

Exploring the extreme universe with the Fermi Gamma-Ray Space Telescope

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Citation: *Phys. Today* **65**(11), 39 (2012); doi: 10.1063/PT.3.1787

View online: <http://dx.doi.org/10.1063/PT.3.1787>

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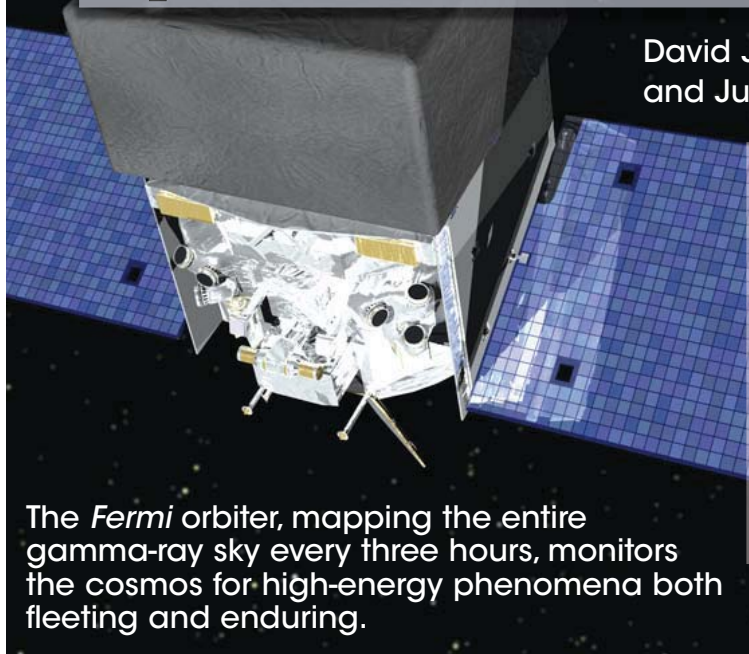
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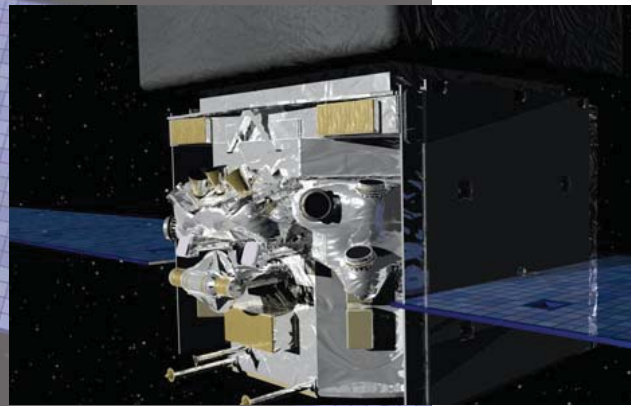
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Exploring the extreme universe with the *Fermi Gamma-Ray Space Telescope*

David J. Thompson, Seth W. Digel, and Judith L. Racusin



The *Fermi* orbiter, mapping the entire gamma-ray sky every three hours, monitors the cosmos for high-energy phenomena both fleeting and enduring.



NASA

In ways similar to experiments in nuclear and particle physics, high-energy astrophysics uses gamma rays and energetic charged particles to probe processes that involve large energy transfers. Since its launch in 2008, the international *Fermi Gamma-Ray Space Telescope* has been exploring natural particle accelerators and the interactions of high-energy particles in the universe. With sources ranging from thunderstorms on Earth to galaxies and exploding stars in distant parts of the cosmos, the telescope's subjects of study are almost as diverse as were those of the scientist whose name it bears.

Although the universe is largely transparent to gamma rays with MeV and GeV energies, Earth's atmosphere presents a forbidding absorption barrier. So direct detection of cosmic gamma rays is inherently a space-based activity. The ways in which the gamma rays interact with detector materials—by Compton scattering, electron-positron pair production, and the photoelectric effect—do not allow reflection or refraction. A gamma “telescope” is, therefore, an imaging gamma detector that uses techniques largely drawn from accelerator experiments, with adaptations to operation in space.

