Fermi's excellent adventure

Since its launch in June 2008, the Fermi Gamma-ray Space Telescope has shed light on some of the brightest, most explosive events in the universe and opened tantalizing windows into dark matter and the nature of space-time. By Kelen Tuttle

Photo-illustration: Sandbox Studio

Three hundred and fifty miles overhead, the Fermi Gamma-ray Space Telescope silently glides through space. From this serene vantage point, the satellite's instruments watch the fiercest processes in the universe unfold. Pulsars spin up to 700 times a second, sweeping powerful beams of gamma-ray light through the cosmos. The hyperactive cores of distant galaxies spew bright jets of plasma. Far beyond, something mysterious explodes with unfathomable power, sending energy waves crashing through the universe.

This gamma-ray show is visible only from space, and Fermi, a joint mission of NASA, the US Department of Energy, and international partners, is the most advanced telescope ever to take it in. The satellite's main instrument, the Large Area Telescope, was assembled at SLAC National Accelerator Laboratory, and its advanced detectors owe much of their design to particle physics. As it orbits, slowly rocking side to side, it takes in a panoptic view of the sky every three hours, seeing gamma rays that have five million to more than 50 billion times more energy than visible light.

In its first year of operation the LAT captured more than 150 million gamma rays, 75 times more than its predecessor, EGRET, collected over a nine-year lifespan. It discovered a new class of pulsars and nabbed hundreds of blazars, revealing a variety of behaviors among these bright objects.

Meanwhile, a second instrument, the Gamma-ray Burst Monitor, has been measuring gamma rays that have lower energies, from 2000 to 10 million times those of visible light. It focuses on quick, erratic flashes called gamma-ray bursts and instantly notifies the LAT so it, too, can turn and look. It's been collecting these bursts at a rate of nearly one a day.

Together, the GBM and the LAT provide a powerful tool for studying the gamma-ray sky over a very large energy range—a range in which researchers previously had very limited data. By combining Fermi's observations with those made by other telescopes at other wavelengths, astrophysicists have a full view of the universe that may not only offer insight into astronomical objects like blazars, pulsars, and gamma-ray bursts, but also shed light on more enigmatic ideas, including dark matter and quantum gravity.

"Fermi has exceeded our expectations in terms of performance. It's performing close to perfection," says LAT Principal Investigator Peter Michelson of Stanford University. "In terms of discovery potential, we're just getting started, really. We've gotten some great first results, but there's a lot more for us to explore."

The blazar zoo

When Fermi looks past our Milky Way galaxy, its view is dominated by active galactic nuclei, compact regions in the centers of other galaxies where something—perhaps a black hole billions of times the mass of the sun—spits out a jet of plasma at nearly the speed of light. When these jets flare, they are among the brightest objects in the sky, emitting some of the highest gamma-ray energies ever detected. When these jets point toward Earth, they are called blazars.

Blazars are so bright and so prevalent that even before official observations began, Fermi identified several of them. In its first 12 months of operation, it detected about 500 sources likely to be associated with blazars, about 10 times the number discovered by EGRET.

Black hole-powered jet of electrons and other subatomic particles streams from the center of galaxy M87.
Image courtesy of NASA and the Hubble Heritage team (STScI/AURA)

These 500 likely blazars demonstrate what LAT researcher and Stanford Professor Roger Romani calls a "zoo of behavior." Some glow more than 10 times brighter than others. Some flicker like candle flames, while others hold relatively constant. And some emit polarized light, whose rays have an intrinsic extra "directionality" at right angles to the light's direction of travel. A blazar's complicated local environment seems to significantly affect how it looks—and, presumably, the details of how it works—so researchers don't yet agree on the basics of these beasts.

The more blazars the LAT records, the easier it will be to determine what makes one blazar different from the next.

"Fermi is challenging theoretical physicists to come up with models capable of producing what we observe," says astrophysicist Greg Madejski of the Kavli Institute for Particle Astrophysics and Cosmology at SLAC and Stanford.

