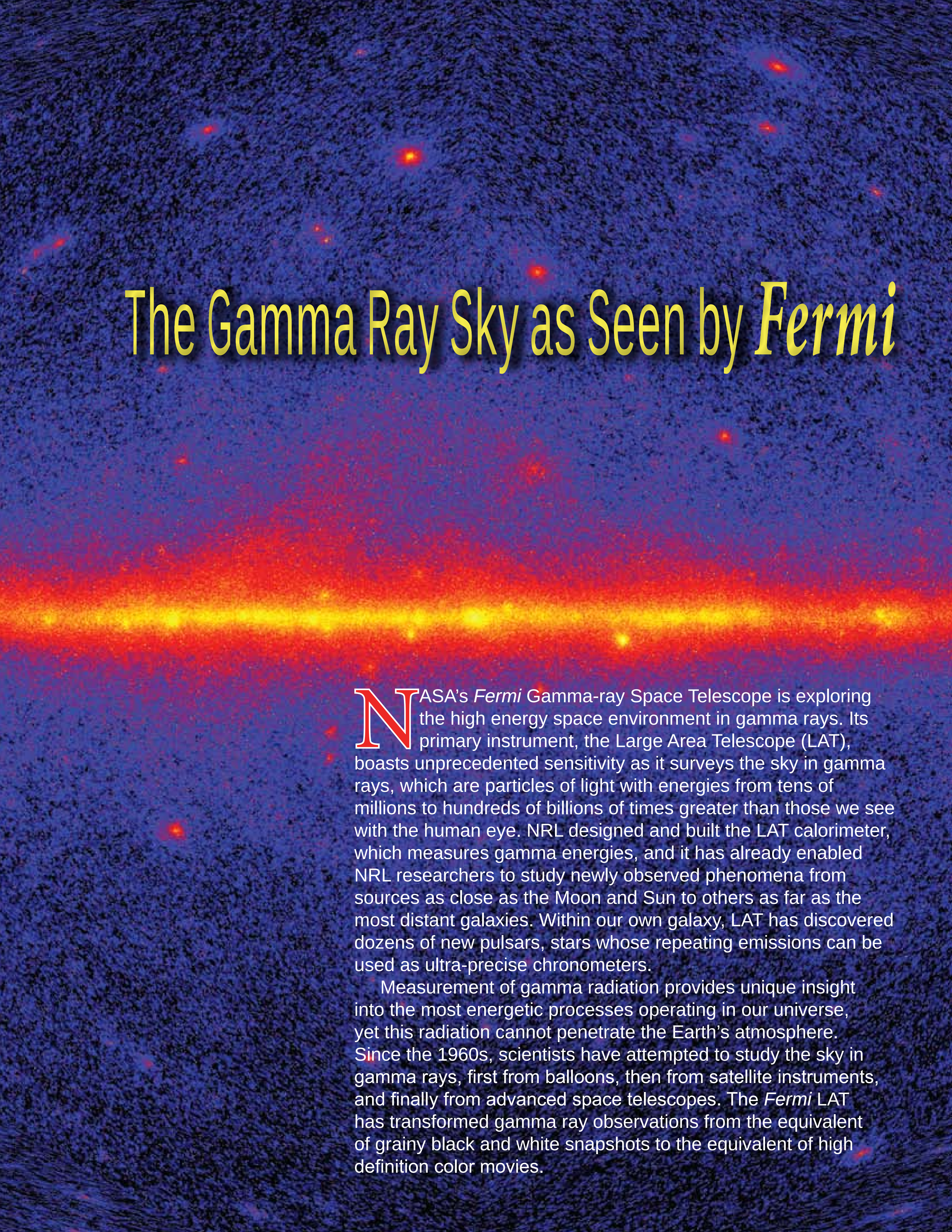
The Gamma Ray Sky as Seen by *Fermi*



NASA's *Fermi* Gamma-ray Space Telescope is exploring the high energy space environment in gamma rays. Its primary instrument, the Large Area Telescope (LAT), boasts unprecedented sensitivity as it surveys the sky in gamma rays, which are particles of light with energies from tens of millions to hundreds of billions of times greater than those we see with the human eye. NRL designed and built the LAT calorimeter, which measures gamma energies, and it has already enabled NRL researchers to study newly observed phenomena from sources as close as the Moon and Sun to others as far as the most distant galaxies. Within our own galaxy, LAT has discovered dozens of new pulsars, stars whose repeating emissions can be used as ultra-precise chronometers.

