Gamma-ray Novae: Rare or Nearby?

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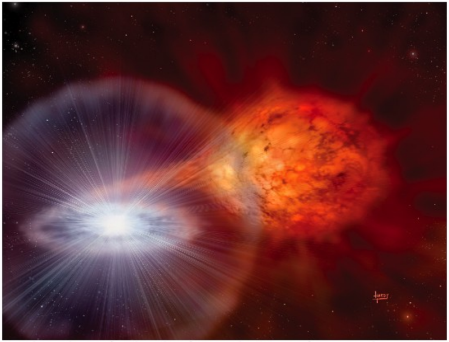
Cataclysmic Variables (CVs): Novae Progenitors

- 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.



Artist's rendition of a white dwarf accumulating mass from a nearby companion star. This type of progenitor system would be considered singly-degenerate.

Image courtesy of David A. Hardy, © David A. Hardy/www.astroart.org.

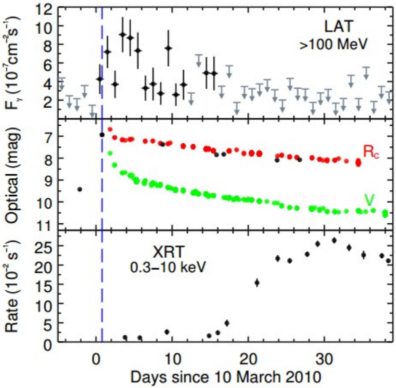
Types of Nova

Nova	Classical	Recurrent	Dwarf
Timescale	$10^{4\text{-}5}$ years	20-40 years	30-300 days
Factor increase in brightness	10^6	10^3	10
Magnitude change	12	8	6
Mechanism	Thermonuclear Runaway (TNR)	Combination of TNR & DI	Disk Instability (DI)

Carroll & Ostlie, 2007

V407 Cyg: The First Gamma-ray Nova

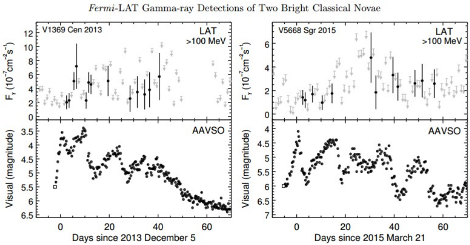
- Observed in gamma-rays during a classical nova outburst in 2010
- Unusual system as the secondary star is a pulsating Mira variable
- Gamma-rays were thought to be caused by interaction between the nova shell and dense Mira wind
- It was concluded that novae would not generally emit gamma-rays



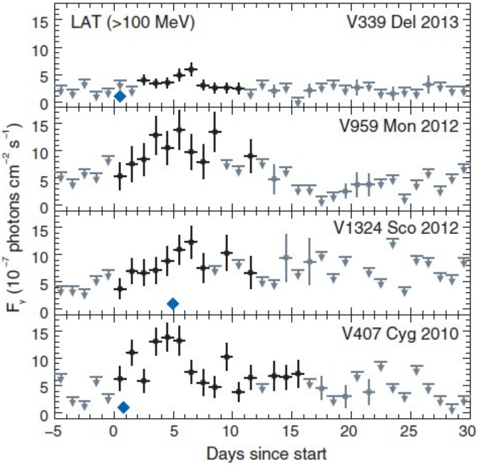
Abdo et al. 2010

The > 5σ 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?

