Recent Results from the Fermi Gamma-Ray Space Telescope

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On behalf of the Fermi Large Area Telescope Collaboration

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• Celestial gamma rays are primarily produced by high-energy charged particles or new kinds of interactions:
  – **Typical processes** are inelastic nuclear collisions ($\pi^0$ production), inverse Compton scattering, Bremsstrahlung, curvature and synchrotron radiation; also possibly from new particle interactions such as dark matter particle annihilation.
  – **Gamma rays**, non deflected by magnetic fields, are probe of particle acceleration sites.
• The Universe is mainly transparent to gamma rays with energies less than 20 GeV, so they can probe distant or obscured regions.
LAT images the sky one photon at a time: γ-ray converts in LAT to an electron and a positron; direction and energy of these particles tell us the direction and energy of the photon.

Launched on June 2008
Fermi LAT Collaboration

- France
  - IN2P3, CEA/Saclay
- Italy
  - INFN, ASI, INAF
- Japan
  - Hiroshima University
  - ISAS/JAXA
  - RIKEN
  - Tokyo Institute of Technology
- Sweden
  - Royal Institute of Technology (KTH)
  - Stockholm University
- United States
  - Stanford University (SLAC, KIPAC, and HEPL/Physics)
  - University of California at Santa Cruz - Santa Cruz Institute for Particle Physics
  - Goddard Space Flight Center
  - Naval Research Laboratory
  - Sonoma State University
  - Ohio State University
  - University of Washington

also members from Australia, Germany, Great Britain, Spain, Austria, Iceland

Sponsoring Agencies

- Department of Energy
- National Aeronautics and Space Administration
- CEA/Saclay, ASI
- IN2P3/CNRS, INFN
- MEXT, K. A. Wallenberg Foundation
- KEK, Swedish Research Council
- JAXA, Swedish National Space Board

LAT construction managed by
SLAC National Accelerator Laboratory,
Stanford University
Large contributions from international collaboration of SLAC Users.
Fermi LAT Collaboration

- France
- Italy
- Japan
- Sweden
- United States
- University of Washington

Fermi @ SLAC
- Receive, process and deliver LAT data to the LAT Collaboration and (through NASA) the public Science Community: 130 billion event triggers; 440 Hz avg output evt rate (1.5 Mbps)
- Maintain and update LAT flight software: 11 updates since launch
- Monitor and optimize LAT performance: 99.3% uptime for physics during Science mission

- Fermi collaborators taking shifts from their home institutions
- SLAC computing facilities are heavily used by the collaboration to perform analysis and simulations
- Collaboration meetings mostly take place at SLAC

also members from Australia, Germany, Great Britain, Spain, Austria, Iceland
Galactic gamma-radiation: largely diffuse emission from cosmic-ray interactions with the interstellar medium.

Despite being known from the beginning of gamma-ray astronomy, the diffuse Galactic radiation has proven challenging to model in detail.
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Nailing down the EGRET “GeV Excess”
Sources are seen against a strong Galactic and extragalactic diffuse background. $E > 1$ GeV image.
The Fermi LAT 1FGL Source Catalog

1451 Sources

(EGRET Catalog : 271)
The Fermi LAT 1FGL Galactic Sources

Yet another new (transient) source class: Gamma-ray Nova! V407 Cygni (ATEL #2487) – Unexpected!
The Pulsing $\gamma$-ray Sky

Good candidates for nearby sources of cosmic-ray electrons.

Over 60 gamma-ray pulsars are now known
(x 10 more pulsars)

Fermi Pulsar Detections

- New pulsars discovered in a blind search
- Millisecond radio pulsars
- Young radio pulsars
- Pulsars seen by Compton Observatory EGRET instrument

Pulses at 1/10th true rate
Where does the emission come from?

- Two scenarios before Fermi

  - “Polar cap”: the emission comes from the **magnetic poles**
  - Stronger magnetic field
  - The spectrum should roll-off steeply (faster than an exponential cut-off)

  - “Outer Gap”: emission comes from **outer magnetosphere**
  - Weaker magnetic field
  - The spectrum has an exponential cut off.
  - Radio beam misaligned w.r.t. the gamma emission.
- Outer Gap emission model favored. Polar Cap model ruled out
  - Radio and \( \gamma \)-ray fan beams separated
  - \( \gamma \)-ray only PSRs

Vela, the brightest point source of gamma rays at LAT energies.
Supernova Remnants - Spatially Resolved

NASA’s Fermi telescope resolves supernova remnants at GeV energies

Note: LAT does not resolve Cas A
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Strong evidence for cosmic ray production in SNR.

