Discovery of Gamma Rays from Novae

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Six Fermi-LAT >100 MeV Novae Detections


  - **V745 Sco 2014**: 2 and 3σ only on Feb 6th and 7th: Cheung, C. C., Jean, P., Shore, S. N. 2014, ATel 5879


Outline

- How Fermi LAT works and how it detects novae (sky-survey vs. target-of-opportunity)
- The six Fermi-LAT >100 MeV detections (chronological)
- Fermi-LAT Light curves, spectra
Large Area Telescope (LAT)
Observes 20% of the sky at any instant, views entire sky every 3 hrs
20 MeV - 300 GeV - includes unexplored region between 10 - 100 GeV

Gamma-ray Burst Monitor (GBM)
Observes entire unocculted sky
Detects transients from 8 keV - 40 MeV

- Unique Capabilities for GeV astrophysics
  - Large effective area
  - Good angular resolution
  - Huge energy range
  - Wide field of view

Launched June 2008
Mission Lifetime:
5 year requirement,
10 year extended mission
LAT images the sky one photon at a time: \(\gamma\)-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.
In 1 day, ability to detect (at $5\sigma$) the weakest EGRET sources

In 2 weeks, detect # of photons that EGRET detected in entire mission
4 days of all-sky exposure

Equivalent to 1 year of Compton EGRET observations
4 days of all-sky exposure

Equivalent to 1 year of Compton EGRET observations
**Fermi Discovery of a γ-ray Nova – the First**

- Initial LAT detection 2010
- March 10, same day as nova V407 Cygni optical discovery
  (Cheung et al. ATEL #2487)
- γ-ray identification via spatial (r_{95%}=3.7') & temporal coincidence with a *symbiotic recurrent nova*

**LAT 0.2-100 GeV**

- Known 1FGL source
- Nova 2010 V407 Cygni

**Large Area Telescope (LAT)**
- E = 20 MeV – 300 GeV
- FOV = 20% of sky

**Abdo et al. 2010 Science, 329, 817**
Fermi Discovery of a γ-ray Nova – the First

Optical Peak

- Particle acceleration in nova ejecta through interactions with dense wind of Red Giant companion (proposed for RS Oph by Tatischeff & Hernanz 2007)

- Initial LAT detection 2010 March 10, same day as nova V407 Cyg optical discovery by Nishiyama & Kabashima

- γ-ray identification via spatial (r_{95\%}=3.7’) & temporal coincidence with a symbiotic recurrent nova

Abdo et al. 2010 Science, 329, 817
Compact cataclysmic variable:  
WD + Main Sequence

Roche lobe overflow

Classical novae

- $a \sim 10^{11} \text{cm} \sim R_{\odot}$
- $P_{\text{rec}} > 10^4 \text{ yr}; P_{\text{orb}} \sim \text{hr-day}$
- rate $\sim 20 – 50 / \text{yr in Galaxy}$

Symbiotic system:  
Massive WD + Red Giant

accretion from a red giant wind

Symbiotic/Recurrent novae

Hydrogen burning in degenerate conditions on top of the white dwarf

- $a \sim 100’s \ R_{\odot}$
- $P_{\text{rec}} < 100 \text{ yrs}; P_{\text{orb}} \sim \text{few years}$
- $\sim 10$ known

Credit: David Hardy

Adapted from M. Hernanz
X-ray Universe 2011 talk
Compact cataclysmic variable: WD + Main Sequence

Roche lobe overflow

Classical novae

γ-ray sources e.g., V407 Cyg

Symbiotic system: Massive WD + Red Giant

accretion from a red giant wind

Hydrogen burning in degenerate conditions on top of the white dwarf

Not γ-ray Sources?

• $a \sim 10^{11}$ cm $\sim R_{\odot}$
• $P_{\text{rec}} > \sim 10^4$ yr; $P_{\text{orb}} \sim$ hr-day
• rate $\sim 20 \sim 50$ / yr in Galaxy

• $a \sim 100$’s $R_{\odot}$
• $P_{\text{rec}} < 100$ yrs; $P_{\text{orb}} \sim$ few years
• \( \sim 10 \) known

Adapted from M. Hernanz X-ray Universe 2011 talk
Other novae typically ~10x fainter than V407 Cyg γ-ray peak – why?

Cheung (2013)
V1312 Sco 2011 Classical Nova
(white dwarf + Main sequence star)

V407 Cyg Symbiotic Recurrent Nova
(white dwarf + Red Giant)

Other novae typically ~10x fainter than V407 Cyg γ-ray peak – why?

