GeV Flares and Particle Acceleration in the Galaxy

Elizabeth Hays (NASA/GSFC) on behalf of the Fermi-LAT Collaboration
GeV Galactic Transients

- Expectations for Fermi
  - Binary Systems
    - High-mass X-ray binaries
    - Microquasars?
  - Colliding wind systems?
    - Massive stars with strong outflows and companions
- What else?
  - EGRET searches for variability in pulsar wind systems, X-ray novae
Some History

- Early gamma-ray detections
- Variable source population along the Galactic plane in EGRET


June 9, 2011
A Galactic transient candidate from EGRET

GRO J1838-04
EGRET observed 3.5 day flare near the Galactic Plane in June 1995


No blazar candidates found

June 9, 2011
LAT as an all-sky monitor

- What the LAT covers
- How the sky is monitored
- Flare monitoring next steps: refinement and follow-up
- What has been found in the Galaxy?
**LAT Sensitivity with Time**

**Transient Science:** Flares, bursts, multiwavelength campaigns, unidentified transients

**Accumulated Science:** New source types, populations, long-term monitoring, spatially extended and diffuse studies

**Deepest and most uniform survey of the sky at these energies**

All-sky in ~3 hrs (2 orbits)

Minor asymmetry due to passages through South Atlantic Anomaly

June 9, 2011

E. Hays
The Steady Sky at 2 Years

Fermi two-year all-sky map

>1 GeV

June 9, 2011

E. Hays
The variable sky

05–AUG–2008

June 9, 2011
The variable sky

05–AUG–2008

June 9, 2011
The Variable Sky

1FGL sources showing monthly deviations

- No association
- Possible association with nearby SNR or PWN
- AGN – blazar
- Starburst Gal
- Pulsar
- Pulsar w/PWN
- AGN – unknown
- Galaxy
- PWN
- Globular cluster
- AGN – non blazar
- SNR
- XRB or MQO

June 9, 2011

E. Hays
LAT Automated Science Processing

All-sky search runs every 6 hours, 1 day, 1 week

>100 Fermi LAT ATels

LAT counts E>100 MeV, 6 hours

LAT Flare advocates monitor the sky daily
- Check for flaring and new sources
- Coordinate multiwavelength follow-up
- Post reports http://fermisky.blogspot.com

Lightcurves for >70 flaring sources hosted by FSSC
http://fermi.gsfc.nasa.gov/ssc

June 9, 2011

E. Hays
Methods for source detection in counting detectors

 togli

Wavelet-based

- Wavelet transforms - Damiani et al. (1997), Ciprini et al. (2007)

Count-based

- Likelihood test, e.g. pointfind in 1FGL - Abdo et al. (2010)
- Clustering, e.g. Minimal Spanning Tree - Campana et al. (2008)
LAT Transients at Low Galactic Latitude

- Originally **unassociated** transients from daily search
- Low latitude blazars from First LAT Catalog

June 9, 2011
LAT Transients at Low Galactic Latitude

- Originally **unassociated** transients from daily search
- Low latitude blazars from First LAT Catalog

June 9, 2011

E. Hays
Two Early Unassociated Transients

3EG J0903-3531

High confidence >10 sigma

Counts per day (E>200 MeV)
- 2 deg radius
- exposure corrected
- scaled to average background rate

Fermi J0910-5041

Average background rate

E. Hays
Counterpart Search - 3EG J0903-3531

3EG J0903-3531 (ATEL #1771)

- October 5, 2008, gamma-ray increase over 3 days
- 5x above 3EG flux
- 15x above average gamma-ray flux
- Swift XRT TOO within 2 days

Updated LAT 95% error circle (8 months) contains a flat-spectrum radio source and Swift/XRT source

June 9, 2011

E. Hays
Counterpart Search - Fermi J0910-5041

**Fermi J0910-5041** (ATEL #1788)

- October 15, 2008
- ~10x above average gamma-ray flux for 2 days
- Swift XRT ToO within 1 day
- 1 of 2 high confidence LAT transients without a firm counterpart

LAT 95% error circle contains Swift XRT source (Landi et al. ATEL #1822) coincident with flat-spectrum radio source from SUMMS and AT20G (Sadler ATEL #1843)
LAT Transient - J1057-6027

Fermi J1057-6027

- June 11, 2009, gamma-ray increase over 1 day
- Coincident with a known LAT source
  - 95% confidence radius 0.07 deg
- 10x above average gamma-ray flux
- Swift XRT TOO within 1 day (ATELS #2082, #2083)
  - AG Carinae, luminous blue variable (LBV) star with X-ray and radio emission, 7.7' away

