X-rays from Nova Shocks

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Plan of Talk

- We often observe 1-10 keV thermal X-rays from novae
  - Embedded novae in symbiotic stars – evidence of external shocks
  - Clean novae in CVs – evidence of internal shocks
- Particle acceleration and thermal X-ray emission
  - Case studies of Fermi-detected novae
  - Case studies of other recent novae (“why weren’t these novae detected with Fermi?”)
- Search for non-thermal X-ray emission

Punchline: In most cases, GeV gamma-rays are seen first, and thermal X-rays are detected later.

- Discussion
  - How we might hide X-rays from shocks
  - Do we need multiple shocks?
When a nova erupts in a symbiotic system (e.g., RS Oph, V407 Cyg, V745 Sco), the ejecta is embedded in the red giant wind. Recurrent novae impulsively eject ~10^{-6} solar masses. Wind is denser near the giant. The giant can be as close as ~1 AU (~1 day travel time for nova ejecta) to 10s of AUs (~a few weeks). A strong external shock is an inevitable consequence; shock should be strongest when the ejecta reach the vicinity of the red giant.
Case Study: V745 Sco

V745 Sco was already a bright X-ray source 3.7 hrs after the optical detection of nova eruption. It was also marginally detected with Fermi/LAT during the first 2 days. During the first 3 days, $N_H$ declined but no changes were apparent in $kT$. (From Page et al. 2015, MNRAS 454, 3108)
Clean Novae: Internal Shocks

- Novae in CVs – those erupting in a clean environment – do emit hard (1-10 keV), thermal X-rays
- Many novae that were monitored frequently with sensitive (imaging) instruments have been detected, with luminosities in the $10^{33}$-$10^{35}$ erg/s range
- There is usually a delay of days to weeks (since the onset of nova eruption) before the first X-ray detection

There is no known external matter for the nova ejecta to run into: Internal Shock
V382 Vel (1999)

- Undetected with RXTE/PCA on Day 5.7
- Strongly detected with ASCA on Day 20
- Evolution traced with RXTE/PCA during days 31-59
- X-ray spectrum indicates a thermal, collisionally excited plasma origin

Broad outline of the model: Initial impulsive, relatively slow (~1000 km/s), ejection of a shell (5x10^{-5} M_\odot) followed by a faster (e.g., ~4000 km/s) wind

- The initial shell provides the observed N_H and could explain the non-detection at day 5.7
- The velocity differential is sufficient to create kT~10 keV plasma; the wind momentum gradually accelerates the shell and lowers the temperature
- The density is low enough for radiative cooling to be inefficient

# Fermi-detected Novae

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Other bright novae of note in the *Fermi* era:
- T Pyx (2011): a recurrent nova in a CV, probably in a clean environment; peak~6th mag, delayed ejection, no Fermi detection
- V5589 Sgr (2012): bright, hard X-ray emission, non-thermal radio, no Fermi/LAT detection
Embedded Novae V745 Sco and V407 Cyg

V745 Sco is a textbook case of external shock:
- Strong shock formed within hours of optical peak
- Shock produced both thermal X-rays and accelerated particles
- Did it also produce non-thermal X-rays? We don’t know, for lack of suitable data (Can we constrain early, non-thermal X-rays in RS Oph?)

V407 Cyg can also be interpreted as external shock, but:
- Requires a much larger binary separation, and a relative low density around white dwarf
- Shock, as seen by thermal X-rays, strongest around day 20, when the blast wave reached the Mira type mass donor
- Brightest in GeV gamma-rays during the first 20 days

2016 Jun 24
Clean Novae: cases of weak early X-rays

- V1324 Sco: non-detections through days 30-50, 80, 140, 365 and 540
  - Given the >6.5 kpc distance (Finzell et al. 2015 ApJ 809, A120), not a stringent upper limit
  - High GeV luminosity is the surprise
- V339 Del: Non-detection through day 35
- V1369 Cen: Non-detection through first 70 days
- V5668 Sgr: Non-detection through first 90 days
- In the latter three cases, initial detection was of kT~1-2.5 keV plasma with NH~5x10^{22} cm^{-2} – probably requires increasing EM, unless NH drop acute.