Cheung (2013)
June 2012: LAT Detected Two Classical Novae

**Nova Monocerotis 2012**

- Historical Optical DSS Image
- Preliminary at the time
- Fermi J0639+0548 (68%)

**Nova Scorpii 2012**

- Swift UVOT image
- Preliminary at the time
- Fermi J1750-3243 (95%)
- SLX 1746-331 (32.2 offset)

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- LAT detections 4 days apart, opposite ends of sky
- Different paths to identification ~1.5 - 2 months later
**Fermi Detection of Nova Sco 2012**

Nova Sco 2012 Classical Nova (?) (white dwarf + Main sequence star)

- V1324 Sco LAT >100 MeV
- Optical (magnitude)
  - Days since 2012 June 15

Optical compiled by Munari et al. (2015, IBVS), predominantly from AAVSO

LAT from Ackermann et al. (2014); see Cheung et al. 2015
Optical discovery of nova Monoceros on Aug 9
(S. Fujikawa, Kagawa Japan)

Historical Optical DSS Image

- Initial LAT discovery of Fermi J0639+0548, \(\sim 20^\circ\) from Sun in late-June (Cheung et al. ATEL #4224)
- Optical discovery of possible nova August 9 (S. Fujikawa, CBET#3202)
- Amateur spectroscopic confirmation Aug 14-16 as ONe type classical nova \(\sim 50\) days after outburst, 3-4 kpc away
- LAT association with Nova Mon 2012 (Cheung, Shore et al. ATEL #4310)
- Inferred optical peak in June of \(\sim 4.5\)-5 mag

VLA observations triggered on the Fermi transient, before the optical nova discovery (later…)
**Fermi “Discovery” of Nova Mon 2012**

Before   Nova

Historical Optical DSS Image

Optical image 2012 August 15

Image: Seiichiro Kiyota (Tsukuba, Japan)
Optical classification as Oxygen-Neon (ONe) type classical nova

ONe type novae typically highest mass WDs with massive & fast ejecta

Initial spectra by amateurs Stéphane Charbonnel (France), James Edlin (Idaho Falls, Idaho), Optical comparison by Ivan de Gennaro Aquino (U. Pisa)

See Shore et al. 2013 A&A 553, A123
Optical classification as Oxygen-Neon (ONe) type classical nova

ONe type novae typically highest mass WDs with massive & fast ejecta

Della Valle et al. (2002)

$\Delta t = 5$ day

$\Delta t = 33$

$\Delta t = 58$

Nova V382 Vel 1999

Initial spectra by amateurs Stéphane Charbonnel (France), James Edlin (Idaho Falls, Idaho), Optical comparison by Ivan de Gennaro Aquino (U. Pisa)

See Shore et al. 2013 A&A 553, A123
Naked-eye Nova Delphini 2013: does Fermi-LAT see it?
Naked-eye Nova Delphini 2013: does Fermi-LAT see it? Yes - a Carbon-Oxygen type!

Fermi-LAT (>100 MeV) counts map

V339 Del

Optical (magnitude)

LAT (>100 MeV) counts map

V339 Del

Galactic latitude (deg)

Galactic longitude (deg)

Counts deg^2

Image Credit & Copyright: Jimmy Westlake (Colorado Mountain College)
Fermi LAT >100 MeV γ-ray Detections

- V407 Cyg 2010
  Symbiotic
  D ~ 2.7 kpc

- V1324 Sco 2012
  CO nova
  D ~ 4.5 kpc

- V959 Mon 2012
  ONe nova
  D ~ 3.6 kpc

- V339 Del 2013
  CO nova
  D ~ 4.2 kpc

E > 100 MeV counts maps

Ackermann et al. 2014
Science 345, 554
- Duration ~ 17-27 days
- $t_{\text{rise}}$ ~ $t_{\text{fall}}$ ~ 2-7 days
- Flux peaks ~ $10^{-6}$ ph/s/cm$^2$
- Total energy ~ $6-13 \times 10^{41}$ erg

(Widening range >100 MeV properties with recent detections N Cen 2013, N Sgr 2015 No. 2)

- Origin and production site of >100 MeV emission is open problem – hadronic or leptonic fit LAT spectra

Ackermann et al. 2014
Science 345, 554
Optical and $\gamma$-ray Peaks / Onsets

$\gamma$-ray peaks lag optical (by up to ~6 days for V339 Del)

$\gamma$-ray onset both before and after optical peak

Optical (predominantly AAVSO data (see Munari et al. 2015 IBVS for Sco); black square = Itagaki discovery mag
Origin and production site of the LAT observed γ-ray emission is an open problem. Hadronic and leptonic models satisfactory fits LAT spectra (cf., Abdo et al. 2010 Sci 329, 817, for V407 Cyg case)
Revisited *Compton* (1991-99) observations of classical novae in light of *Fermi* discoveries

