 [http://coss.gsf.nasa.gov/docs/cgro/index.html](http://coss.gsf.nasa.gov/docs/cgro/index.html)
Figure 2. False-color image of the all-sky gamma-ray intensity map for >100 MeV photons, measured by EGRET during its lifetime. Note the intense diffuse radiation along the Galactic plane. In these coordinates, the Galactic Center lies in the middle of the image. (Credit: NASA.)

a cartoon of a typical track inside the tracking chamber. A plastic anti-coincidence dome surrounded the detector to veto charged-particle cosmic radiation, which outnumbered gamma-rays by a factor of $\approx 10^4$. A triggering hodoscope and time-of-flight system was used to detect the presence of the pair with the correct direction of motion and to initiate the recording of the tracks in the spark chamber by raising the high voltage. The energy of the gamma-rays was measured by a NaI(Tl) calorimeter with a thickness corresponding to eight radiation lengths. A detailed description of the EGRET instrument and a discussion of its sensitivity to point sources and diffuse radiation are given elsewhere [18, 19].

In orbit, typical EGRET observations lasted for a period of one to three weeks, along with shorter GRB or target-of-opportunity (ToO) observations. EGRET operated during the period 1991–2000, although in the latter part of the decade its operations were limited by ageing of the high voltage system and the gas of the spark chambers. Figure 2 shows the EGRET gamma-ray intensity map for the entire mission, highlighting the principal results from EGRET—intense radiation toward the inner part of the Galaxy, along with individual bright point sources that are clearly visible over and above the diffuse radiation, particularly, at high galactic latitudes. A description of the EGRET data products, standard EGRET processing of individual gamma-ray events and analysis techniques may be found at the CGRO Science Support Center (SSC) web site [20].

2.2. AGILE

The success of EGRET motivated the next generation space-based gamma-ray experiments. Its scientific results opened up the new field of gamma-ray astronomy, raised new questions and spurred the need to investigate further the high energy sky. The two high-energy gamma-ray missions conceived were AGILE and Fermi, both based on the gamma-ray pair-conversion
telescope technique, using state-of-the-art silicon-strip detectors for tracking. AGILE has been operational since 2007, and the collaboration has published some of its first results (see for example [21, 22]). It has an advantage over EGRET and Fermi in that it combines for the first time a high-energy gamma-ray imager (30 MeV to 50 GeV) with a hard x-ray imager (15–45 keV), and compared with EGRET it is able to observe over a very large field of view (a fifth of the sky). In addition, a mini calorimeter on board is able to detect independently GRBs and other transients in the 300 keV to 100 MeV energy range. A significant disadvantage of AGILE compared with EGRET and Fermi is its very thin calorimeter, only 1.5 radiation lengths, which limits its spectral capability. Details of the AGILE instrument may be found elsewhere [5]. We include some of AGILE’s scientific highlights in the following sections.

2.3. Fermi

The Fermi Gamma-Ray Space Telescope mission (known as GLAST prior to launch [23]) includes two instruments in low-Earth orbit: the Large Area Telescope (LAT) [24] and the GRB Monitor (GBM) [25]. The GBM is similar to the BATSE instrument on CGRO [26], although it has greater spectral coverage than BATSE. Its primary purpose is to study GRBs by detecting hard x-ray and gamma-ray photons with full-sky coverage. The LAT, like EGRET, is a pair-conversion telescope capable of detecting and measuring the direction and energy of individual gamma-ray photons in the energy range from about 30 MeV up to hundreds of GeV. It employs advanced particle-detection technology to improve upon EGRET’s capabilities in all respects, resulting in an overall improvement in sensitivity to point sources by a factor of 20–100. The two Fermi instruments work together to study GRBs that include high-energy photons within the LAT field of view. The LAT provides improved burst localization as well as observations of their poorly known high-energy behavior, while the GBM completes the spectral coverage from the LAT threshold down to 8 keV.

Similar to AGILE, although much larger, the LAT ‘tracker’ employs silicon-strip technology for tracking the gamma-ray pair conversions, with 73 m$^2$ of active single-sided detectors arrayed in 18 $x, y$ paired layers and interspersed with 16 layers of tungsten converter foils [27]. Fast electronics based on custom application specific integrated circuits (ASICs) encompassing 15 000 chips reading signals from 880 000 strips, read events at rates up to and exceeding 10 kHz and also provide fast signals for the instrument trigger [28]. The LAT calorimeter employs four $x, y$ paired layers of CsI crystals (eight radiation lengths total) to measure the gamma-ray energy. Each of the 1536 crystal ‘logs’ is read from both ends by photodiodes, such that the location of the energy deposition along the length of the crystal can be inferred to millimeter precision by the light ratio. The fine segmentation in depth allows the shower energy to be accurately inferred even when a large fraction of it leaks out the back, while the fine lateral segmentation and localization provide crucial pattern-recognition information for reconstructing gamma-ray events while rejecting cosmic rays. The anticoincidence detector system (ACD) surrounds the tracker and serves as the first line of defense against charged cosmic-ray background [29]. It is based on a single layer of 89 rectangular plastic-scintillator tiles, each read out by photomultiplier tubes connected to the tiles via wavelength shifting fibers. The tiles overlap in one dimension, while the cracks in the orthogonal dimension are covered by eight scintillating fiber ribbons. Less than three minimum-ionizing cosmic-rays out of 10 000 passing through the system fail to leave a signal above threshold, while the system’s segmentation greatly helps to avoid vetoes of
gamma-ray events by albedo x-rays from the calorimeter, a problem that severely limited the EGRET effective area above 10 GeV.

The LAT tracker and calorimeter are each segmented into 16 tower modules, which are supported on an aluminum grid as illustrated in figure 3. The central data acquisition system includes a ‘tower electronics module’ located under each calorimeter module and three RAD750 computers, two used to execute the on board background rejection algorithm and the third used to interface with the spacecraft. Despite its nearly one million readout channels, the LAT consumes less than 650 W of power. The waste heat conducts passively to the grid, where heat pipes carry it to two radiator panels. The entire instrument has a mass of nearly 3000 kg.

The principal level-one trigger of the LAT is a coincidence of three successive $x$, $y$ paired layers in a single tracker tower module, together with an absence of a veto from ACD tiles in the vicinity of the module. The level-one rate is typically 2 kHz, which is reduced by the on board filter to typically 400 Hz (but varying from about 300 Hz to 700 Hz in a single run). On the ground, the data pass through an analysis pipeline that reconstructs the photon conversions to estimate the best energy and direction on the sky. The analysis also rejects background by looking for ACD signals associated with tracks and by detailed analysis of the patterns in the tracker and calorimeter. Typically about 1 Hz of clean gamma-ray events remains for the final science analysis.

The LAT improves upon the EGRET sensitivity in several important ways. The area and field of view are much larger, not only with improved gamma-ray efficiency, but also with improved angular and energy resolutions. The fine segmentation in all three detector systems ensures excellent background rejection without compromising the efficiency, especially at the highest energies, where the EGRET monolithic anti-coincidence dome vetoed most gamma-ray events. In addition, the LAT solid-state detectors, which operate without consumables, ensure a response that is uniform over time and that should endure far longer than the nominal five-year mission lifetime.