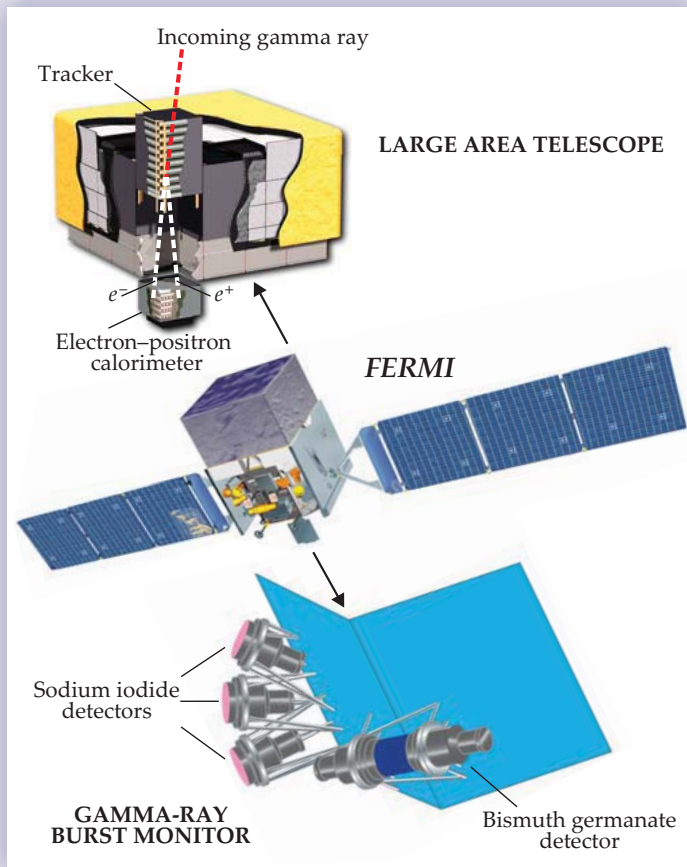
The principal stimulus for the *Fermi* mission was the wealth of scientific information gleaned in the 1990s from NASA's pioneering *Compton Gamma-Ray Observatory*, whose instruments demonstrated the broad scope of gamma-ray astrophysics and the dynamic nature of the gamma-ray sky. (See the article by Neil Gehrels and Jacques Paul in *PHYSICS TODAY*, February 1998, page 26.)

Fermi, shown in figure 1, carries two instruments that are direct successors of the EGRET and BATSE instruments aboard *Compton*:

► The Large Area Telescope (LAT), *Fermi*'s primary instrument, measures the arrival direction, energy, and time of individual gamma rays with energies from about 20 MeV to over 300 GeV, which produce e^+e^- pairs in the LAT.¹ Using silicon-strip charged-particle trackers instead of the EGRET-era spark chambers to image the trajectories of the pair, the LAT achieves an effective

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Figure 1. The *Fermi* Gamma-Ray Space Telescope and its two scientific instruments.¹¹ With its silicon-strip tracker and electron-positron calorimeter, the Large Area Telescope measures arrival directions and energies of photons with energies from 20 MeV to more than 300 GeV. The smaller Gamma-Ray Burst Monitor, with its array of 14 crystal gamma-ray detectors, is primarily designed to detect low-energy transient gamma-ray outbursts at photon energies from 8 keV to 40 MeV.



detector area of about a square meter for gamma rays with energies above 1 GeV. And its angular resolution for a single gamma ray is finer than 1° , which allows localization of most gamma-ray sources to within 10 arcminutes on the sky. For the brightest sources, the localization is better than 1 arcmin. The LAT's field of view exceeds 2.4 steradians. Overall, its sensitivity exceeds EGRET's by more than an order of magnitude.

► *Fermi's* Gamma-Ray Burst Monitor (GBM) is an array of sodium iodide and bismuth germanate crystal scintillators that views everything in the sky not occulted by Earth.² It's sensitive to x rays and gamma rays with energies from 8 keV to 40 MeV. The GBM uses counting rates in the different detectors to measure the energy spectra and celestial locations of bright gamma sources, particularly brief transients such as gamma-ray bursts. Although the GBM is physically smaller than BATSE was, its broader energy range and optimized triggering give it almost the same sensitivity as its predecessor.

Unlike most telescopes, which have fields of view that are arcminutes across and point at indi-

vidual targets, *Fermi* takes advantage of the instruments' huge fields of view to survey the full sky every three hours—that is, two orbits around Earth. That “scanning mode” of operation makes possible two simultaneous approaches to gamma-ray astrophysics:

► Constantly deepening exposure of the gamma-ray sky. The instruments accumulate ever more photons with each orbit, giving deeper and clearer views of persistent sources and spatially extended features as time progresses.

► Time-domain gamma-ray astronomy. By continually monitoring the cosmos, the instruments are sensitive to changes in the gamma-ray sky on time scales ranging from microseconds to years.

We now review examples of discoveries made with those approaches.