Measurement of gamma radiation provides unique insight into the most energetic processes operating in our universe, yet this radiation cannot penetrate the Earth's atmosphere. Since the 1960s, scientists have attempted to study the sky in gamma rays, first from balloons, then from satellite instruments, and finally from advanced space telescopes. The *Fermi* LAT has transformed gamma ray observations from the equivalent of grainy black and white snapshots to the equivalent of high definition color movies.

Opening a New Window on the High Energy Space Environment

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The *Fermi* Gamma-ray Space Telescope, NASA's newest observatory, has begun its mission of exploring the high-energy space environment in gamma rays. Successfully launched from Florida on June 11, 2008, the spacecraft and its instruments passed their orbital checkout and commissioning with flying colors. *Fermi*'s primary instrument, the Large Area Telescope (LAT), is now surveying the gamma-ray sky at energies from tens of millions to hundreds of billions of times greater than those we see with our eyes. With its unprecedented sensitivity and sky-survey viewing, the LAT is revolutionizing our understanding of the near-Earth environment and distant universe in energetic gamma rays, the most penetrating type of electromagnetic radiation. NRL scientists designed and built the LAT calorimeter, which measures the energies of the gamma rays, and led the commissioning of the LAT on orbit. NRL also provided facilities and technical support for the environmental testing of the instrument and observatory.

WHY OBSERVE IN GAMMA RAYS?

For the last 400 years, astronomers have observed the sky using the latest technology to understand the fundamental processes that drive the Sun, the solar system, and the distant stars and galaxies. Observations from radio waves through X-rays have shown that the bulk of the emission from the Sun and stars is thermal radiation, but they have also revealed unexpected non-thermal processes associated with highly relativistic particles. Well above the thermal regime, gamma-ray observations are a direct probe of radiations from the most energetic, non-thermal processes operating throughout the universe — in our Sun, around highly magnetized neutron stars, in jets from black holes and exploding stars in our Milky Way galaxy, and in jets from distant galaxies.

Glimpses of the sky in gamma rays have come from pioneering balloon flights and the OSO-3 spacecraft in the 1960s, from SAS-2 and COS-B in the 1970s, and the EGRET telescope on the *Compton* Gamma Ray Observatory in the 1990s. In mapping the full sky, EGRET expanded the list of gamma-ray sources to a few hundred objects. However, because of the limited sensitivity and long exposures required to make those maps, we have only modest snapshots of the non-thermal engines that drive these objects. Now the technology is in place with the *Fermi* Large Area Telescope (LAT) to take what amounts to color movies of the most violent and extreme environments in the universe.

We can find an example of energetic, gamma-ray-producing processes close to home, in solar flares. Solar flares are explosions that occur in the atmosphere of the Sun, emitting radiation over the full range of the electromagnetic spectrum, from radio to gamma rays. The energy released in a solar flare in a few tens of seconds can be greater than 10^{32} ergs, enough to meet the energy demand of the United States for 100,000 years. At the Earth, the phenomena can disrupt radio communication, damage satellites and destabilize their orbits, cause failures in long-distance power lines, change the terrestrial magnetic field, and even endanger astronauts. The potential impact of such solar activity on DoD assets and enterprises is clear.

High-energy gamma-ray observations of solar flares will open a new, unexplored energy domain for flare science, possibly revealing new processes associated with ion acceleration, transport, and interaction in flares. It will certainly provide critical additional tests and constraints on our understanding of the flare process.

