Gamma-ray Novae: Rare or Nearby?
P. J. Morris, G. Cotter, A. M. Brown & P. M. Chadwick
Cataclysmic Variables (CVs): Novae Progenitors

- White dwarf with a secondary main sequence companion star
- The white dwarf is accreting mass from the secondary
- Eventually enough mass accumulates for a thermonuclear runaway to occur on the surface of the white dwarf. This is a nova event.
# Types of Nova

<table>
<thead>
<tr>
<th>Nova</th>
<th>Classical</th>
<th>Recurrent</th>
<th>Dwarf</th>
</tr>
</thead>
<tbody>
<tr>
<td>Timescale</td>
<td>$10^{4-5}$ years</td>
<td>20-40 years</td>
<td>30-300 days</td>
</tr>
<tr>
<td>Factor increase in brightness</td>
<td>$10^6$</td>
<td>$10^3$</td>
<td>10</td>
</tr>
<tr>
<td>Magnitude change</td>
<td>12</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>Mechanism</td>
<td>Thermonuclear Runaway (TNR)</td>
<td>Combination of TNR &amp; DI</td>
<td>Disk Instability (DI)</td>
</tr>
</tbody>
</table>

Carroll & Ostlie, 2007
V407 Cyg: The First Gamma-ray Nova

- Observed in gamma-rays during a classical nova outburst in 2010
- Unusual system as the secondary star is a pulsating Mira variable
- Gamma-rays were thought to be caused by interaction between the nova shell and dense Mira wind
- It was concluded that novae would not generally emit gamma-rays

Abdo et al. 2010
The $>5\sigma$ Classical Novae

- With the exception of V407 Cyg, the novae are believed to have no unusual characteristics.
- The blue diamonds represent the time of the optical peak.

Cheung et al. 2016

Ackermann et al. 2014
Distances?

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Distance (kpc)</strong></td>
<td>2.7</td>
<td>4.5</td>
<td>3.6</td>
<td>4.2</td>
</tr>
<tr>
<td>Peak magnitude</td>
<td>6.9</td>
<td>100</td>
<td>5*</td>
<td>4.3</td>
</tr>
<tr>
<td>Optical RA, Decl.</td>
<td>315.5409°, +45.7758°</td>
<td>267.7246°, −32.6224°</td>
<td>99.9108°, +5.8980°</td>
<td>305.8792°, +20.7681°</td>
</tr>
<tr>
<td>Optical $I$, $b$</td>
<td>86.9826°, −0.4820°</td>
<td>357.4255°, −2.8723°</td>
<td>206.3406°, +0.0754°</td>
<td>62.2003°, −9.4234°</td>
</tr>
<tr>
<td>LAT RA, Decl.</td>
<td>315.57°, +45.75°</td>
<td>267.72°, −32.69°</td>
<td>99.98°, +5.86°</td>
<td>305.91°, +20.78°</td>
</tr>
<tr>
<td>Optical-LAT offset</td>
<td>0.03°</td>
<td>0.07°</td>
<td>0.08°</td>
<td>0.03°</td>
</tr>
<tr>
<td>LAT error radius (95%)</td>
<td>0.08°</td>
<td>0.09°</td>
<td>0.18°</td>
<td>0.12°</td>
</tr>
<tr>
<td>$t_s$ (date)</td>
<td>10 Mar 2010</td>
<td>15 Jun 2012</td>
<td>19 Jun 2012</td>
<td>16 Aug 2013</td>
</tr>
<tr>
<td>$t_s$ (MJD)</td>
<td>55265</td>
<td>56093</td>
<td>56097</td>
<td>56520</td>
</tr>
<tr>
<td>Duration (days)</td>
<td>22</td>
<td>17</td>
<td>22</td>
<td>27</td>
</tr>
<tr>
<td>$L_\gamma$ ($10^{35}$ erg s$^{-1}$)</td>
<td>3.2</td>
<td>8.6</td>
<td>3.7</td>
<td>2.6</td>
</tr>
<tr>
<td>Total energy ($10^{41}$ erg)</td>
<td>6.1</td>
<td>13</td>
<td>7.1</td>
<td>6.0</td>
</tr>
</tbody>
</table>

*For V959 Mon, the optical peak magnitude of 9.4 (unfiltered) was observed ~50 days after the initial $\gamma$-ray detection, and we adopted an inferred peak of 5 magnitude (9).