The persistent gamma-ray sky

The instruments aboard *Fermi* improve the gamma-ray sky map with every scan, probing deeper into the cosmos to reveal ever more distant and fainter objects. The increased exposure is particularly important at the highest energies because those gamma rays, which carry information about the most energetic astrophysical interactions, are fewest in number.

Figure 2 shows false-color maps of the sky in galactic coordinates at gamma energies above 1 GeV and above 10 GeV. Much of the bright equatorial band across the sky is diffuse emission from the Milky Way, produced by interactions of high-energy charged cosmic-ray particles with interstellar matter and photon fields. The relevant gamma-producing processes are neutral-pion decay, bremsstrahlung, and inverse Compton scattering. This diffuse galactic emission is a valuable source of information about the distribution and interactions of galactic cosmic rays, interstellar radiation, gas, and diffusive magnetic fields.

In fact, the maps show that the gamma-ray sky is not really dark in any direction. The isotropic component is the extragalactic gamma-ray background. It's attributed, in part, to unresolved discrete sources at great distances. But it may include a truly diffuse component.

A major surprise from the LAT survey was the detection of previously unknown giant structures, the so-called Fermi bubbles, above and below the direction of the galactic center. They are most visible at the highest LAT energies.³ And recently they've been seen to correspond to features of the microwave sky recorded by the orbiting *Planck* telescope.⁴

Aspects of the LAT data indicate a unique origin for the Fermi bubbles. Their energy spectrum is flatter (less steeply decreasing with increasing energy) than most diffuse emission in the Milky Way. So the Fermi bubbles stand out at energies above 10 GeV, as one can see by comparing figures 2a and 2b. That implies an origin different from the usual cosmic-ray interactions that dominate the Milky Way emission.

Furthermore, the bubble edges are relatively sharp, transitioning over less than 10° on the sky,

which suggests an origin in a particular event rather than a long-term diffusion process. One possibility is that the Milky Way may once have had activity at its nucleus like that of an active galaxy, including particle-accelerating jets powered by accretion of matter onto the black hole at the center of the galaxy. So the bubble features may well have been created within the past few million years.

Long-term observation of sources

The most recently published LAT catalog includes 1873 sources.⁵ (That's seven times as many as were included in the final EGRET catalog.) The two largest source classes are active galactic nuclei (AGNs) and pulsars within our own galaxy. Of particular interest is the fact that nearly one-third of the cataloged gamma-ray sources have no obvious counterparts at other wavelengths. Are they all simply sources from which the longer-wavelength emission has not been recognized? Or is there some really new type of gamma-ray source? That's an ongoing study involving both multiwavelength observations and theoretical modeling.

Thus far, the identified classes of gamma-ray sources in our galaxy are associated in some way with endpoints of stellar evolution: supernova remnants, white dwarf stars, neutron stars, and black holes. The energetic shock fronts and strong magnetic fields around such collapsed objects have the extreme conditions needed for particle acceleration and gamma-ray production.

A century after Victor Hess's discovery of cosmic rays (see the article by Per Carlson in *PHYSICS TODAY*, February 2012, page 30), supernova remnants (SNRs)—the expanding shells of gas, dust, and shocked plasma left behind by supernovae—remain the prime suspects for their acceleration sites. But the case is not yet closed.

Gamma rays with energies above a TeV (10^{12} electron volts) are largely invisible to *Fermi*. But observations by ground-based telescopes such as HESS, MAGIC, and VERITAS, which record Cherenkov radiation from TeV gamma rays in the atmosphere, leave little doubt that SNRs can accelerate electrons to very high energies. The *Fermi* LAT results provide strong indications that the cosmic-ray protons also come from SNRs.

The brightest SNRs in GeV gamma rays are not the youngest ones such as the 300-year-old Casiopeia A, but rather much older SNRs that produce gamma rays in profusion by feeding cosmic rays to dense nearby clouds of interstellar matter. Radio, x-ray, and TeV-gamma observations of SNRs, considered in the context of the LAT results, suggest that most intragalactic cosmic-ray protons are produced by diffusive shock acceleration in multiple crossings of moving SNR shock fronts (see *PHYSICS TODAY*, January 2010, page 13).

Pulsars

Appearing as highly regular pulsed point sources, pulsars are spinning, city-sized neutron stars left

behind by supernovae. They are ultrastrong magnetic dipoles with surface fields ranging from 10^8 to more than 10^{13} gauss, rotating about an axis not aligned with the dipole. Pulsar periods, given by the neutron star's spin rate, range from milliseconds to seconds.