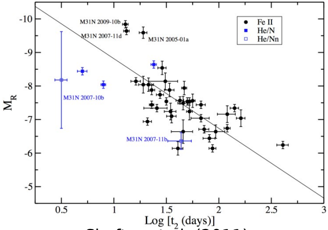
Nova	V407 Cyg 2010	V1324 Sco 2012	V959 Mon 2012	V339 Del 2013
Distance (kpc)	2.7	4.5	3.6	4.2
Peak magnitude	6.9	10.0	5*	4.3
Peak date	10.80 Mar 2010	19.96 Jun 2012	—	16.50 Aug 2013
Optical RA, Decl.	315.5409°, +45.7758°	267.7246°, −32.6224°	99.9108°, +5.8980°	305.8792°, +20.7681°
Optical *l*, *b*	86.9826°, −0.4820°	357.4255°, −2.8723°	206.3406°, +0.0754°	62.2003°, −9.4234°
LAT RA, Decl.	315.57°, +45.75°	267.72°, −32.69°	99.98°, +5.86°	305.91°, +20.78°
Optical-LAT offset	0.03°	0.07°	0.08°	0.03°
LAT error radius (95%)	0.08°	0.09°	0.18°	0.12°
t_s (date)	10 Mar 2010	15 Jun 2012	19 Jun 2012	16 Aug 2013
t_s (MJD)	55265	56093	56097	56520
Duration (days)	22	17	22	27
L_γ (10^{35} erg s^{-1})	3.2	8.6	3.7	2.6
Total energy (10^{41} erg)	6.1	13	7.1	6.0

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

Ackermann et al.
(2012)

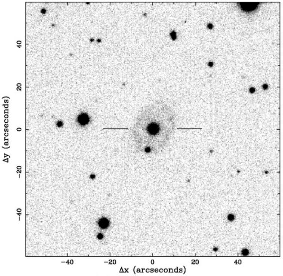
Why Not Just Measure the Distances to multiple novae?

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



Shafter et al. (2011)

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



(a) T Aur, Hα

Sahman et al. (2015)

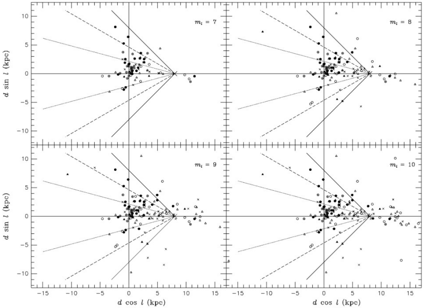
What is the Nova Occurrence Rate? -Galactic Method

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)



$$N_{novae} = 35 \pm 11\ \mathrm{yr}^{-1}$$

Shafter (1997)

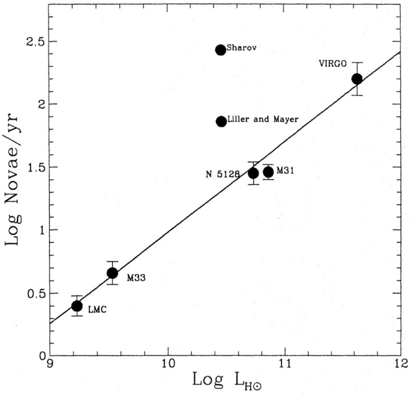
What is the Nova Occurrence Rate? -Extragalactic Method

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

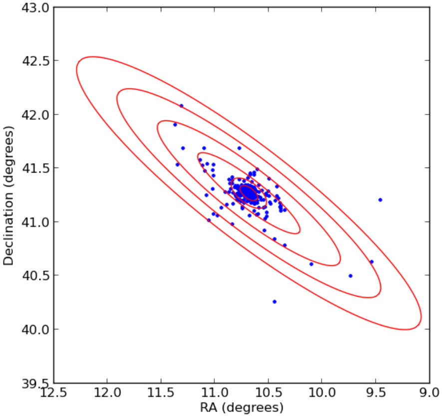


$N_{novae} \sim 20\ \mathrm{yr}^{-1}$

Delle Valle & Livio (1994)

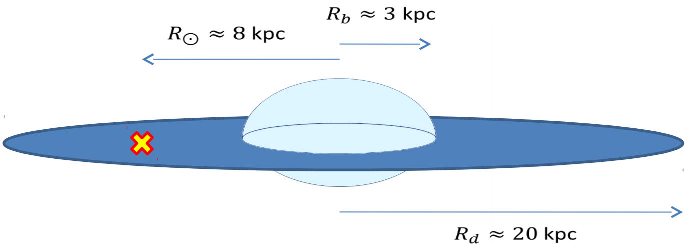
Novae in M31

- 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?