*Figure 3.* Cut-away depiction of the LAT instrument, illustrating the segmentation of the tracker, calorimeter and ACD [24].
Figure 4. Predictions for the performance of the Fermi-LAT. (a) The effective area versus energy. (b) The width of the PSF versus energy. Almost half of the effective area is from conversions in the four layers of thick tungsten foils, for which the PSF is broader, as indicated, due to increased multiple scattering.

Fermi normally operates in an all-sky survey mode, looking outward from the Earth. In order to obtain a nearly uniform exposure over the entire sky, it rocks by 35° from the zenith toward the north orbital pole on one orbit and then by −35° toward the south orbital pole, on the next. It is also capable of making pointed observations, including slews toward alternate targets when the Earth enters the field of view. Furthermore, it can autonomously repoint at any time, by up to 70° in less than 5 min, toward GRB targets detected by the GBM. Note that even when operating in pointed mode the LAT, with its 2.4 sr field of view, observes numerous sources simultaneously.

Figure 4 illustrates some key parameters of the LAT performance: the on-axis effective area and the point-spread-function (PSF). Its energy resolution is better than 15% over its full spectral range and better than 10% from about 500 MeV to 50 GeV. For comparison, the EGRET product of effective area times solid angle was about 38 times smaller than that of the LAT (and half that of AGILE), and its PSF 68% containment angle was 5.85° at 100 MeV and 1.7° at 1 GeV. The LAT 5σ point source sensitivity is \(3 \times 10^{-9} \text{ cm}^{-2} \text{ s}^{-1}\), for a steady source after a 1-year all-sky survey, assuming a high-latitude source with a spectral index of 2.1 and inclusion of all photons above 100 MeV. The corresponding sensitivity for EGRET was about \(6 \times 10^{-8} \text{ cm}^{-2} \text{ s}^{-1}\) for a two-week pointed exposure. Thus, the LAT improves the sensitivity across the sky by at least a factor of 20, and even more in regions with high diffuse background, where the PSF is most important. Another key improvement is in dead time. EGRET was dead for 100 ms after each trigger, while the corresponding number for the LAT is about 26 µs. That improvement is most relevant for observation of bright GRBs.

Figure 5 shows the Fermi-LAT all-sky ‘first-light’ image of data collected during only 95 h of operation. Several Galactic sources (pulsars, such as Vela, Crab and Geminga) are

http://heasarc.gsfc.nasa.gov/docs/cgro/egret/egret_tech.html

New Journal of Physics 11 (2009) 055008 (http://www.njp.org/)
clearly visible, as are several extragalactic sources, in particular, the very brightly flaring AGN 3C 454.3. A comparison with figure 2, the corresponding image obtained from four years of EGRET observations, strongly indicates the great promise afforded by Fermi. Even stronger evidence is the first list of bright Fermi-LAT sources, scheduled for public release after six months in orbit, which appeared as a pre-print in February 2009 with 205 entries, all with greater than 10σ significance [30].

All Fermi-LAT photon data will be released to the public in August 2009, one year after the beginning of science operations, as soon as they are received on the ground and processed by the analysis pipeline into the FT1 and FT2 data summary formats. See the NASA Fermi SSC web site [31] for details on how to access the data and for access to the software tools needed in order to analyze the data.

3. Science

3.1. AGN

At the time of the CGRO launch, there was only one catalogued source of extragalactic gamma rays, 3C 273, detected above 100 MeV by earlier satellite missions [32]. Perhaps one of the most significant contributions of EGRET was the detection of dozens of high-energy gamma-ray blazars, increasing the number of catalogued blazars by two orders of magnitude [3, 33, 34]. Blazars have also been detected in the TeV band by ground-based atmospheric IACTs [35]–[37]. In the unified AGN model, blazars are a class of active galaxies with their relativistic jets oriented very close to the line of sight. EGRET observations of blazars demonstrated that these objects have two remarkable characteristics: (i) in the majority of blazars, the bolometric power in the spectral energy distribution (SED) is dominated by gamma-ray emission, in some cases exceeding the power in the other bands by an order of magnitude and (ii) blazars are variable over a wide range of timescales. In some cases, they exhibit day-scale variability during a flare. Figure 6(a) shows a spectacular gamma-ray blazar flare detected by EGRET, corresponding to
Figure 6. Intense gamma-ray flare from PKS 1622-297. Such short-timescale variability seen in gamma-ray blazars indicates that the high-energy emission must arise in relativistic beamed jets in blazars. Figure from Mattox et al. [38].

Gamma-ray flares were seen in several blazars, such as PKS 1406-076 (correlated nearly simultaneously with an optical flare [41]), 3C 279 (a bright EGRET blazar that exhibited a dramatic flare in 1996, when the flux increased by a factor of 10 [42]) and PKS 0528 + 134 (a blazar detected at a redshift of 2.06 [43]). Not all blazar observations by EGRET were in the ‘high’ or ‘flare’ state. In most cases, EGRET observed blazars during the quiescent state in pre-planned observations. EGRET observation of blazars are described in several journal articles, but a summary of the results may be found in two recent reviews and the references therein [4, 44].

Blazars emit radiation across the electromagnetic spectrum. The gamma-ray observations by EGRET were supported by observations in other wavebands, providing valuable information for the study of blazar physics. EGRET-detected blazars are typically strong radio sources with flat radio spectra, they exhibit rapid optical variability (optically violently variable or OVV), and they exhibit significant polarization at radio frequencies. Very long baseline interferometry (VLBI) observations of EGRET blazars indicate that they are relativistic sources and in many cases exhibit superluminal motion (e.g. see the MOJAVE Program [45]). In fact, EGRET gamma-ray blazars are generally seen to have higher jet Lorentz factors, and more luminous jet features, than typical blazars [46, 47]. This is illustrated in figure 7, which shows the distribution of the 15 GHz luminosity measured in EGRET blazars in comparison with the non-EGRET blazars. Figure 7 also shows a VLBA (2 cm survey) image of the blazar 3C 279, upon which is superimposed the position of a jet component (C4) as compiled from 19 epochs [48], indicating superluminal motion.