To a distant observer, the misalignment looks like a blinking lighthouse. And locally, it produces dynamo action. In certain regions of pulsar magnetospheres, huge induced electric fields directly accelerate electrons and other charged particles to very high energies, and those particles radiate across much of the electromagnetic spectrum. The *Fermi* LAT results for more than 100 gamma-ray pulsars show that the particle acceleration leading to gamma radiation does not take place near the neutron star's surface, where the fields are strongest.⁶ Rather, the acceleration occurs in the outer magnetosphere, close to the limiting distance at which the

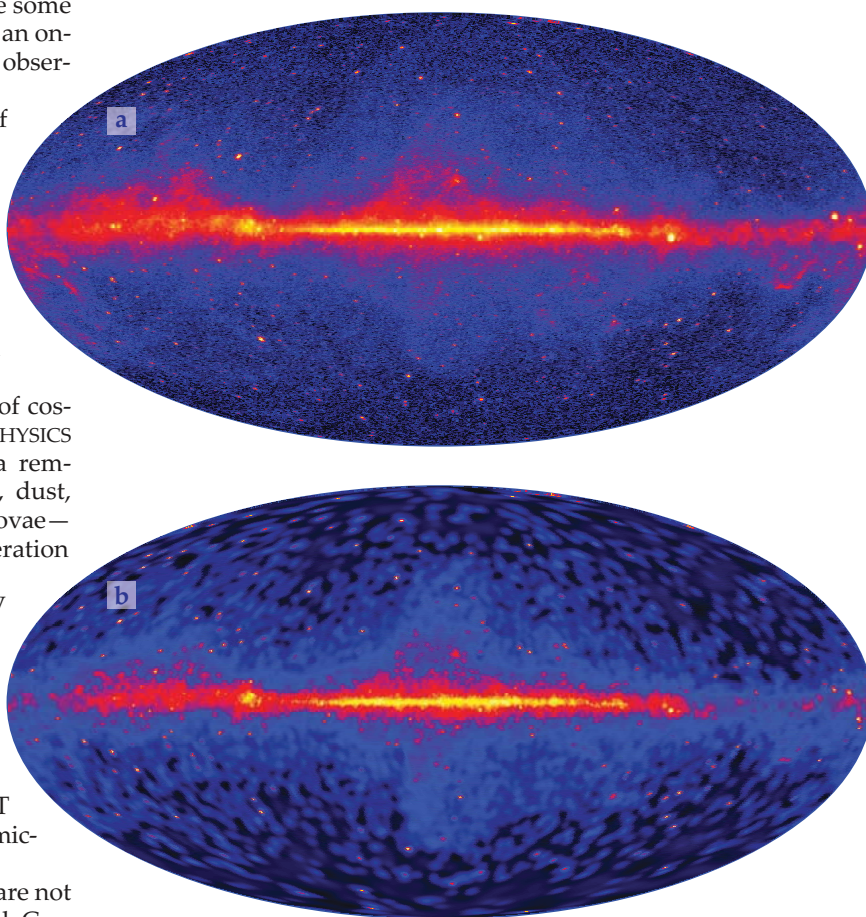
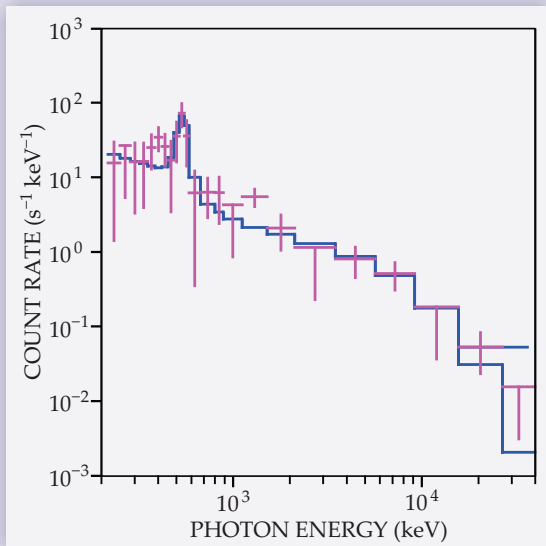


Figure 2. Brightness of the gamma-ray sky mapped over four years by the *Fermi* orbiter's Large Area Telescope for all photon energies (**a**) above 1 GeV and (**b**) above 10 GeV. The maps are in galactic coordinates. The bright equatorial strip is the Milky Way's disk seen edge on, centered on the galactic center. The pointlike sources at high galactic latitudes are mostly active galaxies beyond ours, while bright points nearer the galactic equator are mostly associated with pulsars and supernova remnants in the Milky Way. The diffuse "Fermi bubbles" more prominent in panel b create the pale dumbbell-shaped feature that extends about 50° north and south from the vicinity of the galactic center. They may result from a relatively recent episode of unusual activity near the Milky Way's central black hole. (Figure courtesy of the *Fermi* LAT collaboration.)