X-ray map: Swift XRT (0.3-10 keV)
Radio contours: MGPS

June 9, 2011
LAT Before and After

Fermi Detects Gamma Rays from Nova Cygni 2010

Feb. 19 to March 9, 2010

March 10 to 29, 2010

LAT >100 MeV counts maps

June 9, 2011

E. Hays
Gamma Rays Concurrent with a Nova

- Fermi J2102+4542: First detection of a nova in gamma rays
- 6-8σ in automated processing on 2010 March 13, 14 (Cheung et al. ATEL #2487)
- LAT position within 3.7' of V407 Cygni (white dwarf, red giant binary)
- Further analysis shows gamma rays close in time to nova discovery on March 10 by Nishiyama and Kabashima

June 9, 2011

Science 329, 817 (2010) E. Hays
Historical Optical Lightcurve

V407 Cyg Optical

unfiltered

Magnitudes

Days since 1 April 2008

June 9, 2011

E. Hays
Nova Lightcurves

1) Optical peaks first
2) Gamma rays peak at 3-4 days and last ~2 weeks
3) X-rays peak at ~30 days, last and longest

Relative timing can be understood from the system geometry
Cygnus X-3

First secure gamma-ray detection of Cygnus X-3
- high significance source and binary modulation

E\textgreater{}200 \text{MeV} \\
\begin{align*}
4 \text{deg} \\
\text{Cygnus X-3 in off-pulse}
\end{align*}

High Mass X-ray Binary/Microquasar

\begin{align*}
\text{BH} \\
\text{NS}
\end{align*}

\begin{align*}
\sim \text{10}^{11}\text{cm} \\
e^-
\end{align*}

\begin{align*}
\text{Wolf Rayet} \\
\text{Observer}
\end{align*}

\textbf{Science 326, 1512 (2009)}

June 9, 2011

E. Hays
Gamma-ray Flares and Modulation

Aug. 4 2008 to Sept. 2 2009

4 day

- LAT active periods correspond to soft X-ray state
- Gamma rays modulated at 4.8 hour binary period
- Additional GeV activity during May 2010 (Corbel et al. ATEL #2646)

June 9, 2011
Gamma-ray Flares and Modulation

Aug. 4 2008 to Sept. 2 2009

4 day

✦ LAT active periods correspond to soft X-ray state
✦ Gamma rays modulated at 4.8 hour binary period
✦ Additional GeV activity during May 2010 (Corbel et al. ATEL #2646)

June 9, 2011
Connection to Jet Activity

- LAT active periods correspond to radio flares
  - Possible radio lag is not well constrained by correlation analysis
- Expect high energy electrons somewhere along the jet to scatter the stellar radiation field (UV) via inverse Compton
  - Superior conjunction favored for gamma-ray production
The Crab Nebula

Radio
NRAO/AUI and M. Bietenholz

Optical
NASA/ESA/ASU/J.Hester & A.Loll)

See review
Hester, J. J., 2008,
ARA&A, 46, 127
June 9, 2011

X-ray
E. Hays
The Crab Nebula

See review
Hester, J. J., 2008,
ARAA, 46, 127
June 9, 2011

Radio
NRAO/AUI and M. Bietenholz

Optical
NASA/CXC/ASU/J.Hester

X-ray
NASA/CXC/ASU/J.Hester et al.
The Crab in LAT

**Pulsar** 100 MeV to 20 GeV

**Nebula** from MeV to TeV

Hyper-exponential cutoff excluded at ~5 sigma

Consistent with emission well above the neutron star surface

Two components: Synchrotron + Inverse Compton extending to TeV.
Mean nebula B field of 100 to 200 μG

June 9, 2011


E. Hays
The Crab in LAT

**Pulsar** 100 MeV to 20 GeV
**Nebula** from MeV to TeV

Hyper-exponential cutoff excluded at ~5 sigma
Consistent with emission well above the neutron star surface

Two components: Synchrotron + Inverse Compton extending to TeV.
Mean nebula B field of 100 to 200 μG

June 9, 2011

E. Hays
Our candle is not so standard

- **Crab flickers in hard X-ray**
  - Fermi GBM reports hard X-ray variability, ~3.5% decline per year since launch. Confirmed by multiple instruments (C. A. Wilson-Hodge et al. arXiv:1010.2679v1)

- **Crab flares at high energy (>100 MeV)**
  - AGILE reports enhanced Crab flux over a few days, Sept. 19-21 (M. Tavani et al. ATEL #2855)
  - Fermi LAT confirms flare and triggers LAT ToO (R. Buehler et al. ATEL #2681)
    - Earlier flare found using new offline all-sky variability search developed by R. Buehler
  - Fermi LAT reports end of flare. Variability present in off-pulse phase of pulsar (E. Hays et al. ATEL #2893)
Two Short Flares from the Nebula

Flux of the low energy LAT component

No variability found in pulsar or high energy LAT component.