But the LAT can't unravel the mystery of blazars on its own; it needs a whole fleet of telescopes operating in various wavelengths to get a comprehensive view. When a particularly interesting blazar lights up the sky, the collaboration sends an "Astronomer's Telegram"—nowadays, an e-mail—inviting colleagues at telescopes around the world to watch the flare in a variety of wavelengths, from radio through infrared, visible, ultraviolet, and X-ray light. Each wavelength is like a separate color, and combining them gives researchers the equivalent of a Technicolor picture of where and how a blazar creates its energetic jet.

"Because the LAT is an all-sky monitor, it can observe blazars continuously," says Gino Tosti, a researcher at the University of Perugia and INFN, the Istituto Nazionale di Fisica Nucleare in Italy. He is the co-coordinator of the active galactic nuclei group in the LAT collaboration. "This means we can study the characteristics of a large number of blazars to determine what makes them variable. But we can't do it on our own. We need multi-wavelength measurements to understand what's going on."

By combining these observations, researchers hope to infer what types of particles create blazar jets, what accelerates them to the necessary speeds, and where exactly that acceleration takes place.

"Most of us think we already know how active galactic nuclei work, but then again most of us don't agree with one another," says Roger Blandford, director of the Kavli Institute at SLAC and Stanford. "Fermi is helping us sort it all out."

Winking at Earth

Researchers don't have to look to other galaxies for gamma-ray sources; there are hundreds here in our own Milky Way.

When a collapsed star becomes so dense that a chunk the size of a sugar cube would have a mass of more than a billion tons, it's known as a neutron star. Some neutron stars have magnetic fields trillions of times stronger than Earth's, and those fields accelerate particles into fan-like beams of gamma rays. As the star spins up to 700 times per second, its beam sweeps through space like a search light and resembles a flashing strobe from Earth. These "pulsars" are one of our galaxy's chief sources of gamma rays.

Just four months after Fermi rocketed into space, the LAT collaboration announced its first major discovery: a pulsar that flashes only in gamma rays. Astronomers had discovered pulsars more than 40 years ago by detecting the radio waves they emit, and since then have observed more than 1000 of them that also beam energy in visible light, X-rays, and gamma rays. But never before had anyone discovered a radio-quiet pulsar in gamma rays.

In its first six months, the LAT collaboration observed 16 such gamma-ray-only pulsars. From this sample, researchers concluded that the gamma-ray beams from pulsars must be slightly wider than their beams of radio waves. Some pulsar beams pass over the Earth at such an angle that the wider gamma-ray part hits us, while the narrow radio-wave part misses.

Shortly after that discovery, the LAT collaboration also uncovered the first evidence that a special class of pulsars—"millisecond" pulsars that spin almost a thousand times a second—shines in gamma rays as well as in radio waves.

This gamma-ray view is beginning to reveal the fundamental physics behind pulsars. Much of this research, Romani says, focuses on how the pulsar's extreme electric and magnetic fields, coupled with its breakneck spin, accelerate particles to nearly the speed of light.

One such revelation came from the new gamma-ray-only pulsars. Researchers discovered that gamma rays are much more likely to arise far above the neutron star, within the star's magnetic field, than from close to the star's surface as previously theorized. For the brightest pulsar in the sky, the Vela pulsar, this emission is thought to occur about 300 miles above the surface of the star, which is only 12 miles across.

"The LAT has really helped us solidify the basic story," Romani says. "Now we need to figure out the science behind it."

One-a-day zingers

Although 99 percent of the point-like sources in the gamma-ray sky are blazars and pulsars, Fermi's instruments occasionally see an overwhelmingly bright flash: a gamma-ray burst, the universe's most luminous explosion. These explosions last between a few milliseconds and a few minutes, and never occur in the same place twice.