- V382 Vel 1999 peaked at 2.5 mag May 23rd; Compton/OSSE observations detected at 7σ over 12-days starting 4 days after peak; non-detection in next 14-day

- Early time OSSE spectrum of V382 Vel 1999 compared to LAT data for Nova Mon 2012, both oxygen-neon novae
Thermo-Nuclear Family
Two new LAT nova detections bring total to six GeV novae to date

1. V407 Cyg, reported in 2010 Sci – symbiotic-like system, “but few binary systems with a WD are known to have a similar environment; hence, we expect g-ray novae to be rare.”
2. Three classical novae, reported in 2014 Sci – similar GeV properties, nearby, <~4-5 kpc => (Are all novae GeV emitters??)

Two new classical novae in gamma-rays systematically fainter, lower luminosity, and longer duration

- Multiple optical peaks with fainter γ-ray emission detected (sporadically) for longer-duration than in previous LAT cases
- Widening diversity of γ-ray properties than suggested in 2014 Sci paper => Bodes well for future LAT novae studies

- select recurrent novae and very nearby (~1 kpc) classical novae could be seen brightly by all current / impending hard X-ray missions, prospective MeV missions. Or not.
Two optically brightest novae since 1999. Multiple optical peaks with fainter γ-ray emission detected sporadically for longer-duration than in previous cases.

Nearby, ~2-2.5 kpc (previous 2.7 to >4.5 kpc)
- Cen ToO 5+5 days with 3 day gap; Sgr ToO 15 days
- Unanticipated signal at late times (past ~2-3 weeks as in previous cases)
- Late Cen 12-day exposure gap due to SN14J / M81 ToO
Spectra + Modeling

- Fit average LAT spectra with power-law and exponential PL indistinguishable because faint / lower TS than in prior examples

- Hadronic and leptonic indistinguishable also
**Spectral Results -- details**

**TABLE 2**

*Fermi*-LAT $>100$ MeV $\gamma$-ray spectral and model fit results for the two classical novae

<table>
<thead>
<tr>
<th>Nova</th>
<th>V1369 Cen 2013</th>
<th>V5668 Sgr 2015</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Single Power Law</td>
<td></td>
</tr>
<tr>
<td>Flux, $F_\gamma$</td>
<td>$25.4 \pm 4.1$</td>
<td>$11.4 \pm 2.2$</td>
</tr>
<tr>
<td>Photon index</td>
<td>$2.37 \pm 0.09$</td>
<td>$2.42 \pm 0.13$</td>
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<tr>
<td>TS</td>
<td>99.9</td>
<td>70.4</td>
</tr>
<tr>
<td></td>
<td>Exponentially Cutoff Power Law</td>
<td></td>
</tr>
<tr>
<td>Flux, $F_\gamma$</td>
<td>$21.1 \pm 4.2$</td>
<td>$10.9 \pm 2.4$</td>
</tr>
<tr>
<td>Slope, $s$</td>
<td>$1.84 \pm 0.23$</td>
<td>$2.27 \pm 0.25$</td>
</tr>
<tr>
<td>$E_c$</td>
<td>$2.3 \pm 1.0$</td>
<td>$9 \pm 14$</td>
</tr>
<tr>
<td>TS</td>
<td>110.6</td>
<td>71.1</td>
</tr>
<tr>
<td></td>
<td>Hadronic Model</td>
<td></td>
</tr>
<tr>
<td>Flux $F_\gamma$</td>
<td>$20.7 \pm 3.6$</td>
<td>$8.2^{+1.2}_{-1.1}$</td>
</tr>
<tr>
<td>Slope, $s_p$</td>
<td>$3.0^{+0.9}_{-0.4}$</td>
<td>$3.1^{+0.3}_{-0.9}$</td>
</tr>
<tr>
<td>$E_{cp}$</td>
<td>$&gt;10$</td>
<td>$&gt;10$</td>
</tr>
<tr>
<td>TS</td>
<td>115.3</td>
<td>70.7</td>
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<tr>
<td></td>
<td>Leptonic Model</td>
<td></td>
</tr>
<tr>
<td>Flux, $F_\gamma$</td>
<td>$20.0^{+2.6}_{-4.4}$</td>
<td>$10.1^{+3.0}_{-2.2}$</td>
</tr>
<tr>
<td>Slope, $s_e$</td>
<td>$1.3^{+1.3}_{-1.6}$</td>
<td>$2.8^{+0.5}_{-1.5}$</td>
</tr>
<tr>
<td>$E_{ce}$</td>
<td>$3.2^{+7.1}_{-1.4}$</td>
<td>$&gt;3.2$</td>
</tr>
<tr>
<td>TS</td>
<td>111.2</td>
<td>71.1</td>
</tr>
</tbody>
</table>