THE *FERMI* GAMMA-RAY SPACE TELESCOPE

Gamma rays are the most energetic and most penetrating type of electromagnetic radiation and have no trouble crossing the billions of light-years through most of the visible universe or passing through dust lanes and gas clouds that block X-rays and most lower-energy radiations from reaching us. Nevertheless, they cannot penetrate the dense atmosphere of our Earth. To see them, we have to launch specialized telescopes into space.

The *Fermi* Gamma-ray Space Telescope, known before launch as GLAST, the Gamma-ray Large Area Space Telescope, carries two scientific instruments covering more than a factor of 10 million in energy across the electromagnetic spectrum. It is the first gamma-ray observatory to survey the entire sky every day, and the first with high sensitivity. As such, it provides a unique opportunity to study the ever-changing universe at extreme energies. Figure 1 shows the *Fermi* telescope being prepared for launch, and Fig. 2 shows the June 11, 2008, launch of the Delta II rocket that bore the *Fermi* telescope.[1]

The primary instrument on *Fermi*, the Large Area Telescope, is a state-of-the-art, wide-field-of-view imaging spectrometer for high-energy gamma rays from approximately 20 million electron volts (MeV) to greater than 300 billion electron volts (GeV), to use the conventional units of energy in this regime. (For comparison, photons of visible light have energies of a few eV.) The LAT will collect more than 100 times the number of gamma rays of the previous-generation instrument, the *Compton* EGRET, more than 30 million every year. Its field of view (FOV) covers approximately 20 percent of the sky at a time — roughly the same as the human eye — and it surveys the entire sky approximately every 3 hours. This capability is extremely important, as one of the primary conclusions from EGRET was that the gamma-ray sky is extraordinarily variable. Every week, the LAT achieves the same source sensitivity that EGRET reached only after its entire nine-year lifetime.

The 3000-kg LAT was designed and manufactured by an international collaboration under the leadership of Stanford University. The Stanford Linear Accelerator Center (SLAC) managed the overall program and integrated the substantial hardware contributions from institutions in France, Italy, Japan, Sweden, and the United States.[2]

HOW THE INSTRUMENT WORKS

Far too energetic to be focused or captured using conventional optics, gamma rays require technology adapted from ground-based particle accelerator experiments and medical imaging systems. A high-energy gamma ray interacts with matter by converting some of its energy directly into a matter and anti-matter pair of charged particles, an electron and a positron. The remainder of the energy of the gamma ray becomes the kinetic energy of the electron-positron pair and carries the pair forward in the direction of the gamma ray at ultra-relativistic speeds. By tracking the electron-positron pair, we can therefore measure the direction of the incoming gamma ray. As the pair passes through more material, it multiplies and cascades into a family of charged particles and photons in an "electromagnetic shower," depositing its energy in a well-understood profile. By measuring the profile of energy deposition, we can measure the energy of the original gamma

FIGURE 1
The first half of the payload fairing is moved into place around the *Fermi* observatory as the vehicle is prepared for launch. (Credit: NASA – Jim Grossmann.)

FIGURE 2
Fermi Gamma-ray Space Telescope launches from the Cape Canaveral Air Force Station aboard a Delta II Heavy rocket on June 11, 2008. (Credit: United Launch Alliance – Carleton Bailie.)

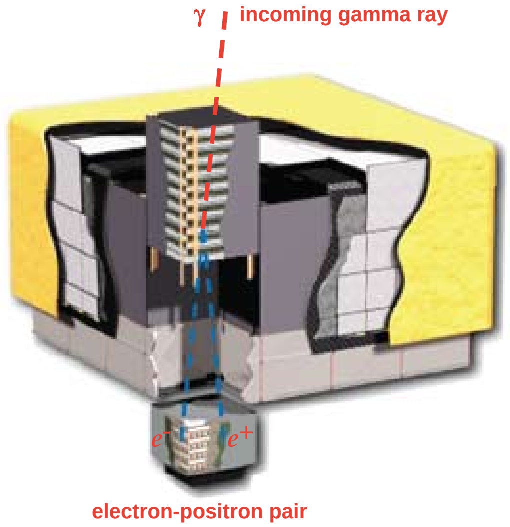

FIGURE 3
Artist's rendering of a gamma ray converting into an electron-positron pair within the Large Area Telescope tracker. Precise measurement of the direction of the pair in the tracker gives the direction of the incoming gamma ray. The pair propagates into the calorimeter and cascades in an electromagnetic shower (not shown) that deposits the energy of the gamma ray into the calorimeter. The tracker and calorimeter are modular assemblies of 16 identical towers.