Figure 8 is an example of the SED of the blazar 3C 279 during several different epochs showing the power per logarithmic energy band [42]. Note the spectral variability in the
Figure 7. (a) A comparison of the 15 GHz luminosity for individual jet components in EGRET-detected and non-EGRET AGN, as seen in VLBI radio studies of blazars. EGRET blazars are seen to have higher average jet speeds and more luminous jet features. Figure from Lister and Homan [46]. (b) VLBA 2 cm image of 3C 279 (see [48] for details). The figure shows the trajectory of the jet component C4 for 19 epochs since 1988. Figure from Homan et al [48].

gamma-ray band between the different observing periods. The figure also shows multiwavelength data obtained in coordinated broadband campaigns with lower energy observatories. Such multiwavelength SEDs have been important in constraining particle acceleration and emission models in blazars [49]. The SED of 3C 279 shows the characteristic ‘double-hump’ structure seen in EGRET blazars, with a synchrotron peak in the radio-optical band and a high energy peak in the gamma-ray band. The location of the peaks in the blazar SEDs are used to define broad sub-classes of blazars (e.g. [50, 51]). Flat-spectrum radio quasars (FSRQs) are the largest class of EGRET blazars and have their synchrotron and Compton peaks at lower energies in comparison with the lower-luminosity LBLs and HBLs (low- and high-energy peaked BL Lacs, respectively). EGRET did not detect the majority of the HBLs seen by ground-based IACTs, except for the closest ones such as Mrk 421, Mrk 501 and PKS 2155-304. Fermi should be able to detect many more such sources, given its much better sensitivity in comparison with EGRET. The IBLs (intermediate-energy peaked BL Lacs) are particularly interesting for simultaneous detection by Fermi and the IACTs. For example, W Comae seen by VERITAS [14] appears in the 3rd EGRET catalog (3EG J1222+2841) [3] and also appears in the first LAT bright source list as 0FGL J1221.7+2814 [30].

The current paradigm of blazar emission is that they are powered by accretion of matter onto a central supermassive black hole, with gamma-ray emission originating in relativistically beamed jets. This understanding is supported by the observations of high
luminosity, superluminal motion and short timescale variability in gamma-ray blazars, as discussed above. Gamma-ray emission is explained by the energy losses of relativistic particles via synchrotron and Compton-scatter processes. Competing blazar emission models are broadly divided into ‘leptonic’ and ‘hadronic’ classes, based on the type of relativistic-charged particles in the blazar jets. Several reviews discuss blazar models and the constraints placed on them by the EGRET observations (see e.g. [52, 53]). The nature of the particles in the blazar jet is still an open question in high energy astrophysics, which calls for careful coordinated study with Fermi and other broadband observatories.

Fermi is certain to make major contributions to the field of blazar astrophysics. The LAT collaboration has already announced the detection of several blazar flares via the Astronomer’s Telegram (ATel), including 3C 66A (after a flare was reported by VERITAS), PKS 0537-441 (one of the most variable BL Lac objects), PKS 0208-512, AO 0235 + 164 (which exhibited strong activity on short timescales) and the detection of 3C 273 and PKS 1510-089 in the flaring state [54]–[57], among others. A paper on the discovery of gamma-ray emission from the FSQR PKS 1454-354 has also been submitted for publication [58] and a list of 106 AGN associated with high confidence to bright LAT sources detected in the first three months of operation has recently appeared as a preprint [59]. Together with high sensitivity observations at TeV energies by IACTs, the next decade will address many fundamental questions such as particle acceleration in blazars, the powering and formation of blazar jets, details of the

**Figure 8.** SED of 3C 279 from radio to gamma-ray energies for several different epochs. The figure demonstrates the high variability that is often seen in the broadband spectra of blazars. Figure from Wehrle et al [42].
jet structure, as well as population studies and unification models and the contribution of blazars to the extragalactic diffuse gamma-ray background (see the presentation at the First GLAST Symposium by Padovani [60]). Fermi has also detected emission from non-blazar active galaxies, such as the radio galaxies Cen A and NGC 1275 [59], and TeV emission with rapid flux variations has been detected by IACTs from the relatively nearby radio galaxy M87 [61]–[63].

3.2. GRBs

While much progress in understanding GRBs has been made in the past several years, especially since the launch of Swift [64], still very little is known about their highest energy photons (see [65] for a complete review). Only five bursts were detected with pair conversions in the EGRET spark chambers [66]. The most impressive one occurred on 17 February 1994, with 28 photons detected by EGRET ranging in energy from 36 MeV to 18 GeV [67]. Another, on 31 January 1993, had 16 EGRET photons up to 1.2 GeV in energy [68], but the others each had just a handful of EGRET photons, all with energies well below a GeV.

The most surprising result from the EGRET observations was the detection of delayed emission in some of the bursts, long after cessation of the low-energy (hard x-ray) emission detected by BATSE. Again, GRB 940217 was the most impressive example, with 18 of the 28 photons detected after the end of the 180 s BATSE-detected burst. In fact, the Earth occulted the view 780 s after the burst, and the last 10 photons, including the 18 GeV photon, were detected after the source emerged from the Earth’s shadow, 4700 s after the burst trigger! (see figure 9). Since BATSE and EGRET were both on CGRO, BATSE could not look for lower-energy emission during the occultation. However, the Ulysses experiment saw no signal in the 25–150 keV range during that period [67, 69].

The observations of multi-GeV photons from GRBs provide challenges for models of the sources, requiring very high bulk Lorenz factors in the initial jet-like burst to allow those photons to escape before interacting. Delayed emission of high-energy gamma-rays is also problematic, but it is possible that they are delayed in transit by interaction with the intergalactic medium. For example, a very high energy photon could interact with the cosmic microwave background.
Figure 10. A ±30° degree field before and after the beginning of GRB080916c, showing LAT photon locations. The empty lower-left corner is outside of the LAT field of view.

(CMB), producing electrons and positrons that are deflected by the intergalactic magnetic field before interacting again to produce gamma-rays observed on Earth [70, 71].

The AGILE detector saw one burst (GRB080514b, GCN 7716), shortly before the Fermi launch, with about 10 photons >30 MeV detected by pair conversions in the silicon-strip detectors. The burst again showed evidence of delayed emission, of at least 13 s, for the high-energy photons [72].

In the first five months following launch, the LAT on the Fermi mission submitted GCN circulars for three GRBs detected from reconstructed gamma-ray conversions. The first of those was a marginal detection (GRB-080825C, GCN 8183), but the second (GRB-080916c, GCN 8246) was spectacular. The LAT detected hundreds of photons, with more than 10 above 1 GeV and up to just above 10 GeV [73]. Figure 10 gives a view of the burst in the sky as observed by the LAT. The third burst (GRB-081024b, GCN 8407) was not as large but included 10 photons above 100 MeV and two above 1 GeV, up to a 3 GeV maximum. Furthermore, it was particularly interesting in that the GBM signal had two distinct peaks in the time profile (a short-long burst). While the LAT GRB rate has not been as high as the more optimistic projections made pre-launch, it is consistent with the limited EGRET observations. It is already clear that over its lifetime of at least five years the Fermi mission will greatly advance our knowledge of GRBs, especially high-energy delayed emission.