Before Fermi's launch, gamma-ray bursts were understood to come from two distinct processes. Bursts lasting less than a second or two might be created by catastrophic collisions of neutron stars. Longer ones, lasting up to several minutes, might be released when large stars explode and send out jets of material as they collapse into black holes. Yet a

This image merges the view through Swift's Ultraviolet/Optical Telescope, which shows bright stars, and its X-ray Telescope, which captures the burst (orange and yellow).
Image courtesy of NASA/Swift/Stefan Immler

thorough understanding of these bursts remains elusive.

With its wide field of view and a detector tuned to pick up gamma-ray-burst wavelengths, the GBM instrument is well-positioned to see these events, and indeed records nearly one a day. The fact that the GBM automatically tells the LAT about the burst and reorients the spacecraft so the LAT can view it is "really exciting and really new," says Valerie Connaughton, a research scientist at the University of Alabama in Huntsville and a member of the GBM team. "The space-craft can reorient in about 100 seconds, letting the LAT see extended emission from gamma-ray bursts."

The LAT chimed in on observations of nine gamma-ray bursts in its first year. Together, the two instruments have a very broad view of the gamma-ray-burst energy spectrum. As Blandford puts it, "The Gamma Ray Burst Monitor and the LAT are looking at something like three or four pianos worth of range, whereas our eyes can only see one octave." To extend this range even further, Fermi collaborates with other satellites to fill in even lower notes.

So far, the instruments have confirmed that the radiation from gamma-ray bursts is extremely high energy and travels very fast. Surprisingly, the LAT data shows little difference between short and long bursts, suggesting that they could come from the same type of astronomical process rather than different ones, as previous data implied.

"With Fermi's eyes, they look quite similar," Blandford says. "As we observe more gamma-ray bursts, I think that we'll start to see patterns and begin to understand them much better."

Is space-time quantumly foamy?

Fermi may also reveal important insights into the nature of space-time.

Some theorists postulate that at its smallest scale space-time is not smooth, but a turbulent, boiling froth of "quantum foam." In direct violation of Einstein's theory that all light travels at the same speed through space, some models of quantum gravity posit that the less energetic a gamma ray is, the faster it travels through the quantum foam.

A recent paper published by the GBM and LAT collaborations reported that low-energy gamma rays from one burst, known as GRB 090510, arrived at the telescope within nine-tenths of a second of the highest energy ray—which was a real whopper, a few billion times more energetic than visible light.

Some models of quantum gravity had predicted a much larger delay between gamma rays with such vastly different energies. The observation that the time delay is so small rules out those models. However, not too much can be read into the existence of some time delay. The inner workings of gamma-ray bursts could have processes that emit higher-energy gamma rays at different times or from slightly different locations, meaning that they arrive earlier or later than lower-energy gamma rays.

"From our measurements, we can't say for sure whether quantum gravity exists," says Fermi Project Scientist Julie McEnery of NASA's Goddard Space Flight Center. "But we have already been able to eliminate several particular models of quantum gravity in this way."

Stalking dark matter

Meanwhile, other Fermi observations may provide evidence for dark matter, the elusive stuff that makes up a quarter of the universe but has never been directly seen.

One possible way to do it is through cosmic rays, subatomic particles—mostly protons and electrons—that rocket through the universe with extreme energies. Cosmic rays are known to stream from the sun; but theorists also postulate that if two dark matter particles collide, they might annihilate one another, blip out of existence and leave a cosmic ray in their place. Theoretical models predict just how energetic those cosmic rays should be, and finding large numbers of them could constitute evidence for dark matter.

Other experiments, including a satellite called PAMELA and a detector called ATIC that floated above Antarctica under a huge balloon, have observed markedly more cosmic-ray electrons at certain energies than predicted by theorists. These electrons could have originated from dark matter particles crashing into one another or from a more mundane source, like a nearby pulsar. Data collected by the LAT show a much smaller excess of cosmic-ray electrons at these energies than other telescopes had reported, an excess possibly explained by nearby pulsars.