Figure 3. A terrestrial gamma-ray flash recorded by *Fermi*'s Gamma-Ray Burst Monitor on 13 August 2009. The spectrum exhibits the 511-keV annihilation line resulting from positrons interacting with the material of the satellite. The blue curve is a model fit that takes account of the burst monitor's instrumental resolution. (Adapted from ref. 7.)



magnetic field co-rotates with the star at the speed of light.

More than 30 gamma-ray pulsars have been discovered by periodicity searches of the accumulated LAT data. They provide an entirely new window on neutron stars. The absence of radio counterparts for most of them implies that the gamma-ray beams are very broad. That suggests that they represent a relatively unbiased sample of rotating neutron stars within 3000 light-years of Earth.

Radio astronomers searching for counterparts of otherwise unidentified LAT sources have discovered more than 40 new millisecond pulsars not in globular clusters of stars. That harvest compares favorably with the 70 previously known. Though it seems counterintuitive, the pulsars with the highest spin rates are the oldest. They were spun up over long times by binary partners; that's why they're called recycled pulsars. The surface magnetic fields of those millisecond oldsters are several orders of magnitude smaller than those of young pulsars like the thousand-year-old one in the Crab SNR. But they all produce gamma rays in a similar fashion.

Beyond the intrinsic interest in how millisecond pulsars work, there's also a practical interest in aid of other disciplines. Radio astronomers have been eager to find more fast pulsars because of their accurate timing properties. An array of well-timed millisecond pulsars can in principle be used to detect the predicted stochastic background of gravitational waves in the galaxy.

Time-domain gamma-ray astronomy

Fermi's scanning mode, coupled with the instruments' ability to measure gamma-ray arrival times,

makes possible variability studies of gamma-ray sources over time scales from microseconds to multiple years. Blazars and other AGNs are prime examples of sources with variability measured down to *Fermi*'s orbital time scale.

Although the Milky Way dominates the gamma-ray sky, it does so primarily because it's our neighborhood. The brightest extragalactic gamma-ray sources are AGNs, galaxies with cores that are much more luminous than our own over a broad range of photon energies. AGNs are thought to be powered by active accretion of matter onto their central supermassive black holes. Many AGNs produce powerful jets of photons and particles with ultrarelativistic bulk velocities that serve as strong, highly variable sources of collimated gamma rays. The largest single class of sources seen by the LAT is blazars, AGNs for which the relativistic jets happen to be beamed within a few degrees of our direction.

Because the jet emission is seen across the electromagnetic spectrum, study of AGNs is most productively a multiwavelength endeavor. *Fermi*'s continuous monitoring of the entire sky allows the variability studies to be correlated with observations at other wavelengths, often involving a multitude of telescopes. The results, including rapid flaring seen on time scales of hours as well as evolution extending over years, show that blazars exhibit significant diversity.

The detection of "orphan" blazar flares in the optical, x-ray, GeV, or TeV bands—without counterparts in other wavelength bands—demonstrates that those jets are not homogeneous flows. So does the frequent absence of broadband correlated variability in non-orphan blazar flares. In some cases, multiwavelength observations suggest that the jet must contain an ordered magnetic field that maintains its structure over long distances. The observations also suggest that the particle acceleration involves multiple processes, including simple shock and turbulent-plasma acceleration, and possibly magnetic field-line reconnections that convert stored magnetic-field energy into strong electric fields and hence kinetic energy of charged particles.

Local surprises

In March 2010 a previously unknown bright gamma-ray source appeared in the constellation Cygnus and then faded away about two weeks later. A comparison with optical and x-ray observations showed that the new source was something unexpected: a gamma-ray nova. Labeled V407 Cygni, it manifests an unusual stellar system called a symbiotic binary, with a red giant star and a white dwarf bound in close orbit.

When enough material shed by the red giant falls onto the white dwarf, it triggers a thermonuclear conflagration that produces a bright optical outburst—a nova. Such novae were not expected to be capable of accelerating particles to the energies required for producing gamma rays. But in V407 Cygni, the blast apparently generated a shock wave that accelerated material to such energies. Because novae are more numerous than the

far more powerful supernovae, the discovery that at least one nova is a particle accelerator suggests another class of cosmic-ray sources in the galaxy.