3.3. Pulsars, SNR, PWN and other galactic sources

Although there are about 2000 radio pulsars known, only six rotation-powered pulsars were confidently detected at high energies by EGRET, with possibly three other radio pulsars associated with EGRET sources at lower confidence (see for a review [74]). The latter group includes PSR J0218 + 4232 [75], the only millisecond pulsar that was thought also to be possibly an EGRET source. Broadband studies of EGRET pulsars have been important in understanding particle acceleration and interaction mechanisms that are responsible for producing the detected
pulsed emission. Figure 11 shows the multiwavelength spectra of the seven highest-confidence pulsars detected by EGRET. The figure shows that their dominant power output is in high-energy gamma-rays, which are most likely produced by the interactions of energetic particles in the pulsar magnetosphere. These pulsars are generally flat spectrum sources at EGRET energies (indices of $-2.0$ or less), and some indicate a break in the 1–4 GeV band [4]. EGRET did not detect pulsed emission from any pulsar above 30 GeV. Except for recent evidence of pulsed emission from the Crab above 25 GeV by MAGIC [76], no pulsed emission has been detected from any pulsar above 30 GeV. The spectral cutoff of pulsed emission from high-energy pulsars between 30 and 100 GeV will be an important area for Fermi pulsar studies, and could help us to differentiate between pulsar models (e.g. see [77] and the references therein).

Figure 11. Broadband spectra of the seven EGRET pulsars detected with the highest level of confidence. The figure shows the observed power for each pulsar per frequency interval. No pulsed emission was detected by EGRET above 30 GeV. Figure from Thompson [4].
Figure 12. Efficiency (high-energy luminosity/spin down luminosity) as a function of open field line voltage $V$ for EGRET pulsars (circles). Lower-confidence pulsar associations are also shown (triangles). Fermi will be able to test the limit of gamma radiation efficiency in pulsars. Figure from Thompson [4].

It has been noted [78] that the efficiency of conversion of spin-down energy into high energy emission is inversely related to the open field line voltage. Figure 12 shows the dependency for the seven high-confidence EGRET pulsars as well as the three tentative pulsar associations. With better statistics and a greater number of pulsar detections Fermi will address many unresolved questions of pulsar physics, such as the site of acceleration of high energy particles in the pulsar magnetosphere, the mechanisms of high energy radiations, the ratio of radio-loud to radio-quiet pulsars, and the limit to gamma-ray radiation efficiency (figure 12).

Although several additional EGRET sources were associated with candidate pulsars, the identifications could not be confirmed due to the lack of contemporaneous $\gamma$-ray and radio timing information. This will now change with both Fermi and AGILE in operation. The first post-EGRET gamma-ray pulsar was detected by AGILE in the Cygnus region, PSR J2021 + 3651 = AGL J2020.5 + 3653 [79], likely associated with the COS-B source 2CG075 + 00. The pulsed emission, detected in the 100–1500 MeV range, shows two sharp peaks separated by slightly less than 0.5 cycle, similar to that seen in other EGRET pulsars.

At the time of writing, the Fermi/LAT collaboration has already been actively engaged in pulsar detection. All of the EGRET pulsars have been detected with high significance. In fact, the LAT data for the brightest pulsars, such as Vela, allow the high-energy emission of those objects to be studied with unprecedented detail with just the first few months of data. For example, see [80], where the high statistics and sharpness of the Vela-pulsar light curve, as well as the excellent spectral information, are used to analyze details of the gamma-ray emission region in various pulsar models. In addition, the LAT has detected pulsation from many new...
Figure 13. The light curve of the CTA-1 radio-quiet pulsar as observed by the Fermi/LAT observatory [83], showing two identical periods.

sources [81], both known radio loud pulsars, for which the radio ephemeris is used to fold the data onto a single phase, and new radio-quiet sources, for which an FFT-based method is used in the initial detection [82]. The new radio-loud pulsars include at least 12 young pulsars and at least 7 ms pulsars. The first detection of a radio-quiet pulsar by the gamma-ray signal alone, of the CTA-1 pulsar, was the first LAT publication of a science result [83]. The LAT light curve is shown in figure 13. This is just the first of many such detections expected over the first year of data (at least 15 have been detected so far), and the results will help us to constrain models of gamma-ray production in the outer magnetosphere of young pulsars as well as clarify the nature of SNRs such as CTA 1.

Energetic charged particles accelerated in the vicinity of a pulsar form a shock when they flow out into the supernova ejecta, and the shock can further accelerate particles to relativistic speeds. A pulsar wind nebula (PWN) is produced due to the interactions of high energy particles with the surrounding medium, and is often detectable at x-ray and radio energies. It is interesting to note that PWN constitute the largest fraction of the Galactic TeV sources detected by ground-based ACTs like HESS [84]. The Crab, a prototypical PWN, was the only such source detected by EGRET.

SNRs are believed to be sites of cosmic-ray acceleration in our Galaxy. Non-thermal x-ray emission has been detected from shell-type SNRs, suggesting acceleration of electrons to multi-TeV energies, and some SNRs have been detected in TeV gamma rays by IACTs. However, none of the EGRET sources were unambiguously identified with SNRs, although several unidentified Galactic EGRET sources show tentative associations with SNRs. In terms of population studies, the distribution of a large number of the Galactic gamma-ray sources is similar to that of SNRs [85, 86]. The two strongest point-like EGRET sources coincident with SNRs are γ Cygni and IC 443 [85]. With better angular resolution compared with EGRET, Fermi will be able to make more confident associations between SNRs and gamma-ray sources. Some recent reviews describe the structure and evolution of PWN [87] and the prospects of studying SNRs with Fermi [88].
3.4. Unidentified gamma-ray sources

More than half the sources in the 3EG Catalog have not been identified or associated with obvious counterparts at other wavebands. Of the identified sources, the majority are blazars, with a handful of pulsars. This was largely due to the fact that EGRET sources typically had large error circles, and identifications of sources with known source classes, e.g. blazars and pulsars, were generally the most confident ones. Identifications of galactic sources were further hampered by the presence of bright galactic diffuse emission along the plane. The nature of these unidentified gamma-ray sources has remained elusive, in some cases since the COS-B era (e.g. sources discovered by COS-B along the Galactic plane) [32].

Since the publication of the EGRET catalog, several attempts have been made to identify those EGRET sources using the best-determined positions, on a case-by-case basis using archival multiwavelength information (see reviews by Caraveo [89], Mukherjee and Halpern [90]). Although this is a time-consuming process, and clearly impractical for a very large number of sources (e.g. in the case of Fermi), in some cases the error boxes of individual EGRET sources did reveal interesting candidates at other wavelengths, whose properties suggested that they were related to the EGRET source. One of the first exhaustive studies of this kind was carried out by Roberts et al [91] in which they looked for x-ray counterparts in the 2–10 keV band using ASCA data covering the EGRET fields. Figure 14 shows an example of a case where a hard, non-thermal x-ray source with no optical counterpart was discovered in the ROSAT HRI data within the field of an unidentified Galactic EGRET source 3EG J2227 + 6122 [92]. Subsequent Chandra observations clearly showed a point source surrounded by diffuse emission, and Halpern et al [93] reported radio and x-ray pulsations at a period of 51.6 ms. These x-ray and radio observations left little doubt that the EGRET source 3EG J2227 + 6122 was indeed the young and energetic x-ray/radio pulsar PSR J2229 + 6122.