4 week intervals

Sun passages excluded

4 day intervals covering flare periods

Abdo et al. 2011, Science, 331, 739
Crab Flare Spectra

Low energy LAT component shows spectral variability

25 month index: $3.69 \pm 0.11$

Feb 2009 index: $4.3 \pm 0.3$

Sept 2010 index: $2.7 \pm 0.2$

Abdo et al. 2011, Science, 331, 739
Origin of the Gamma-ray Flares?

- Gamma-ray luminosity is a small fraction of the pulsar power
  - $10^{35}$ erg/s in the flare $\rightarrow$ $\sim 10^{-3} L_{\text{rot}}$ of the pulsar
  - About $10^{28}$ Watts or $\sim 100x$ Solar luminosity
- The Crab Pulsar is an immensely powerful dynamo
  - Voltage drop $\sim 50$ PV
Origin of the Gamma-ray Flares?

- Gamma-ray luminosity is a small fraction of the pulsar power ($10^{35}$ erg/s $\rightarrow \sim 10^{-3} L_{\text{rot}}$)
- 4 day duration implies small region size, diameter $< 1.4 \times 10^{-2}$ pc ($\sim 1.5$ arcsec) ($3 \times 10^{16}$ cm)
Crash Course in Nebula Structure

Polar wind

Equatorial wind - magnetized plasma

Termination shock

Basics from Rees and Gunn 1974

June 9, 2011

E. Hays
Origin of the Gamma-ray Flares?

✦ Items

✦ Gamma-ray luminosity is a small fraction of the pulsar power ($10^{35} \text{ erg/s} \rightarrow \sim 10^{-3} L_{\text{rot}}$)

✦ 4-day duration implies small region size, diameter $< 1.4 \times 10^{-2} \text{ pc} \sim 1.5 \text{ arcsec}$

✦ Electron synchrotron cooling time in 200 uG $< \sim 15 \text{ days}$

✦ Competing processes (brehmsstrahlung, inverse Compton) require $> \sim \text{ Myr}$

✦ Conclude

✦ LAT low energy spectral form + short timescale variability support a synchrotron interpretation

✦ Implies electrons accelerated to $> \text{PeV}$ in structures somewhere in the inner region of the nebula near the termination shock or base of the jet
Searching for the Emission Region

No corresponding variability found in radio, optical, infrared, soft and hard X-rays around time of flare

June 9, 2011
Inner Nebula Dynamics

Inner Nebula Dynamics

Inner Nebula Dynamics (low res)


June 9, 2011
Inner Nebula Dynamics (low res)


June 9, 2011
And then...

New, extremely bright flare in April 2011! (Buehler et al. ATel #3276)

LAT TOO captured peak of the flare (Hays et al. ATEL #3284)

Quick identification enabled sequence of Chandra observations

Rapid variability of PeV electrons poses severe challenges for acceleration mechanisms

June 9, 2011

http://fermi.gsfc.nasa.gov/ssc/data/access/lat/msl_lc/

E. Hays
Three day Crab synch. 32 month light curve

Average $\sim 6 \times 10^{-7}$ ph/cm$^2$/s and persistently variable

Slides from R. Buehler
Flare light curve and ToO

Synchrotron Nebula
~3h time binning

Flux > 100 MeV (10^{-7} \text{s}^{-1}\text{cm}^{-2})

Time (MJD)

55660 55662 55664 55666 55668 55670

Synchrotron nebula increased by factor \sim 30
Very good Chandra coverage

Preliminary
20 min flare light curve

- Synchrotron Nebula
- ~20 min time bins

Fast variability (<1h)

Homework! Run Chuck’s variability time prescription...

\[ t < 1\text{hr} \Rightarrow r < 4 \times 10^{14} \text{ cm} \] (assume \( \delta_D < 4.4 \) and region moving toward us)
Nebula Flare spectrum

Flare spectrum well described by power law of index 1.6 with exponential cutoff at 580 MeV
No sign of pulsation in flare photons found yet
Open Questions

✦ What is the flare emission mechanism?
✦ Where do the flares originate in the nebula?
✦ Is there (can there be) variability in the VHE energies? (See, for example, Bednarek 2011, MNRAS, 551)
Summary

✦ LAT is revealing sites and mechanisms of particle acceleration in the Galaxy

✦ Small, but interesting number of variable/transient sources in the Galaxy
 ✦ Result of a variety of monitoring methods
✦ Variability is an important tool! (See Chuck’s lectures)
✦ Fast, high-energy gamma-ray flares from the Crab
 ✦ Indirectly ‘seeing’ the highest energy astrophysical electrons we can pinpoint...but where are they?

http://fermi.gsfc.nasa.gov

June 9, 2011

E. Hays