**Classical Novae in 2014 Sci:**

- 23-59 (E-8 ph/cm2/s)
- 2.2-2.3 (+/- 0.1)
- 156-198
- 1.7-1.8 (+/- 0.2-0.7)
- 1.5-4.1 (+6/-1) GeV
- 170-209
- 2.4-2.6 (+/- 1)
- >3-30 GeV
- 178-211
- 0.3-2.0 (+/- 1 or 2)
- 2-10 (+/- large) GeV
- 170-210
LAT Observed Parameters

(Classical) Novae in 2014 Sci:
- Durations 17-27 days
- $L_\gamma \sim (3-4)\times10^{35} \text{ erg/s,}$
- Duration x $L_\gamma = \text{total energies } \sim (6-7)\times10^{41} \text{ erg,}$
- and $\sim 2\times$ greater for Sco

We noted similarity in LAT-observed properties, but also the subtle differences (spectral, $L_\gamma$)

(internally and not in print, we debated whether novae were “standard candles in \gamma-rays”)

Table 1 – Summary of the Four Novae. Tabulated are optical peak magnitudes and adopted distances from (19) for V407 Cyg, estimate of $\sim 4-5$ kpc V1324 Sco based on the maximum magnitude rate of decline relation (17) notwithstanding the large uncertainties in this method (29), (9) for V959 Mon (scaled from V1974 Cyg 1992), and (30) for V339 Del (scaled from OS Andromedae 1986), and observed dates of the optical peaks (unfiltered from (3), V-band, adopted, and visual magnitudes, respectively). Positions in J2000.0 equinox (right ascension, RA; declination, Decl.), Galactic longitude ($l$) and latitude ($b$), 95% confidence localization error radius, and offset between the LAT and optical positions in units of degrees. Adopted start dates $t_0$ (J3) are given in Gregorian Dates and Modified Julian Days (MJD). The $\gamma$-ray luminosities $L_\gamma$, and total emitted energies were estimated with the average fluxes from the power law fits of the $\sim l00 \text{ MeV LAT spectra integrated up to 10 GeV and durations from}$ $t_0$ up to the last $> 2\sigma$ daily bin LAT detection. For V339 Del, the $\gamma$ rays were detected for 25 days in 1-day bins (Fig. 2), but there was a hint of a detection two days earlier on the day of the optical peak in 0.5-day binned data (13), leading to a 27 day duration.

*Note that for V959 Mon the optical peak magnitude of 9.4 (unfiltered) was observed $\sim 50$ days after the initial $\gamma$-ray detection, and we adopted an inferred peak of 5 magnitude (9).
- Observed apparent inverse relationship between >100 MeV LAT emission durations and total emitted energies (as well as total number of photons)
- Qualitative explanation only: more compact ejecta with higher density produce shorter emission durations
The one symbiotic-like recurrent nova and the five classical novae detected in γ-rays so far share similarities & differences so γ-ray emission mechanism not necessarily the same.

Fermi acceleration in nova shell:
- Interaction with massive red giant wind plays important role in symbiotic recurrent novae (V407 Cyg).
- Shell-shell interactions in classical novae?
- Necessary conditions: massive WD & fast and massive ejecta?
- All appear nearby – detects ones within ~4-6 kpc; varying LAT exposure should be considered on case-by-case basis.
LAT $E > 100$ MeV observed spectra and lightcurves:
- Soft $\gamma$-ray spectra; emission up to ~few GeV (~10 GeV for V1324 Sco 2012) and evidence for curvature in brightest ones
- $\gamma$-ray durations of ~2 – 3 weeks for early detections; ~39-55 days for recent optically-brightest cases
- >100 MeV luminosities ~$(3 – 4) \times 10^{35}$ ergs s$^{-1}$ and total emitted energies ~$(6 – 7) \times 10^{41}$ ergs; V1324 Sco ~2x larger
- latest (optical brightest) detections systematically fainter/lower luminosity and longer duration, revealing wider diversity of properties

$\gamma$-ray detection rate ~1 yr$^{-1}$ over Fermi mission, consistent with the rate of nearby Galactic novae, suggesting all novae are potential $\gamma$-ray sources
$\gamma$-ray emission mechanism and production site still open problem
Symbiotic recurrent novae like V407 Cyg probe important role of companions in $\gamma$-ray production not fully explored in classical novae; important recurrences awaiting outbursts in Fermi + CTA era (RS Oph, T CrB)
Compton/OSSE observed spectrum of V382 Vel 1999 indicate classical novae spectra extend down to ~0.1 MeV energies; important for modeling