As an energetic young pulsar spins down, most of its lost energy is carried away in a magnetized particle wind. That wind expands into the surrounding medium, decelerating as it sweeps up ejecta from the supernova that gave it birth and forming a so-called termination shock front. Pulsar-wind nebulae like the Crab SNR contain particles accelerated by their pulsars as well as particles accelerated in their termination shocks. In the latter case, the acceleration has generally been thought to be second-order Fermi acceleration—particles accumulating kinetic energy in a turbulent plasma by scattering from colliding regions of magnetized plasma.

Fermi's GBM and LAT have both seen surprising behavior from the Crab nebula, which had long been considered a steady calibration source because the Crab pulsar appeared to pump energy into the nebula at an essentially constant rate. But the GBM and other x-ray telescopes found a steady decline in the Crab's hard-x-ray flux on a time scale of years. And recently the LAT (along with the small Italian gamma-ray telescope *AGILE*) has detected intense gamma-ray flares exhibiting variability on time scales of hours (see *PHYSICS TODAY*, March 2011, page 12). Those flares are strongly peaked at photon energies just below 1 GeV. Their rapid variability argues against Fermi acceleration. Instead, it suggests the alternative mechanism of magnetic reconnection, with some of the charged particles being accelerated to PeV (10^{15} eV) energies.

Nearer to home, the Sun, when it flares, can briefly become by far the brightest gamma-ray source in the sky. The particles responsible for a solar flare are probably accelerated by magnetic reconnection. In addition to producing distinct gamma-ray spectral lines by creating nuclear excitations, accelerated particles also interact with the ambient solar medium by bremsstrahlung and pion production to generate gamma rays over a broad range of energies. A solar flare on 7 March of this year produced gamma rays with energies up to 4 GeV. It was detectable with the LAT for more than 20 hours. *Fermi* was able, for the first time, to localize the gamma-ray emission to a specific active region on the Sun's disk where, presumably, the instigating particle acceleration was occurring.

Gamma-ray bursts

Visible over large intergalactic distances, gamma-ray bursts (GRBs) are thought to result from cataclysmic stellar events such as the collapse of a massive star or the merger of two compact objects—neutron stars or black holes. The outbursts, often described as the most powerful explosions since the Big Bang, last from a fraction of a second to minutes. But their afterglows at lower photon energies last much longer. Sensitive high-energy observations with the LAT and GBM have made possible detailed studies of the temporal and spectral behavior of GRBs over seven decades of photon energy.

Such studies provide insight into GRB emission mechanisms. A remarkable finding by *Fermi* is the discovery of systematic behaviors that provide vital clues to the underlying physics. The emission of photons with energies above 100 MeV starts after the onset of the keV-to-MeV burst, and the higher-energy burst lasts longer, decaying with a scale-free power-law dependence on time. This observation implies that the gamma radiation has at least two distinct components.

In some bursts, additional thermal and nonthermal components are also seen in the prompt emission spectra, revealing more complexity in those GRBs. *Fermi* observations of unusually energetic GRBs and follow-up observations at longer wavelengths reveal ultrarelativistic bulk-matter ejections. The total energy release implied by such observations is too high for conventional GRB models. Perhaps there's a separate class of hyperenergetic GRBs created by different mechanisms.

One particularly interesting GRB has yielded the most stringent constraint to date on quantum theories of gravity that predict violations of Lorentz invariance. Using sharp temporal features in GRB emission, one might be able to detect tiny energy-dependent variations in the speeds of photons traveling over cosmological distances. Observing a high-redshift, short-burst GRB on 10 May 2009, *Fermi* recorded that the gamma-ray photons, with energies from 8 keV to 31 GeV, arrived within one second of each other after the 7-billion-year journey implied by the GRB's redshift ($z = 0.903$). For the quantum-gravity theories, that null result translates into a lower limit of 1.4×10^{19} GeV (1.2 Planck masses) on the energy scale of photon velocity variation.