These 4 novae were undetected as X-ray sources during Fermi/LAT detection. In two cases (V1369 Cen, V5668 Sgr), optical light curves showed oscillations.
V959 Mon: a missed opportunity

- V959 was unobservable with X-ray instruments for ~60 days since initial Fermi/LAT detection due to solar conjunction.
- Already X-ray bright by the time of first Swift observation; bright enough for Chandra/HETG observation. Spectra indicate enhanced abundance of some elements and NEI.
- $N_H$ evolution suggests the outer, slow shell (presumably responsible for the time-dependent X-ray absorption) was not ejected till ~day 30. (cf. Linford et al. 2015, ApJ, 805, A136)
Case Study: 2011 eruption of T Pyx

- T Pyx is an unusual recurrent nova: CV that is accreting at an inexplicably high rate
- Its 2011 eruption was among the optical brightest novae not to be detected in GeV gamma-rays with Fermi/LAT
- Main X-ray turn-on around day 115 (Chomiuk et al. 2014, ApJ, 778, A130), with weak X-ray (and radio) detection around day 15
- Strong case for a delayed ejection: TNR puffs up the white dwarf envelope to red giant dimension, with small amount of ejection; additional energy input leads to main ejection around day ~60
Case Study: V5589 Sgr (2012)

- X-ray was not detected on day 1 & day 6
- Strongly detected on day 40 (Nelson et al. 2012, ATel 4110)
- \( N_H \) was low (\( \sim 3 \times 10^{21} \) cm\(^{-2} \)) and \( kT \) was extremely high (>20 keV), requiring velocity differential of >4000 km/s
- Optical spectra indicated ejecta velocity as high as 6500 km/s, so this is feasible

- Particle acceleration ought to be more efficient for higher velocity shocks – so this is a prime candidate for it. Yet no detection was reported with Fermi/LAT (NB it was not observed in pointing mode – could have been as bright as V339 Del, for example)
- On the other hand, radio observations likely indicate the presence of synchrotron emission from relativistic particles (Weston et al. 2016, MNRAS, in press)
Takei et al. (2009, ApJLett, 697, L54) reports on the possible detection of non-thermal X-rays from V2491 Cyg (which erupted ~2 months before the launch of Fermi) on day 9 but not on day 29, using non-imaging Suzaku/HXD.

Orio et al. (2015, MNRASL, 448, L35) detected only thermal X-ray emission from V745 Sco with NuSTAR and Swift on Day 10.

Mukai et al. (in preparation) observed V339 Del on day 9 and V5668 Sgr on day 13 and obtained only upper limits for both thermal and non-thermal X-rays.

Thermal X-ray spectrum of V745 Sco – probably too late to catch any non-thermal X-rays.
Hiding Thermal X-rays from Shocks

- Any shocks that can efficiently accelerate particles probably have high enough temperatures for ISM to hide.
- However, intrinsic absorption – that by the outer slow shell – can possibly do the trick, if it is massive enough.
  - If the slow shell is promptly ejected, it will take an extraordinary massive (>10^{-4} M_\odot) shell to keep hiding shock X-rays for more than a week or two.
- On the other extreme, if the shock density is low enough, the cooling time becomes sufficiently long (i.e., X-ray emission becomes inefficient) so X-ray luminosity will be low.
  - NEI signatures seen in deep snapshot observations of several novae suggest the observed thermal X-rays are not too far from this regime.

\[
v_s = \sqrt{\frac{16 \ kT_{br}}{3 \ \mu \ m_H}}
\]

\[
v_s \quad \text{in} \ \text{km s}^{-1} = \sqrt{\frac{T_{br}}{1.4 \times 10^7 \ K}}
\]

\[
t_c = 6.8 \times 10^{14} \sqrt{\frac{K}{n}} \ \text{s}
\]
Discussion: Multiple shocks, and other questions

- Do we need one explanation for GeV emission from embedded novae and a different explanation for clean novae? Or can a single mechanism work for both?
  - GeV emission appears prompt, while thermal X-rays are delayed in clean novae
- In clean novae, do we need one shock that emit observed thermal X-rays and another to accelerate particles? Or can a single mechanism work for both?
  - If the main shell in V959 Mon was indeed not ejected till 25-30 days after the initial Fermi detection, particle acceleration and X-ray emission were due to different shocks.
- Do we need one explanation for novae with long plateau/oscillations (T Pyx, V1369 Cen, and V5668 Sgr) and another explanation for novae without?
  - If the main ejection was delayed, with the WD in RG-like configuration, X-rays from any shocks inside the envelope will remain hidden
- What is the origin of the early, faint X-ray emission, and is that related to particle acceleration?
- Why was V1324 Sco so GeV bright? It was a relatively slow nova – high mass ejecta?