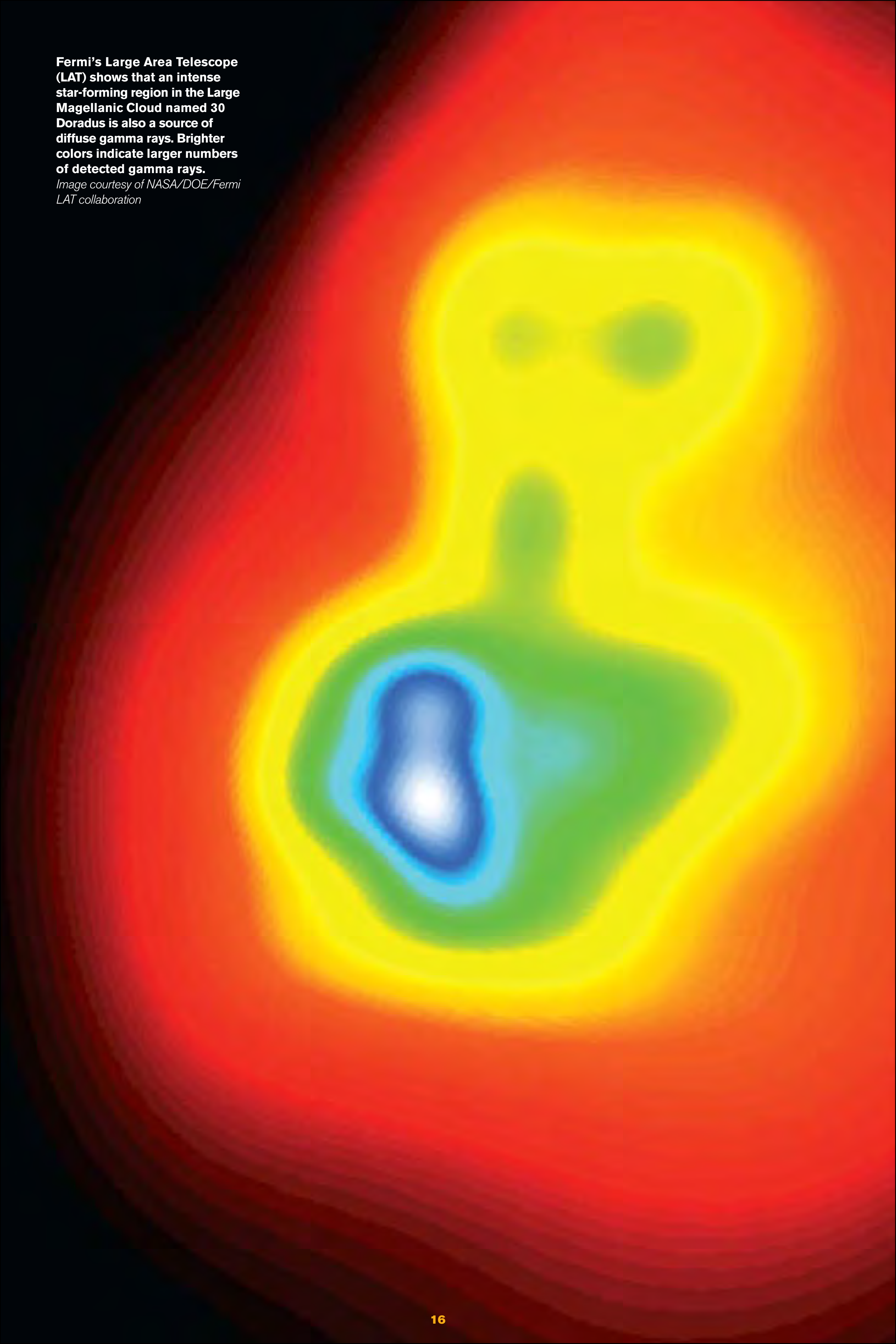
Similarly, EGRET reported finding an excess of gamma rays over most of the sky, including a bright halo surrounding the center of the Milky Way. Some researchers theorized that this excess was the byproduct of dark matter interactions; but the LAT has detected no such strong signal.