Cosmological GRBs have modest mimics in our own atmosphere. Though *Fermi's* principal goals are studies of gamma rays from far away, one intriguing finding involves terrestrial gamma-ray flashes

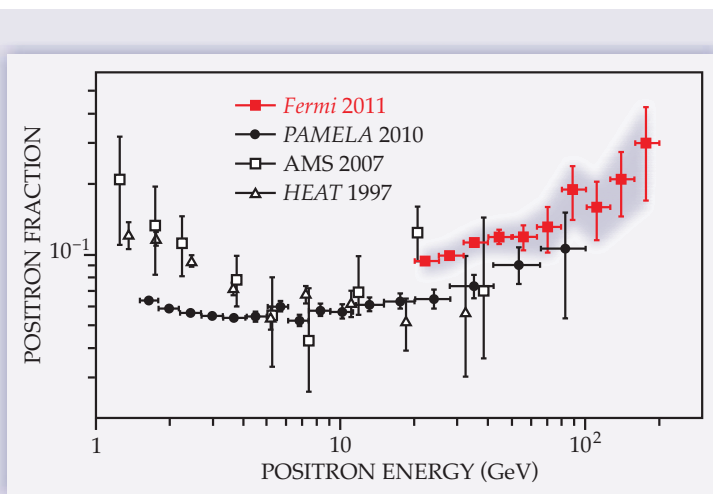
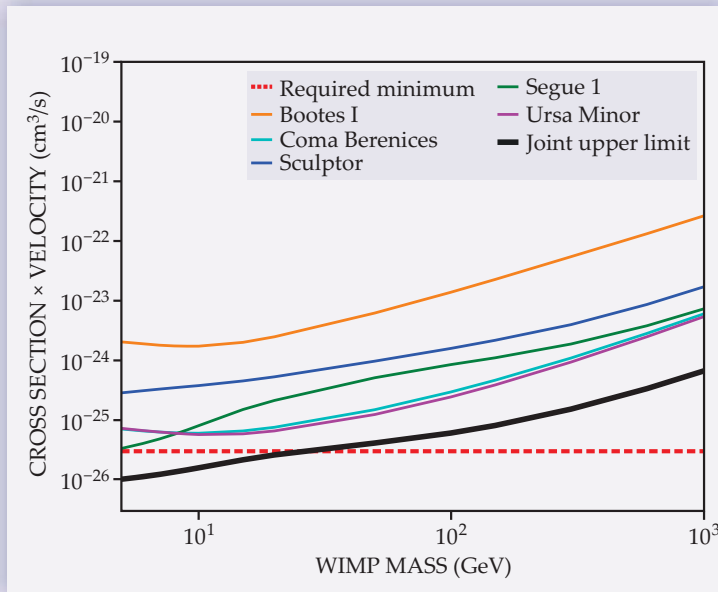


Figure 4. Fraction of the cosmic-ray flux of electrons and positrons attributable to the much rarer positrons, as measured by *Fermi* and earlier orbiters. The *Fermi* data confirm and extend the surprising rise of the positron fraction with increasing energy first reported by the *PAMELA* team. (Adapted from ref. 8.)

Figure 5. Upper limits (at 95% confidence) on the product of annihilation cross section and mean collision velocity for WIMPs, as yet undiscovered weakly interacting massive particles thought to be responsible for most of the dark matter in the cosmos. The joint limit as a function of WIMP mass comes from null results of *Fermi* gamma-ray observations of 10 nearby dwarf galaxies. Colored curves show individual upper limits from five of them. The red line at $3 \times 10^{-26} \text{ cm}^3/\text{s}$ represents the minimum required if WIMPs are to account for the presumed mean density of nonbaryonic dark matter in the cosmos. (Adapted from ref. 9.)



(TGFs)—radiation associated with thunderstorms. First seen by the *Compton* orbiter and more recently studied by *AGILE* and NASA's *RHESSI* satellite, TGFs are attributed to runaway electromagnetic cascades produced by particles accelerated in the strong electric fields of thunderstorms (see *PHYSICS TODAY*, January 2011, page 16). In addition to millisecond bursts of gamma rays with energies up to 100 MeV, the atmospheric cascades generate electrons and positrons. Trapped on geomagnetic field lines, the positrons can annihilate with *Fermi*'s material to produce characteristic 511-keV annihilation gamma rays. The annihilation peak is seen in figure 3, which shows the spectrum recorded⁷ by the GBM during a TGF on 13 August 2009.

Fermi as a particle detector

Though designed primarily to detect gamma-ray photons, the LAT is inherently a charged-particle detector. Judicious event selection has produced important results about cosmic-ray electrons and positrons. Measurements of electrons with energies from GeV to TeV by the LAT—with far greater counting statistics than obtained by previous instruments—have established that the spectrum is flatter than expected by conventional models of cosmic-ray diffusion in the Milky Way. And those data have set stringent limits on the anisotropy of galactic cosmic-ray electrons. The flatter spectrum suggests a source in our local corner of the Milky Way.