ray. Celestial gamma ray sources are, unfortunately, not particularly bright objects, and their emissions are dwarfed by high fluxes of charged particles in low Earth orbit. Therefore, a gamma ray telescope must be extremely efficient at identifying and rejecting this charged-particle background.

Following on these concepts, the LAT (see Fig. 3) consists of three detector subsystems — a tracker to convert the gamma ray and image the electron-positron pair, a calorimeter to measure the energy and profile of the electromagnetic shower, and a covering anti-coincidence detector to help identify background charged particles. The tracker contains multiple layers of thin tungsten foil converters and silicon strip detectors to track the electron and positron. The calorimeter, which was developed and assembled at NRL, consists of multiple layers of scintillating cesium iodide crystals, which are dense enough to develop and contain most of the electromagnetic shower.

The shower of particles through the cesium iodide produces flashes of scintillation light proportional to the energy deposited in the crystals. This scintillation light is then converted by photodiodes bonded to each crystal into electrical signals that are digitized and recorded on board. The cesium iodide bars are arranged in two orthogonal directions (see Fig. 4) to image the development of the shower within the calorimeter — improving the energy measurement — and to help reject background particles, since their pattern of energy deposition is different from that of gamma rays.

The accuracy of the energy measurement is largely determined by the ability of the calorimeter to collect all the energy from the cascade of particles in the electromagnetic shower. The penetrating nature of these particles means that a massive detector is required to stop or capture them. The LAT calorimeter is assembled from more than 1500 thallium-doped cesium iodide, CsI(Tl), crystals totaling 1350 kg, about half of the weight of the entire LAT instrument.

Because the gamma-ray flux from celestial sources is small, gamma-ray telescopes must be very large: the square LAT "aperture" is 1.8 m on a side. Even in this large, state-of-the-art telescope, the brightest persistent celestial source registers only one photon every 4 minutes, and the total rate of celestial gamma rays in the LAT FOV is only about one per second! (Transient events such as solar flares and gamma ray bursts can, however, be orders of magnitude brighter.)

Digitized signals from the calorimeter, tracker, and anti-coincidence detector are processed by the LAT's three onboard computers. Conservative pattern-recognition algorithms developed from extensive

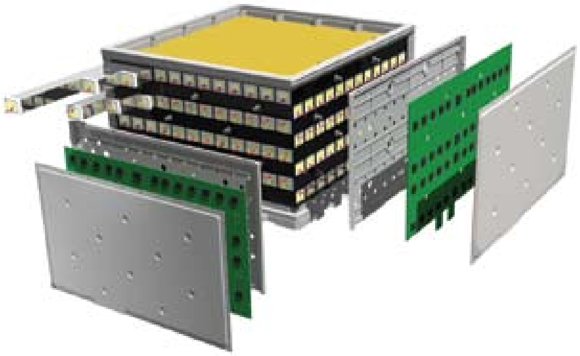

FIGURE 4
Exploded rendering of a calorimeter module containing an array of CsI(T1) scintillating crystals with electronic readout. The full calorimeter consists of 16 of these modules.

Monte Carlo simulations of gamma-ray and charged-particle interactions in the LAT then identify and reject approximately 90 percent of the background charged particles in the LAT data on board, reducing the bandwidth enough to allow the gamma ray data to be sent to the ground through the spacecraft's high-gain antenna. The remainder of background rejection is performed on the ground by much more sophisticated versions of those same algorithms.