The hope of discovering dark matter is not lost, however. Over the coming years, Fermi researchers may be able to detect it in other ways.

One promising hunting ground is the core of the Milky Way, where theorists think the density of dark matter is greatest. If that is the case, Fermi should see an excess of gamma rays flowing from this direction. In fact, several groups of researchers outside the LAT collaboration, working with data that was publicly released after the instrument's first year of operation, have reported seeing such a signal.

However, Simona Murgia, an astrophysicist at the Kavli Institute who co-coordinates the LAT collaboration's dark matter and new physics group, says it's much too early to say if these reports are valid.

"This region of the sky is very complicated," she says. "It's a promising place to look for dark matter, but there's so much going on there that we really need to understand it better before we can make a solid dark-matter claim." The center of the galaxy is a boisterous place; unlike our own galactic neighborhood, where



Fermi's Large Area Telescope (LAT) shows that an intense star-forming region in the Large Magellanic Cloud named 30 Doradus is also a source of diffuse gamma rays. Brighter colors indicate larger numbers of detected gamma rays.
Image courtesy of NASA/DOE/Fermi LAT collaboration

each star is typically a few light years from its closest neighbor, there are two million stars within a single light year of the center. Add to that a black hole more than four million times the mass of the sun, a sprinkling of pulsars and jets, and a fog of gas and dust, and you have very complicated region. Murgia suggests the evidence for dark matter seen by other researchers could just as easily be attributed to one—or several—of these more conventional objects.

"We need to be cautious and rule out the other, simpler explanations before we make a dark matter claim," she says. "But I believe that if there is something out there to find, we have a good chance of seeing it."

Fermi researchers are also combing the extragalactic gamma-ray background—a diffuse and relatively uniform blanket of gamma rays emanating from all directions—for signs of dark matter. If dark matter annihilations contribute to this gamma-ray fog, researchers expect to see a specific signature.

So far, the collaboration has seen no conclusive evidence of dark matter. But this in itself is useful, because it rules out models of dark matter that predict a very strong gamma-ray signal.

"Our studies of dark matter are only just beginning," says SLAC Professor Elliott Bloom. "This is not the low-hanging fruit on this mission, and we'll need years of data before we can set the most constraining dark matter limits."

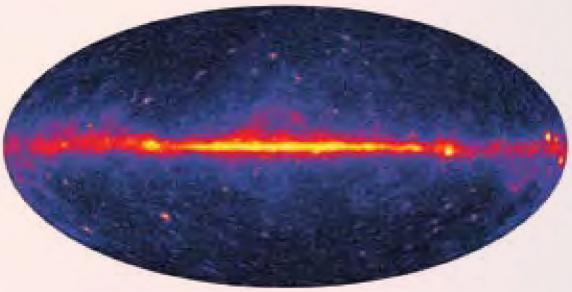
The road ahead

The collaboration is making advances in other areas as well. Fermi researchers are investigating "starburst" galaxies that serve as stellar nurseries; the extended emissions left by supernovae; pairs of stars, pulsars, and other cosmic objects that orbit each other; a soft gamma-ray glow from an abundance of sources in our galaxy and others; and even gamma rays from the sun and the moon. Wherever they look, the sky is ablaze.

As researchers move past the "low-hanging fruit" and push on to more complicated and advanced analyses of these objects, the LAT and GBM will continue to take data 24 hours a day, seven days a week for at least another four years.

"Fermi has no real consumables, so it could last quite a while longer. The Fermi team hopes to operate for 10 years," says Blandford. "The science will continue for all those years, and longer. There's 10 years worth of good observing there, that's for sure."

The avalanche of results has begun.



This view of the gamma-ray sky constructed from one year of Fermi LAT observations is the best view of the extreme universe to date. The map shows the rate at which the LAT detects gamma rays with energies above 300 million electron volts–about 120 million times the energy of visible light–from different sky directions. Brighter colors equal higher rates.
Image courtesy of NASA/DOE/Fermi LAT Collaboration