Interpreting the nature of unidentified gamma-ray sources is one of the first studies being done with Fermi, which offers far better source localization for individual sources, thus enabling more confident counterpart associations. Fermi will also generate its own catalog of unidentified gamma-ray sources, especially weak sources in crowded regions with few high-energy photons to aid in localization. For many sources like 3EG J2227 + 6122, which very likely corresponds to the radio pulsar PSR J2229 + 6114, pulsation searches in the gamma-ray data with Fermi, making use of the radio ephemerides, could result in a conclusive identification. In fact, PSR J2229 + 6114 appears in the LAT bright source list [30], and the Fermi-LAT collaboration has already made preliminary reports of detection of its pulsation at very high confidence [94]. Fermi is also performing 'blind' pulsation searches on all point sources not already conclusively identified and not already associated with known radio pulsars. In fact, at least 15 such identifications have already been made and will be published in the coming year [81].

However, for the large number of Fermi sources, population studies of gamma-ray sources and correlation of gamma-ray source properties with those at other wavelengths will likely play key roles in source identification strategies. There were several such studies of spectral and temporal properties of unidentified sources carried out with EGRET data, as well as correlation of EGRET sources with known galactic populations such as SNRs, pulsars and star forming regions (see e.g. [95] and the references therein). A large fraction of the high-energy gamma-ray sources seen at TeV energies by ground-based IACTs are also unidentified [84], and in some cases referred to as ‘dark accelerators’, due to the lack of detected emission in other wavebands [96]. The operation of Fermi in survey mode will benefit IACTs by providing...
Figure 14. (a) Top: composite ROSAT HRI image of the 3EG J2227 + 6122 field, indicated by the dashed circle, which corresponds to the 95% error contour of the EGRET source. All the x-ray point sources (plus signs) are bright stars, except for no. 1, the only unidentified HRI source, which is coincident with a bright, hard source seen in the ASCA GIS image (contours). The ASCA GIS field is indicated by the solid circle. This x-ray source, RX/AX J2229.0 + 6114, has been suggested as the most likely counterpart to the EGRET source. Figure from [92]. (b) Bottom: radio pulse profile of PSR J2229 + 6114 at 1412 MHz as observed with the Lovell radio telescope at the Jodrell Bank. Figure from [93].

Contemporaneous views of the gamma-ray sky and could help in resolving the nature of these unidentified TeV sources. The detection of two high-mass x-ray binary sources at TeV energies, LSI + 61°303 [11, 12] and LS 5039 [97], that are positionally consistent with the two EGRET unidentified sources 3EG J0241 + 6103 and 3EG J1824-1514, respectively, offers the possibility...
of a new class of Galactic GeV/TeV sources. *Fermi* observations of these sources in coincidence with TeV observations will provide further evidence to judge whether the EGRET sources are indeed these binary sources. In fact, preliminary *Fermi* observations of LSI +61°303 have already been reported that strengthen this association [30, 98].

3.5. Diffuse emissions

EGRET measured intense Galactic diffuse emission in the 30 MeV to 100 GeV energy range as is evident in the intensity map shown in figure 2. The Galactic diffuse emission is related to the density of cosmic rays and the distribution of gas and radiation in the interstellar medium (ISM) and is likely to have some contributions from unresolved point sources. The physical processes giving rise to the diffuse radiation include interactions of cosmic-ray particles with interstellar gas producing gamma-rays via pion decay, inverse Compton scattering of optical and infrared photons off relativistic electrons, and the production of gamma-rays via bremsstrahlung. An accurate modeling of the Galactic diffuse emission is important not only to understand the astrophysical processes leading to the production of gamma-rays but also to successfully discriminate between point sources and interstellar emission and to be sensitive to emission from as-yet unknown sources (see section 3.6). A model of the diffuse emission by the EGRET Team [99] found a reasonably good fit to the data, but with an interesting 'excess' of gamma-ray emission at GeV energies. The physical origin on this GeV excess has been a subject of debate, and an analysis by Strong *et al* [100] suggested that the model of cosmic-ray spectra could be optimized to explain the detected gamma-ray intensities, by removing some constraints imposed by measurements of the local cosmic-ray spectra (since the spectra, particularly for electrons, could fluctuate around the galaxy according to varying distances from randomly distributed sources). However, others have questioned the calibration of EGRET as an explanation for the discrepancy [101], and in January 2009 the *Fermi*-LAT collaboration presented preliminary results showing no indication of the GeV excess in the diffuse emission from the Galactic latitude range $10° \leq |b| \leq 20°$ [102].

A review of the interstellar emission model and a discussion of approaches for determining cosmic ray densities for diffuse gamma rays was presented at the First GLAST Symposium [103]. A new Galactic interstellar emission model based on the most current data on $CO$, $HI$, dark gas and interstellar radiation field was used recently by Casandjian and Grenier [104] to model the Galactic background and search for gamma-ray point sources in the EGRET data. The results were found not to be completely in agreement with the EGRET 3EG catalog. Evidently a careful modeling of the diffuse background will be important for *Fermi* to carry out point source searches, especially in the Galactic plane.

After accounting for the Galactic diffuse emission and subtracting out the contribution of catalogued gamma-ray point sources, EGRET data revealed an isotropic component of the diffuse emission that may emanate from beyond our Galaxy. Figure 15 shows the multiwavelength spectrum of the extragalactic diffuse emission from x-ray to gamma-ray energies. The EGRET measurements are shown in the 30 MeV to 100 GeV energy range, fit with a power-law photon spectral index of $-2.10 \pm 0.03$ [105]. The figure also shows a re-analysis of the EGRET data by Strong *et al* [106] showing a steeper EGRET spectrum and a break at 2 GeV.

The nature of the extragalactic gamma-ray background is an open question, subject to much debate. In addition to a truly diffuse component, the emission is most likely made up of unresolved gamma-ray sources, with contributions from blazars, radio galaxies, starburst...
Figure 15. Extragalactic x-ray and gamma-ray spectrum showing the estimated contribution to the background from various sources such as Seyfert 1, Seyfert 2, steep-spectrum quasars and Type Ia supernovae [100, 105]. The extragalactic gamma-ray background calculated from the re-calibrated EGRET data by Strong \textit{et al} (labeled SMR2004 [106]) shows a break at 2 GeV and is steeper than the spectrum calculated by Sreekumar \textit{et al} [105] in the energy range 30 MeV to 2 GeV. Figure from [110].

galaxies, normal galaxies, as well as other source classes such as galaxy clusters and distant GRBs (for a review, see [107] and the references therein, presented at the First GLAST Symposium). Solar-system contributions have also been considered [108, 109], and possible remaining residual cosmic-ray background should also be kept in mind. It is often argued that gamma-ray blazars are likely to make up the bulk of the contribution, and a recent analysis of the recalibrated EGRET data shows a blazar spectral index of $-2.25 \pm 0.03$ [110], close to the spectral index obtained for the extragalactic gamma ray background obtained by Strong \textit{et al} [106]. \textit{Fermi} data will probably resolve the nature of this background and determine whether it includes contributions from as yet unknown source classes, from anomalous gamma-ray emission signatures related to hadronic acceleration in blazar or GRB jets, or perhaps from diffuse emission from pair annihilation of dark matter particles.