Ackermann et al.
(2012)
Why Not Just Measure the Distances to multiple novae?

- **Method 1:** Novae as standardisable candles
  - Poor correlation
  - Affected by interstellar reddening

- **Method 2:** Resolving the nova shell
  - Accurate
  - Likely only able to resolve the shells of nearby novae.

---

Shafter et al. (2011)

Sahman et al. (2015)
What is the Nova Occurrence Rate?
-Galactic Method

Advantages
- Based on Milky Way, hence novae more likely to represent Galactic population

Disadvantages
- Unable to see whole population due to location in the disc
- Reddening effects difficult to account for
- Galaxy may not be axis-symmetric
- Requires observations of the whole sky
- Relies on the assumption that novae are standardisable candles (Cohen, 1985)

\[ N_{\text{novae}} = 35 \pm 11 \text{ yr}^{-1} \]

Shafter (1997)
Advantages
- Reddening roughly constant for all sources
- Sources approximately equidistant
- Can spatially sample a large fraction of the total population

Disadvantages
- Relies on scaling relations
- Ignores local effects
- Can be influenced by the relative inclination of the host galaxy

What is the Nova Occurrence Rate?
- Extragalactic Method

$N_{\text{novae}} \sim 20 \text{ yr}^{-1}$
Delle Valle & Livio (1994)
Novae in M31

- As the closest galaxy, M31 is a prime candidate for a nova survey.
- Spatial binning of novae in M31.
- Ellipses defined differently for bulge and disc regions.
- Data available online (http://www.mpe.mpg.de/~m31novae/opt/m31/index.php)

Based on 176+86 (disc+bulge) R-band novae
Defining Milky Way properties
- Well constrained parameters?

- Milky Way radius: Typically believed to be in the range 15-25 kpc
- Solar distance from the Galactic centre is well constrained to be close to 8 kpc
- The bulge/disc boundary is not well defined

\[ R_\odot \approx 8 \text{ kpc} \]
\[ R_b \approx 3 \text{ kpc} \]
\[ R_d \approx 20 \text{ kpc} \]

\[ \times \]

\[ e.g. \text{ Carroll and Ostlie (2007)} \]
The axis of the Solar System to the Galactic centre was taken as $\phi = 20^\circ$ (Binney et al. 1997).

We assume that novae are likely to be found within the thin disc of the Milky Way, such that $P(z) \propto \exp \frac{z}{z_d}$,

where $z_d = 350$ pc is the characteristic scale height (e.g. Dawson & Johnson, 1994).
The below functions used to model bulge infra-red isophotes from Dwek et al. 1995 and Binney et al. 1997 were assessed for nova z production.

\[
\rho_B = \rho_0 \frac{e^{-a^2/a_0^2}}{(1 + a/a_0)^{1.8}},
\]

(1a)

\[
a = \left( x^2 + \frac{y^2}{y_0^2} + \frac{z^2}{z_0^2} \right)^{1/2},
\]

(1b)

\[
\rho_1 = \rho_0 \exp(-0.5r^2),
\]

(2a)

\[
\rho_2 = \rho_0 r^{-1.8} \exp(-r^3),
\]

(2b)

\[
\rho_3 = \rho_0 \exp(-r),
\]

(2c)

where \( r \) is defined by,

\[
r = \left[ \left( \frac{x}{x_0} \right)^2 + \left( \frac{y}{y_0} \right)^2 + \left( \frac{z}{z_0} \right)^2 \right]^{\frac{1}{2}}.
\]

(3)

---

<table>
<thead>
<tr>
<th>Model</th>
<th>( \rho_0 )</th>
<th>( x_0 )</th>
<th>( y_0 )</th>
<th>( z_0 )</th>
<th>( a_0 )</th>
<th>( a_m )</th>
<th>PKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eqn. 1a</td>
<td>890</td>
<td>-</td>
<td>0.674</td>
<td>1.00</td>
<td>0.01</td>
<td>1.0</td>
<td>0.771</td>
</tr>
<tr>
<td>Eqn. 2a</td>
<td>( 1 \times 10^6 )</td>
<td>4.17</td>
<td>0.674</td>
<td>0.344</td>
<td>-</td>
<td>-</td>
<td>0.949</td>
</tr>
<tr>
<td>Eqn. 2b</td>
<td>( 1 \times 10^6 )</td>
<td>0.817</td>
<td>0.838</td>
<td>0.45</td>
<td>-</td>
<td>-</td>
<td>0.893</td>
</tr>
<tr>
<td>Eqn. 2c</td>
<td>( 1 \times 10^7 )</td>
<td>1.11</td>
<td>0.744</td>
<td>1.00</td>
<td>-</td>
<td>-</td>
<td>0.575</td>
</tr>
</tbody>
</table>