NRL'S ROLE IN THE *FERMI* GLAST MISSION

The High Energy Space Environment Branch of NRL's Space Science Division (SSD) has played a leading role in the *Fermi* GLAST mission for more than 14 years, from when the early concepts for the LAT instrument were first designed and tested. The SSD led the team from U.S., French, and Swedish institutions in the design and manufacture of the LAT calorimeter. We assembled and tested the calorimeter hardware in the Spacecraft Engineering Department of the Naval Center for Space Technology (NCST) at NRL and completed delivery of the calorimeter detectors to the Stanford Linear Accelerator Center in May 2005, where they were subsequently integrated with other components into the LAT instrument.

In May 2006, the LAT instrument came to the NCST at NRL for environmental testing, subjecting it to dynamic, thermal, and vacuum environments exceeding those at launch and testing its electromagnetic emissions and susceptibility. The four-month test program was executed on schedule with great success. In August 2007, the LAT returned to NRL, now fully integrated into the *Fermi* GLAST observatory, for thermal-vacuum testing at the NCST.

After its successful launch in June 2008, the observatory underwent a 60-day on-orbit commissioning program and transitioned to normal science operations in early August 2008. A team of 14 NRL astrophysicists in the High Energy Space Environment Branch, including three NRC post-docs and a graduate student, are currently actively mining the LAT data.

EARLY SCIENTIFIC RESULTS

As a hint of the discoveries to come, here we show just a few of the early scientific results from the first three months of LAT operations.

The Gamma-ray Sky

Figure 5 shows an image of the full sky accumulated over the first three months of LAT science operations. Here the entire celestial sphere is shown split open and laid flat in an Aitoff projection, with the center of our Milky Way galaxy in the center of

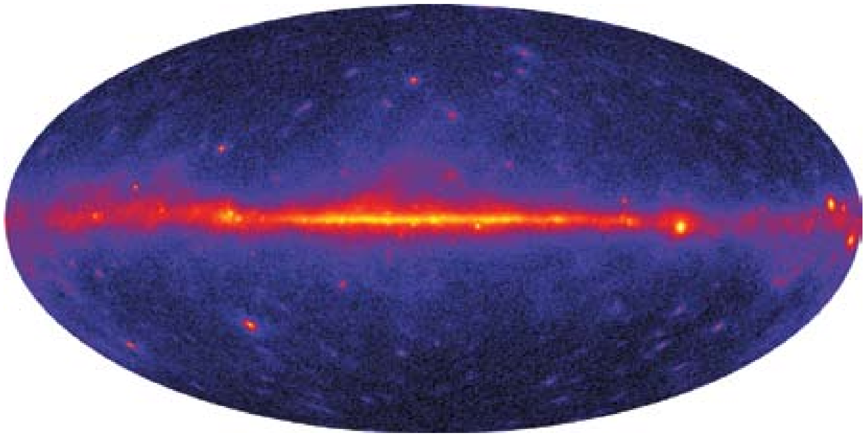

FIGURE 5
False-color image of the full sky in gamma rays created from three months of LAT data, shown as an Aitoff (equal-area) projection in galactic coordinates. The color indicates the intensity of the gamma-ray flux. The plane of our Milky Way galaxy is the bright horizontal band. Over 200 bright sources are detected in this image.

the image, and the galactic anti-center at the left-most and right-most edges of the projection. The bright band is the plane of our galaxy, which glows brightly in gamma rays as energetic cosmic ray charged particles collide with interstellar gas and dust. Shining out of that diffuse glow are a number of bright point sources, mostly gamma ray pulsars — rotating, magnetized neutron stars — as discussed below. The bright sources above and below the galactic plane are predominantly distant active galactic nuclei (AGN) called blazars, galaxies fueled by a central supermassive black hole and emitting a jet of relativistic particles that happens to point directly at us, along our line of sight.

This three-month image contains over 200 bright sources (sources detected at greater than 10σ significance) and hundreds more at lower statistical significance.[3] By comparison, in its nine-year lifetime, EGRET found fewer than 30 sources at this confidence level. Also faintly visible in the upper right quadrant is the track of the Sun. Although no major solar flares have occurred since the launch of *Fermi*, the LAT is able to detect persistent gamma-ray emission caused by cosmic rays striking the atmosphere of the Sun. Long-term studies of this quiescent emission will provide a unique diagnostic of the Sun's magnetic field.