3.6. Signals for new physics

One of the greatest outstanding problems in astrophysics and fundamental physics is the nature of dark matter. A favorite hypothesis is that it is composed of relic weakly interacting massive particles (WIMPs), such as hypothetical massive supersymmetric partners to the known gauge
bosons [111]. In regions of highest dark-matter density, it is possible that the annihilation cross section of WIMPs is high enough that gamma-rays resulting from the annihilation could be detected by satellite observatories. In fact, cosmological predictions based on supersymmetric theories tend to place the cross section in a range that might be observable, especially if extensive clumping of dark matter occurs as expected. The sensitivity to detection generally falls with increasing WIMP mass, but for very high masses the ground-based IACTs, with their enormous collection area, might be able to make the detection.

Numerical many-body simulations of galaxy formation predict a main galactic halo surrounded by a swarm of subhalos over a very large range of smaller mass scales [112, 113]. Gamma-rays from WIMP annihilation might be seen from the Galactic center, where there should be the highest concentration of dark matter, but unfortunately also a complex background from diffuse radiation and point sources. The signal might also be detected throughout the main halo of the Milky Way, but our limited knowledge of the galactic diffuse radiation produced by cosmic-ray interactions makes isolating the signal challenging. It might also be seen emanating from the subhalos, either those corresponding to known local dwarf spheroidal galaxies or ones as yet unknown. The clearest signal would be a narrow gamma-ray line at the WIMP mass, from annihilation to gamma-ray pairs. However, the branching ratio to that final state is expected to be very small, such that most efforts concentrate on looking for a continuous spectrum of gamma-rays originating from WIMP annihilation to hadronic jets.

The EGRET GeV excess (see section 3.5) has been interpreted in a detailed analysis as a result of WIMP annihilation [114], although with a fairly high ‘boost’ of 100 from presumed WIMP density clumping and an unusual galactic dark-matter density profile that includes two toroidal rings on top of an isothermal profile. However, given the questions raised about systematics in the EGRET data, especially at high energy, as well as the more prosaic explanations of the excess in terms of modifications of the galactic-diffuse models (see section 3.5), confirmation of the excess by Fermi is needed. In fact, the preliminary results from Fermi have not supported the EGRET measurements in at least part of the sky [102], and even if Fermi sees a high-energy excess in other Galactic regions, detection of dark satellite subhalos may be necessary for confidence in a WIMP annihilation interpretation.

Many estimates have been published on the Fermi-LAT sensitivity to WIMP annihilation. See, for example [115], where several models and detection modes are considered, including the sensitivity for searches for dark satellites based on a quasi-analytic model. Similar estimates have been made based on the latest many-body simulations of galaxy formation [113, 116]. The results suggest that Fermi has a fair chance to see WIMP annihilation in the main galactic halo and in a handful of sub-halos. However, given the large model dependence remaining in the underlying theory (e.g. supersymmetry) as well as in the galactic dark-matter distribution, a non-detection by Fermi would rule out only a small fraction of the model space. An accelerator-based detection of a WIMP candidate, a real possibility in the near future at the CERN Large Hadron Collider, would greatly help to narrow down the astrophysical searches [117].

Another attention-grabbing new-physics hypothesis that is related to observations by gamma-ray telescopes is violation of Lorentz invariance at high energy [118]. Even a tiny dispersion in electromagnetic wave propagation through intergalactic space could be observable over cosmological distances. For example, a transient signal from a GRB or an AGN flare might be detected later at high energy than at low energy. That raised the exciting possibility of observing quantum gravity effects at the Planck scale in the Fermi data. However, disentangling such a signal from intrinsic behavior of the sources is problematic. A large statistical sample

New Journal of Physics 11 (2009) 055008 (http://www.njp.org/)
may be needed, hopefully to identify some universal temporal behavior along with observation of a clear dependence on redshift.

4. Summary and future prospects

EGRET provided pioneering views of the gamma-ray sky and discovered a surprisingly large number of energetic gamma-ray sources, which generally exhibit variability over a wide range of timescales. Its results motivated further study in the field and spurred the development of a new generation of satellite-based gamma-ray experiments such as AGILE and Fermi. With much larger effective area and field of view and improved sensitivity over EGRET, Fermi offers unique promise for gamma-ray studies of the Universe above 30 MeV. It will address many of the open questions in high-energy astrophysics and perhaps resolve the outstanding mysteries from EGRET (see [4] for an excellent compilation of the questions raised by EGRET). This is a particularly exciting time for particle astrophysics, as the view of the gamma-ray sky from space-based experiments is complemented by IACTs such as HESS, MAGIC and VERITAS operating with much higher sensitivity than the first-generation ground-based telescopes. Together these experiments will offer an unprecedented correlated broadband view of the highest-energy particle accelerators in the Universe and give us our best opportunity yet to understand the particle acceleration and energy loss mechanisms in these sources. Indeed, the most significant result from Fermi might be the as yet unknown, the surprises it finds in the gamma-ray sky, and the questions it raises for future study, which will inevitably motivate further advancement and growth in the field.

References

[1] Swanenburg B N et al 1978 COS B observation of high-energy gamma radiation from 3C273 Nature 275 298
[2] Mayer-Hasselwander H A 1982 Large-scale distribution of galactic gamma radiation observed by COS-B Astron. Astrophys. 105 164
[3] Hartman R C et al 1999 The third EGRET catalog of high-energy gamma-ray sources Astrophys. J. Suppl. 123 79
[4] Thompson D J 2008 Gamma ray astrophysics: the EGRET results Rep. Prog. Phys. 71 116901
[5] Tavani M et al 2008 The AGILE space mission Nucl. Instrum. Methods Phys. Res. A 588 52
[6] HESS web site http://www.mpi-hd.mpg.de/hfm/HESS/HESS.html
[7] MAGIC web site http://wwwmagic.mppmu.mpg.de/publications/articles/index.html
[8] VERITAS web site http://veritas.saao.arizona.edu/
[9] Aharonian F et al 2008 HESS very-high-energy gamma-ray sources without identified counterparts Astron. Astrophys. 477 353
[10] Aharonian F et al 2006 A detailed spectral and morphological study of the gamma-ray supernova remnant RX J1713.7-3946 with HESS Astron. Astrophys. 449 223
[11] Albert J et al 2006 Variable very-high-energy gamma-ray emission from the microquasar LSI +61 303 Science 312 1771
[12] Acciari V A et al 2008 VERITAS observations of the $\gamma$-ray binary LS I +61 303 Astrophys. J. 679 1427
[13] de Naurois M et al 2007 HESS observations of LS 5039 Astrophys. Space Sci. 309 277
[14] Acciari V A et al 2008 VERITAS discovery of $> 200$ GeV gamma-ray emission from the intermediate-frequency-peaked BL Lacertae object W Comae Astrophys. J. 684 73