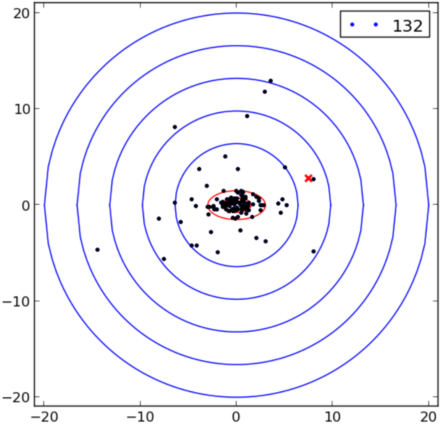


- Milky Way radius: Typically believed to be in the range 15-25 kpc
- Solar distance from the Galactic centre is well constrained to be close to 8 kpc
- The bulge/disc boundary is not well defined

e.g. Carroll and Ostlie (2007)

Populating the Milky Way in 2D

- 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).



Populating the Milky Way: Bulge

- 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.

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

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

$$\rho_1 = \rho_0 \exp(-0.5r^2), \quad (2a)$$

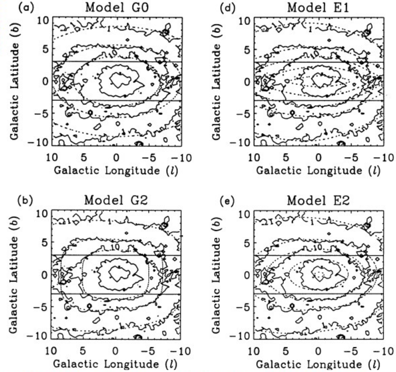
$$\rho_2 = \rho_0 r^{-1.8} \exp(-r^3), \quad (2b)$$

$$\rho_3 = \rho_0 \exp(-r), \quad (2c)$$

where r is defined by,

$$r = \left[\left(\frac{x}{x_0}\right)^2 + \left(\frac{y}{y_0}\right)^2 + \left(\frac{z}{z_0}\right)^2\right]^{\frac{1}{2}}, \quad (3)$$

Dwek et al. 1995



Model	ρ_0	x_0	y_0	z_0	a_0	a_m	p_{KS}
Eqn. 1a	890	-	0.674	1.00	0.01	1.0	0.771
Eqn. 2a	1×10^6	4.17	0.674	0.344	-	-	0.949
Eqn. 2b	1×10^6	0.817	0.838	0.45	-	-	0.893
Eqn. 2c	1×10^7	1.11	0.744	1.00	-	-	0.575

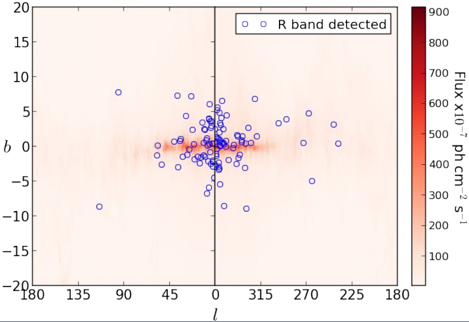
Morris et al. (2017)

Reddening

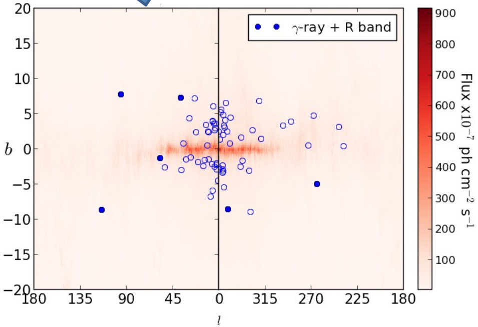
- Model of Dawson and Johnson (1994), where $\alpha_{GC} = 9.4\, m_V\ \mathrm{pc}^{-1}$, $r_d = 5\mathrm{kpc}$ and $z_d = 0.2\ \mathrm{kpc}$

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

Entire Simulated population

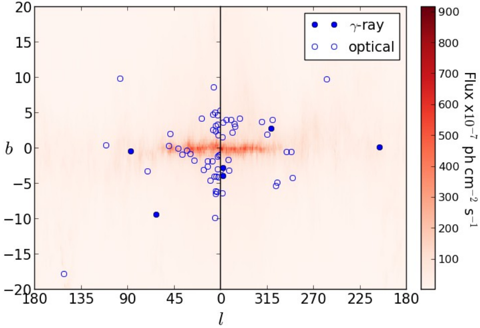


Those that would be optically visible



Galactic Novae Statistics

- List by Koji Mukai: http://asd.gsfc.nasa.gov/Koji.Mukai/novae/novae.html
- 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