Gamma-ray Bursts

The *Fermi* LAT has already made several important discoveries about gamma-ray bursts (GRBs), intense flashes of gamma-ray light observed about once per day from random locations on the sky. GRBs are thought to be produced when a black hole is formed from the collapse of a massive stellar core, or from the coalescence of compact objects such as neutron stars and white dwarfs. The GLAST Burst Monitor, the secondary instrument on *Fermi,* has already detected over 100 GRBs with energies ranging from several hundreds of keV to GeV energies and higher.

The most dramatic case is that of GRB 080916C, so named because it was the third GRB detected on September 16, 2008. In this instance, the 100 MeV to GeV radiation suddenly appeared about 5 seconds after the initial burst of radiation that triggered the Burst Monitor. Theorists are actively trying to understand the puzzle of the late-appearing GeV radiation, and whether it is related to a separate radiation component, possibly due to the acceleration of cosmic-ray protons following the more rapid, lower-energy signal formed by accelerated electrons.

Neutron Stars

Perhaps the most important early discoveries of Fermi have been from objects in our galaxy. The LAT has discovered 12 new pulsars that seem to be visible only in gamma rays and has detected gamma-ray pulses from at least 18 radio pulsars, including seven with rotational periods of only milliseconds.

A pulsar is a rapidly rotating and highly magnetized neutron star, the remnant core of a massive star that has gone supernova. Most of the 1800 known pulsars were discovered through their sharply pulsed radio emission, which is thought to be a narrow lighthouse beam originating from the star's magnetic poles. But this radio emission comprises only a few parts per million of the pulsar's total power output. For the half-dozen pulsars known prior to the *Fermi* mission to be gamma-ray emitters, those gamma rays, in contrast, carry more than 10 percent of the pulsar's power. The much larger population of LAT pulsars is now allowing us to see and understand the dynamo engine that powers these objects.

The supernova remnant CTA 1 has been known to astronomy since 1960 when it was discovered in a radio survey. Follow-up work in X-rays found the nebular remnant of the stellar explosion and a point source suggestive of a neutron star. It was logical to expect this point source to be a pulsar, but deep searches for pulsations in X-ray and radio were not successful. The LAT, however, quickly revealed the pulsar in data from the early checkout of the instrument. The age and energetics of this source are now understood, and it is recognized as a young pulsar and nebula similar in many ways to the Crab Pulsar and Nebula.[4] In one respect, however, CTA 1 is strikingly different: the pulses are seen in gamma rays alone, unlike the pulses of the Crab. The gamma-ray sensitivity provided by *Fermi* LAT is the only way this pulsar could have been found and understood. Eleven other pulsars previously unknown at other wavelengths have now been discovered by LAT.

Finally, the discovery of pulsed gamma rays from several radio pulsars with millisecond spin periods, previously suggested in just one such object by the EGRET instrument, is particularly intriguing. These stars spin so rapidly that the portion of the magnetosphere that co-rotates with the neutron star — the region where LAT data show the gamma rays originate — cannot be more than several stellar radii in size, or particles on those field lines would be forced to travel faster than the speed of light, in clear violation of Special Relativity. Deciphering the pattern of observed gamma rays will undoubtedly lead to new insight into the extreme environment surrounding these relativistic stars.

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[Sponsored by NASA]

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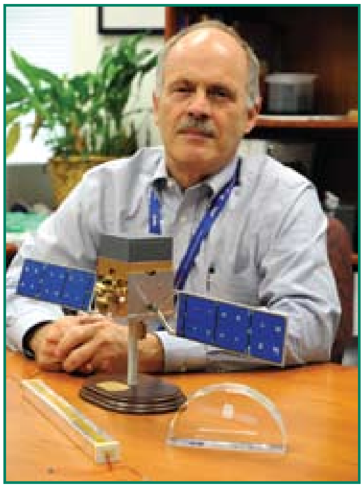

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