New Journal of Physics 11 (2009) 055008 (http://www.njp.org/)
Abdo A A et al 2007 TeV gamma-ray sources from a survey of the galactic plane with Milagro Astrophys. J. 664 91
Horns D 2008 High-(energy)-lights—the very high energy gamma-ray sky Rev. Mod. Astron. to appear (arXiv:0808.3744)
Bignami G et al 1975 High-energy galactic gamma radiation from cosmic rays concentrated in spiral arms Space Sci. Instrum. 1 245
Kanbach G et al 1988 The project EGRET (Energetic Gamma-Ray Experiment Telescope) on NASA’s Gamma-Ray Observatory (GRO) Space Sci. Rev. 49 69
Thompson D J et al 1993 Calibration of the Energetic Gamma-Ray Experiment Telescope (EGRET) for the Compton Gamma-Ray Observatory Astrophys. J. Suppl. 86 629
CGRO Science Support Center web site http://heasarc.gsfc.nasa.gov/docs/cgro/
Vercellone S et al 2008 AGILE detection of a strong gamma-ray flare from the blazar 3C 454.3 Astrophys. J. 676 L13
Pellizzoni A et al 2009 High-resolution timing observations of spin-powered pulsars with the AGILE gamma-ray telescope Astrophys. J. 691 1618
Atwood W B et al 1994 Gamma Large Area Silicon Telescope (GLAST) applying silicon strip detector technology to the detection of gamma rays in space Nucl. Instrum. Methods A 342 302
Atwood W B et al 2009 The large area telescope on the Fermi gamma-ray space telescope mission Astrophys. J. at press (arXiv:0902.1089)
Meegan C et al 2007 The GLAST Burst Monitor Proc. First GLAST Symp. (AIP Conf. Proc. vol 921) p 13
Fishman G J et al 1994 The first BATSE gamma-ray burst catalog Astrophys. J. Suppl. 92 229
Atwood W B et al 2007 Design and initial tests of the Tracker-converter of the gamma-ray large area space telescope Astropart. Phys. 28 422
Baldini L et al 2006 The silicon tracker readout electronics of the gamma-ray large area space telescope IEEE Trans. Nucl. Sci. 53 466
Moiseev A A et al 2007 The anti-coincidence detector for the GLAST large area telescope Astropart. Phys. 27 339
Abdo A A et al 2009 Fermi large area telescope bright gamma-ray source list Astrophys. J. Suppl. submitted (arXiv:0902.1340v1)
Fermi Science Support Center web site http://fermi.gsfc.nasa.gov/ssc/
Swanenburg B N et al 1981 Second COS B catalog of high-energy gamma-ray sources Astrophys. J. 243 L69
Mukherjee R et al 1997 EGRET observations of high-energy gamma-ray emission from blazars: an update Astrophys. J. 490 116
Sowards-Emmerd D et al 2003 The gamma-ray blazar content of the Northern Sky Astrophys. J. 590 109
Punch M et al 1992 Detection of TeV photons from the active galaxy Markarian 421 Nature 358 477
Krawczynski H 2004 TeV blazars—observations and models New Astron. Rev. 48 367
Begelman M C, Fabian A C and Rees M J 2008 Implications of very rapid TeV variability in blazars Mon. Not. R. Astron. Soc. 384 L19
Mattox J R et al 1997 An intense gamma-ray flare of PKS 1622-297 Astrophys. J. 476 692
Mattox J R et al 1993 The EGRET detection of quasar 1633 + 382 Astrophys. J. 410 609
Sikora M, Begelman M C and Rees M J 1994 Comptonization of diffuse ambient radiation by a relativistic jet: the source of gamma rays from blazars? Astrophys. J. 421 153
Wagner S J et al 1995 High-energy gamma rays from PKS 1406-076 and the observation of correlated gamma-ray and optical emission Astrophys. J. 454 L97
Wehrle A et al 1998 Multiwavelength observations of a dramatic high-energy flare in the Blazar 3C 279 Astrophys. J. 497 178
Mukherjee R et al 1999 Broadband spectral analysis of PKS 0528 + 134: a report on six years of EGRET observations Astrophys. J. 527 132

New Journal of Physics 11 (2009) 055008 (http://www.njp.org/)
[44] Mukherjee R 2001 EGRET (GeV) blazars AIP Conf. Proc. 558 324
[45] Monitoring of Jets in Active Galaxies with Experiments VLBA (MOJAVE): http://www.physics.purdue.edu/astro/MOJAVE
[46] Lister M L and Homan D C 2005 MOJAVE: monitoring of jets in active galactic nuclei with VLBA experiments. I. First-Epoch 15 GHz linear polarization images Astron. J. 130 1389
[47] Kellerman K I et al 2004 Sub-milliarcsecond imaging of quasars and active galactic nuclei. III. Kinematics of parsec-scale radio jets Astrophys. J. 609 539
[48] Homan D C et al 2003 Jet collimation in action: realignment on kiloparsec scales in 3C 279 Astrophys. J. 589 L9
[49] Hartman R C et al 2001 Multiepoch multiwavelength spectra and models for Blazar 3C 279 Astrophys. J. 553 683
[50] Fossati G et al 1998 A unifying view of the spectral energy distributions of blazars Mon. Not. R. Astron. Soc. 299 433
[51] Padovani P 2007 The blazar sequence: validity and predictions Astrophys. Space Sci. 309 63
[52] Boettcher M 2007 Modeling the emission processes in blazars Astrophys. Space Sci. 309 95
[53] Reimer A, Joshi M and Boettcher M 2008 The Blazar 3C 66A in 2003–2004: hadronic versus leptonic model fits HIGH ENERGY GAMMA-RAY ASTRONOMY: Proc. 4th Int. Meeting on High Energy Gamma-Ray Astronomy (AIP Conf. Proc. vol 1085) p 502
[54] Tosti G 2008 Fermi LAT detections of gamma ray activity in three blazars: 3C 66A, PKS 0208-512, PKS 0537-441, ATel no. 1759
[55] Foschini L 2008 Fermi/LAT detection of strong activity on short timescales of the Blazar AO 0235 + 164, ATel no. 1784
[56] Marelli M 2008 Fermi LAT detection of 3C 273 in flaring state, ATel no. 1707
[57] Tramacere A 2008 Fermi LAT observations of the PKS 1510-089 outburst, ATel no. 1743
[58] Abdo A A et al 2009 Fermi/LAT discovery of gamma-ray emission from the flat-spectrum radio quasar PKS 1454-354 Astrophys. J. at press (arXiv:0903.1713)
[59] Abdo A A et al 2009 Bright AGN source list from the first three months of the Fermi large area telescope sky survey Astrophys. J. submitted (arXiv:0902.1559)
[60] Padovani P 2007 Gamma-ray emitting AGN and GLAST Proc. First GLAST Symp. (AIP Conf. Proc. vol 921) p 19
[61] Aharonian F et al 2006 Fast variability of tera-electron volt rays from the radio galaxy M87 Science 314 1424
[62] Acciari V A et al 2008 Observation of gamma-ray emission from the Galaxy M87 above 250 GeV with VERITAS Astrophys. J. 679 397
[63] Albert J et al 2008 Very high energy gamma-ray observations of a strong flaring activity in M87 in 2008 February Astrophys. J. 685 L23
[64] Gehrels N 2004 The Swift gamma-ray burst mission New Astron. Rev. 48 431
[65] Mészáros P 2006 Gamma-ray bursts Rep. Prog. Phys. 69 2259
[66] Merck M et al 1995 Flares and Flashes (Lecture Notes in Physics vol 454) ed J Greiner, H W Duerbeck and R E Gershberg (Berlin: Springer) p 358
[67] Hurley K et al 1994 Detection of a gamma-ray burst of very long duration and very high energy Nature 372 652
[68] Sommer M et al 1994 High-energy gamma rays from the intense 1993 January 31 gamma-ray burst Astrophys. J. 422 L63
[69] Hurley K et al 1992 The solar x-ray/cosmic gamma-ray burst experiment aboard ULYSSES Astron. Astrophys. Suppl. 92 401
[70] Blaga R 1995 Detecting intergalactic magnetic fields using time delays in pulses of γ-rays Nature 374 430
[71] Wang X Y et al 2004 Constraining the origin of TeV photons from gamma-ray bursts with delayed MeV–GeV emission formed by interaction with cosmic infrared/microwave background photons Astrophys. J. 604 306