Morris et al. (2017)
Reddening

- Model of Dawson and Johnson (1994), where $\alpha_{GC} = 9.4 \, m_V \, pc^{-1}$, $r_d = 5 \, kpc$ and $z_d = 0.2 \, kpc$

$$\alpha(r, z) = \frac{A_R}{A_V} \alpha_{GC} \exp \left( \frac{-r}{r_d} \right) \exp \left( \frac{-|z|}{z_d} \right), \quad \Delta m_R = \sum_i \alpha_i \Delta s_i.$$
Galactic Novae Statistics

- In the first 8 years of LAT observations, 69 optically identified novae, 6 observed to $> 5\sigma$ in gamma-rays
- Dimmest has $m_V \approx 17.5$
Assigning Gamma-ray Fluxes

<table>
<thead>
<tr>
<th>nova</th>
<th>V407 Cyg</th>
<th>V1324 Sco</th>
<th>V959 Mon</th>
<th>V339 Del</th>
<th>V1369 Cen</th>
<th>V5668 Sgr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak daily flux, $F_\gamma$ ($10^{-7}$ ph s$^{-1}$ m$^{-2}$)</td>
<td>13.9±2.6</td>
<td>12.3±2.9</td>
<td>13.8±3.7</td>
<td>5.9±1.1</td>
<td>5.1±1.3</td>
<td>1.8±0.8</td>
</tr>
<tr>
<td>$F_\gamma/F_{\text{GalDiff}}$</td>
<td>0.254</td>
<td>0.185</td>
<td>0.305</td>
<td>0.381</td>
<td>0.0897</td>
<td>0.0704</td>
</tr>
<tr>
<td>TS value</td>
<td>56.8</td>
<td>35.0</td>
<td>27.7</td>
<td>65.7</td>
<td>37.6</td>
<td>11.6</td>
</tr>
<tr>
<td>Distance (kpc)</td>
<td>3.5±0.3</td>
<td>4.3±0.9</td>
<td>1.4±0.4</td>
<td>3.2±0.3</td>
<td>2.5</td>
<td>1.5±0.2</td>
</tr>
</tbody>
</table>

- For gamma-rays,
  \[ F_\gamma = \frac{L_\gamma}{4\pi d^2}, \]
  hence $L_\gamma$ can be obtained for every source.
- As there is a very small sample size, a flat distribution was assumed between them, and used to assign gamma-ray fluxes to simulated novae.
Results

- Simulations were able to produce the observed percentage of gamma-ray detected novae
- Simulations return $5 \pm 2$ gamma-ray novae for $68 \pm 12$ optical novae.
- The limiting factor is always the gamma-ray background and not optical visibility
• The number of optical novae detected strongly depends on threshold magnitude
• The number of novae discovered in gamma-rays and optically is independent of this
• Therefore, the limiting factor is always the gamma-ray background and not optical visibility
Results

- Novae with $m_R > 12$ are unlikely to be observed in gamma-rays.
- The same is true for novae at $d > 8$ kpc, though at this distance we can realistically only expect to observe gamma-ray bright novae.
New Gamma-ray Novae

- V5856 Sgr (Li et al., 2016, 2017) has a gamma-ray peak of $9.7 \times 10^{-7}$ ph s$^{-1}$ cm$^{-2}$, a distance of 4.2 kpc and V band peak of 5.4.
- Two more gamma-ray novae, V5855 Sgr and V407 Lup have also been detected (Li & Chomiuk, 2016; Cheung et al., 2016) though as of yet they have no distance estimates.
Conclusions

• Novae with $m_R > 12$ are unlikely to be observed in gamma-rays.
• We expect all gamma-ray detected novae do occur within a distance $d < 8$ kpc
• The gamma-ray sky background is the greatest inhibition to the discovery of gamma-ray novae.
• The Fermi LAT has detected most, if not all, gamma-ray novae that occur in locations not dominated by the gamma-ray sky background.
• All classical novae are sources of gamma-rays, and their apparent rarity is a consequence of us only being able to detect a nearby sub-sample.