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Green contours are from Spitzer IRAC, shocked $H_2$

Gamma Ray emission from region heated by the passage of the shock wave of the W44 SNR
Sources such as pulsars, pulsar wind nebulae, and binaries may all contribute to the electron spectrum.
Dark matter searches

- Search for Dark matter signal in different places:
  - Galactic Center, Galactic Halo, Dwarf Galaxies
- Search for different signals:
  - Lines, continuum
- No evidence of dark matter found so far.
  - Upper limits start cutting into the interesting phase space region

“Extraordinary claims would require extraordinary evidence.” Remember in your readings…
Over half the bright sources seen with LAT appear to be associated with Active Galactic Nuclei (AGN)

- Power comes from material falling toward a supermassive black hole
- Some of this energy fuels a jet of high-energy particles that travel at nearly the speed of light
- Fermi LAT sees primarily blazars, for which the jet is pointed toward Earth.
The spectral Energy Distribution (SED) of this blazar is complex, requiring multiple components that vary with time.

Fermi LAT continuously monitors the sky, looking for transient and alerting other observatories.

A key result for Fermi and multiwavelength studies: in most cases, simple models for blazars are inadequate.
AGN are not all pointing toward us...

Centaurus A – AGN, Radio Galaxy.
Composite image with Chandra (blue, X-rays), APEX (Radio, red), ESO/WFI (true)
Over $\frac{1}{2}$ of the total (>100 MeV) flux observed is in the lobes.

Requires 0.1-1 TeV electrons in giant ‘relic’ lobes: accelerated in-situ or efficiently transported from center.
Towards a complete picture

Galaxies Dominated by Cosmic-Ray Interactions (Non AGN)

Large Magellanic Cloud  M82  NGC253

Milky Way

GeV gamma rays in these galaxies come primarily from the interactions of cosmic ray hadrons and electrons with interstellar matter and photon fields.
Towards a complete picture

Galaxies Dominated by Cosmic-Ray Interactions (Non AGN)

The product of the supernova rate and the total mass of gas in these galaxies appears to show a trend, supporting the long-held expectation that supernovae are the principal accelerators of cosmic rays (at least hadrons).
Gamma-Ray Bursts (GRB)

- Rapid flashes of radiation, probably related to the end of life of massive stars in the early Universe
- Long (>2 seconds) vs short (<2 seconds) bursts:
  - do they have the same progenitor?
  - do they share the same characteristics?
- Physics of “colliding relativistic shells”
- Before Fermi:
  - 7 GRB known above >100 MeV from EGRET and AGILE
• 20 GRB have been seen by LAT above 100 MeV
• Both long (>2 sec) and short (<2 sec) bursts have been seen
• Some bursts show high-energy emission afterglow
• Constraint: lower limit of bulk Lorentz factor of the colliding shells: $\Gamma_{\text{min}} \sim 1000$
• Some bursts have an extra spectral component (a different mechanism at high energy?)
• These short, distant and bright flashes can be used as tools to probe basic physics, as in the example here.

Constraints on the quantum gravity mass scale ($M_{\text{QG}}$) by direct measurement of photon arrival times, testing Lorentz invariance violation.

For linear dispersion:

$$M_{\text{QG},1}/M_{\text{Planck}} > 1.19$$
Gamma-ray Sky:

- Continuous monitor of the sky is a golden resource for astrophysics of high energy sources.
- Discovery of new gamma-ray emitters.
- Multiwavelength observations key for understanding the universe.
- Gamma rays seen with Fermi probe: particle acceleration and interaction, ranging from distant Gamma-ray bursts and Active Galactic Nuclei to sources in our Solar System.

Cosmic-ray Acceleration:

- The Fermi results support, but have yet to prove definitively, the idea that supernovae are a primary source of cosmic rays.
- Pulsars, PWN, SNR, binary systems contribute to the Cosmic-ray electron population.
- No evidence of Dark Matter found yet. Upper limits start ruling out models.

All the Fermi gamma-ray data are public. Join the fun!

http://fermi.gsfc.nasa.gov/ssc/