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

- For gamma-rays,

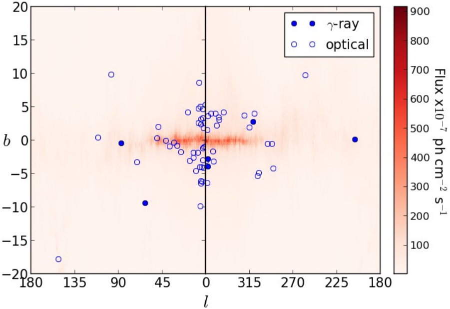
$$F_\gamma = \frac{L_\gamma}{4\pi d^2},$$

hence L_γ can be obtained for every source.

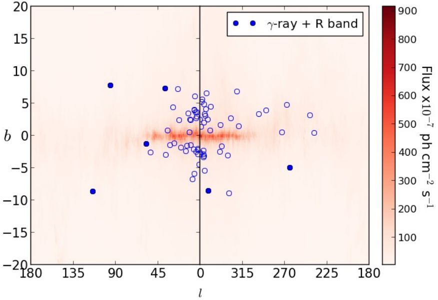
- As there is a very small sample size, a flat distribution was assumed between them, and used to assign gamma-ray fluxes to simulated novae.

Results

- Simulations were able to produce the observed percentage of gamma-ray detected novae
- Simulations return 5 ± 2 gamma-ray novae for 68 ± 12 optical novae.
- The limiting factor is always the gamma-ray background and not optical visibility



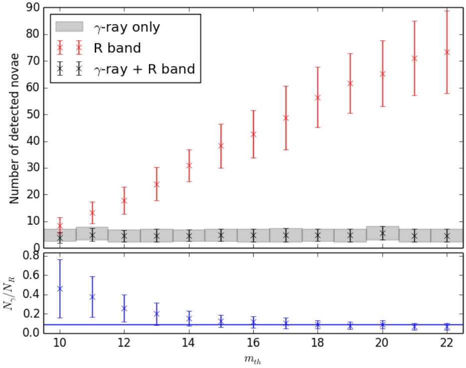
Observed



Simulated

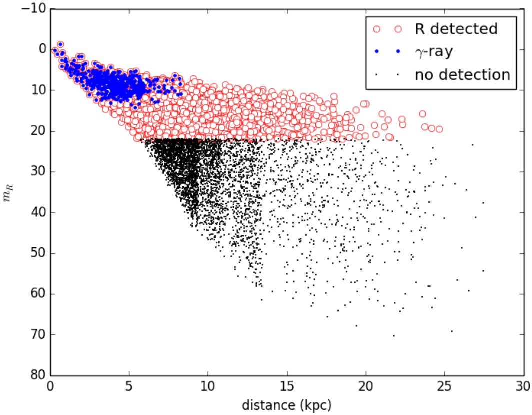
Results

- 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

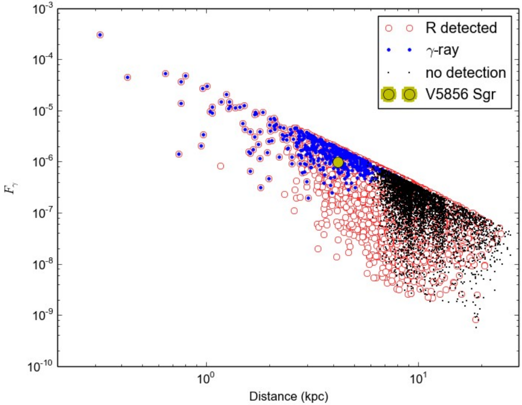


Results

- 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 Srg (Li et al., 2016, 2017) has a gamma-ray peak of 9.7×10^{-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 $\mathrm{d} < 8$ 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.