New Journal of Physics 11 (2009) 055008 (http://www.njp.org/)
25

[72] Giuliani A et al 2008 AGILE detection of delayed gamma-ray emission from GRB 080514B Astron. Astrophys. 491 L25

[73] Abdo A A et al 2009 Fermi observations of high-energy gamma-ray emission from GRB 080916C Science 323 1688

[74] Thompson D J 2004 Gamma ray pulsars Astrophys. Space Sci. Libr. 304 149

[75] Kuiper L et al 2002 High-resolution spatial and timing observations of millisecond pulsar PSR J0218 + 4232 with Chandra Astrophys. J. 577 917

[76] Aliu E et al 2008 Observation of pulsed γ-rays above 25 GeV from the crab pulsar with MAGIC Science 322 1221

[77] Harding A K 2007 Pulsar high-energy emission from the polar cap and slot gap Invited Review at 363-Heraeus-Semin. on Neutron Stars and Pulsars ed W Becker (arXiv:0710.3517)

[78] Arons J 1996 Pulsars as gamma ray sources Astron. Astrophys. Suppl. 120 49

[79] Halpern J P et al 2001 A possible x-ray and radio counterpart of the high-energy gamma-ray source 3EG J2227 + 6122 Astrophys. J. 547 323

[80] Halpern J P et al 2001 PSR J2229 + 6114: discovery of an energetic young pulsar in the error box of the source EGRET 3EG J2227 + 6122 Astrophys. J. 552 L125

[81] Parent D 2009 PSR J0205 + 6449, PSR J2229 + 6114 and their cousins—young and noisy gamma ray pulsars Contribution to The 44th Rencontres de Moriond 2009, on Very High Energy Phenomena in the Universe, February 2009, La Thuile, Italy

[82] Roberts M S E, Romani R W and Kawai N 2001 The catalog ASCA of potential x-ray counterparts of GeV sources Astrophys. J. Suppl. 133 451

[83] Reimer O and Torres D 2007 Identification of high energy gamma-ray sources and source populations in the era of deep all-sky coverage Astrophys. Space Sci. 309 57

[84] Pühlhofer G 2008 Using x-ray observations to identify the particle acceleration mechanisms in VHE SNRs and ‘dark’ VHE sources Astron. Nachr. 329 186 (arXiv:0710.3363)

[85] Aharonian F A et al 2006 3.9 day orbital modulation in the TeV γ-ray flux and spectrum from the x-ray binary LS 5039 Astron. Astrophys. 460 743
[98] Dubois R 2008 GLAST LAT: sky survey Contribution to The 7th Microquasar Mtg., Microquasars and Beyond, Turkey, September 2008
[99] Hunter S D et al 1997 EGRET observations of the diffuse gamma-ray emission from the galactic plane Astrophys. J. 481 205
[100] Strong A et al 2004 Diffuse galactic continuum gamma rays: a model compatible with EGRET data and cosmic-ray measurements Astrophys. J. 613 956
[101] Stecker F W et al 2008 The likely cause of the EGRET GeV anomaly and its implications Astropart. Phys. 29 25
[102] Johansson G 2009 A first look at diffuse galactic emission with Fermi LAT 213th AAS 2009 January Meeting, Long Beach no. 355.06
[103] Digel S W 2007 Galactic diffuse emissions Proc. First GLAST Symp. (AIP Conf. Proc. vol 921) p 117
[104] Casandjian J M and Grenier A 2008 A revised catalogue of EGRET gamma-ray sources Astron. Astrophys. 489 849
[105] Sreekumar P et al 1998 EGRET observations of the extragalactic gamma-ray emission Astrophys. J. 494 523
[106] Strong A et al 2004 A new determination of the extragalactic diffuse gamma-ray background from data EGRET Astrophys. J. 613 956
[107] Dermer C 2007 The extragalactic gamma-ray background Proc. First GLAST Symp. (AIP Conf. Proc. vol 921) p 122
[108] Moskalenko I V et al 2006 Inverse Compton scattering on solar photons, heliospheric modulation and neutrino astrophysics Astrophys. J. 652 L65
[109] Moskalenko I V et al 2008 A celestial gamma-ray foreground due to the albedo of small solar system bodies and a remote probe of the interstellar cosmic-ray spectrum Astrophys. J. 681 1708
[110] Nandikotkur G et al 2007 Does the blazar gamma-ray spectrum harden with increasing flux? Analysis of 9 years of EGRET data Astrophys. J. 657 706
[111] Bergström L 2000 Non-baryonic dark matter: observational evidence and detection methods Rep. Prog. Phys. 63 793
[112] Madau P et al 2008 Dark matter subhalos and the dwarf satellites of the Milky Way Astrophys. J. 679 1260
[113] Springel V et al 2008 The Aquarius project: the subhaloes of galactic haloes Mon. Not. R. Astron. Soc. 391 1685
[114] de Boer W et al 2005 EGRET excess of diffuse galactic gamma rays as tracer of dark matter Astron. Astrophys. 444 51
[115] Balz E A et al 2008 Pre-launch estimates for GLAST sensitivity to dark matter annihilation signals J. Cosmol. Astropart. Phys. JCAP07(2008)013
[116] Kuhlen M et al 2008 The dark matter annihilation signal from galactic substructure: predictions for GLAST Astrophys. J. 686 262
[117] Kane G and Watson S 2008 Dark matter and LHC: what is the connection? Mod. Phys. Lett. A 23 2103
[118] Amelino-Camilia G et al 1998 Tests of quantum gravity from observations of γ-ray bursts Nature 393 763