Although *Fermi* doesn't carry a magnet that can

distinguish a rare cosmic-ray positron from an electron by the sign of its curvature, one can exploit the geomagnetic field to that end. Thus *Fermi* has been able to measure the small positron fraction of the cosmic-ray flux above the atmosphere at energies beyond those accessible to earlier missions.⁸

The results, plotted in figure 4, confirm and extend results from the *PAMELA* satellite that showed a surprising rise in the ratio of positrons to electrons with increasing energy above about 10 GeV. That rise contradicts expectations from models that take all local positrons to be secondary products of cosmic-ray interactions in interstellar space. It suggests the presence of one or more nearby pulsars generating high-energy electrons and positrons.

The search for dark matter

For more than half a century, astronomers have known from the clustering and rotation of galaxies that a significant fraction of the gravitating mass in the universe is invisible. The evidence for a dominant nonbaryonic component (without protons or neutrons) of dark matter on cosmic scales is compelling.

It's not known what the nonbaryonic dark-matter particles are, but a great variety of cosmological and astrophysical observations constrain many of their properties. Favored candidates nowadays are weakly interacting massive particles (WIMPs), perhaps 100 times as heavy as the proton, predicted by extensions of the standard model of particle physics. WIMPs are presumed to be their own antiparticles and therefore capable of mutual annihilation.

But no such particles have as yet been discovered in satellite searches for WIMP-annihilation gamma rays, direct searches for WIMPs interacting in ultrasensitive underground detectors, or accelerator experiments that might actually produce WIMPs in collisions between high-energy beam particles. The three-pronged WIMP search is deemed to be essential for discovery and elucidation.

In the satellite search for dark matter, what the LAT does *not* see is important. The most stringent upper limits thus far on the interaction cross section and flux of WIMPs come from the observation of dwarf spheroidal galaxies, satellites of the Milky Way that are known to have little ongoing star formation and much dark matter.

Surveillance of a number of such dwarf galaxies by the LAT has thus far revealed no clear signal of WIMP annihilation. With plausible models and assumptions, the LAT null results yield upper limits on the product of the annihilation cross section and some characteristic collision velocity.⁹ Those upper limits are shown in figure 5 as a function of putative WIMP mass. (The cross sections in the figure consider only readily detectable annihilation channels involving the creation of b-quark pairs.) For reference, the horizontal line at $3 \times 10^{-26} \text{ cm}^3/\text{s}$ roughly indicates the minimum value required if WIMPs alone are to account for the generally accepted nonbaryonic mass density of the cosmos. That requirement already seems to exclude a WIMP mass lower than about 20 GeV.

Fermi is less than halfway through its nominal 10-year mission. Its orbit is stable, the detectors have no consumables that restrict their useful lives, and none of the instrumentation on board has yet shown any significant degradation. Because the gamma-ray sky is dynamic on so many time scales, new results and surprises are virtually assured.

Because the LAT's integrated sensitivity above 10 GeV is limited by the accumulating number of arriving high-energy photons rather than by the diffuse background, it grows almost linearly with time at the upper end of its energy range. That growing sensitivity will be particularly important in ongoing searches for signs of dark matter.

The top of its energy range is also where the LAT has its best angular resolution. That excellent resolution promises more detailed mapping of sources such as SNRs in the future. The GBM is shifting to a new data-taking mode that will time-tag each individual gamma-ray photon recorded by the burst monitor. The new mode should yield improved studies of transient phenomena like the terrestrial gamma-ray flashes.

All of *Fermi*'s gamma-ray data are released to the scientific community immediately, along with analysis software and documentation, all coordinated with the instrument teams by the *Fermi* Science Support Center¹⁰ at NASA's Goddard Space Flight Center. A guest-investigator program provides both funding and telescope time at multiwavelength resources such as the Arecibo radio telescope, National Radio Astronomy Observatory, the National Optical Astronomy Observatory, the *Suzaku* x-ray telescope, and the VERITAS TeV telescope.

A key lesson from the past decade has been the value of coordinated observations. With new facilities coming on line for the observation of celestial neutrinos and gravitational waves as well as photons, *Fermi* will continue to play an essential role in the exploration of the high-energy universe.

This article was written in cooperation with Julie McEnery, the Fermi project scientist. We thank the project staff, the instrument teams, and the broader user community for continuing efforts to produce scientific results such as those described here.

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