X-ray Observations of Shocked Nova Ejecta

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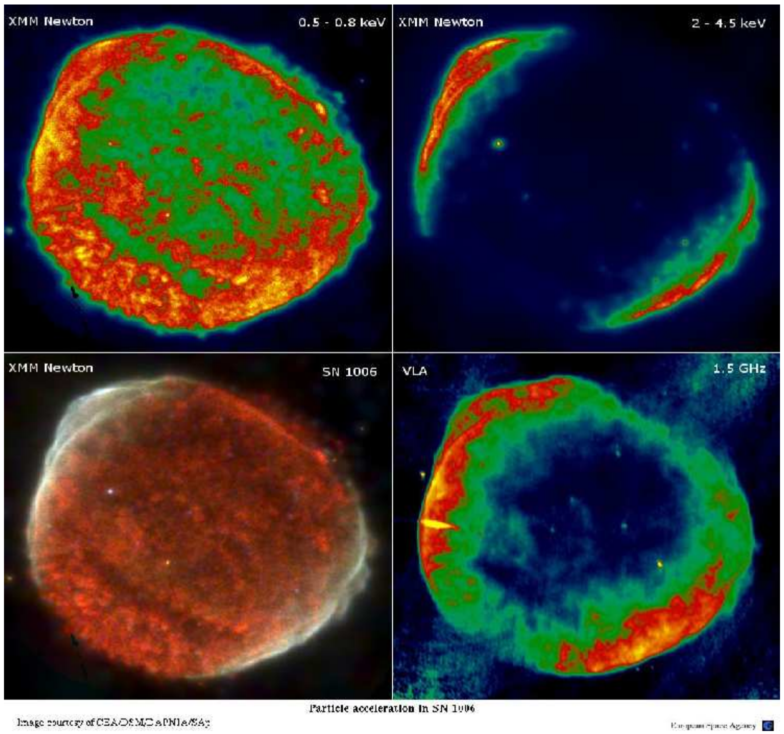
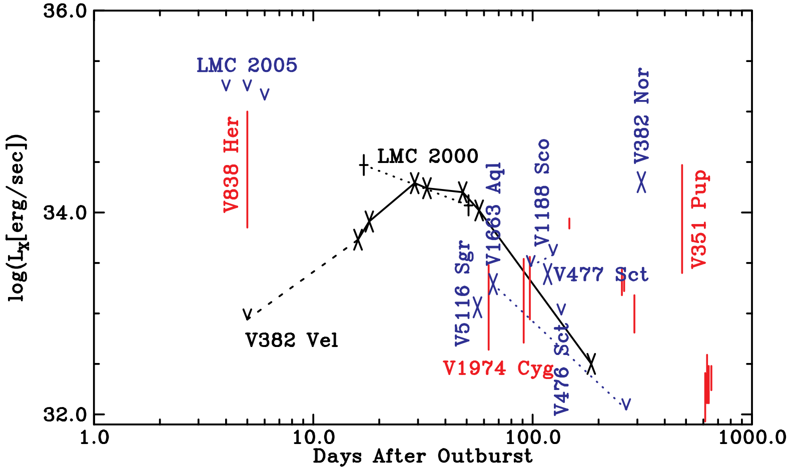
Introduction



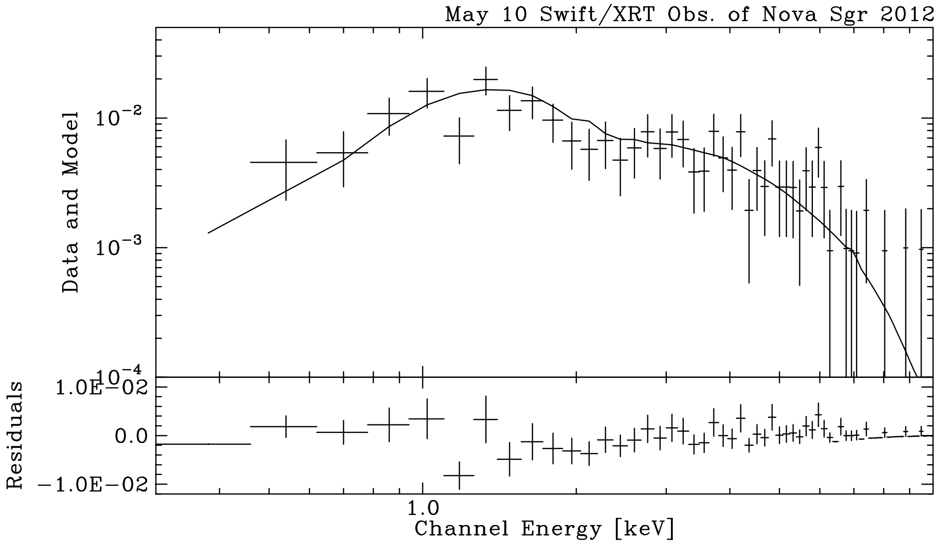
- Hard (1–10 keV), optically thin thermal X-ray emission is a common feature of novae days to months after the peak.
- In RS Oph and V407 Cyg ("embedded novae"), the shock was due to the collision of ejecta and the dense wind of the M giant.
- In supernova remnants, ejecta eventually sweeps up enough ISM to produce X-ray and cosmic-ray producing shocks.
- In most classical novae, we must invoke internal shocks, caused by a significant δV within the ejecta.

Some Basic Numbers

- Total kinetic energy of ejecta: $\sim 1 \times 10^{45}$ ergs (for 10^{-5} $M_\odot$ and 3,000 km s^{-1}).
- Density, if in a $\delta R = 0.1R$ shell: 6×10^{10} [t/1 day]$^{-3}$ cm^{-3}.
- Swept-up ISM for 3,000 km s^{-1} ejection: $\sim 3 \times 10^{-9} \times [t/1yr]^3$ $M_\odot$ (for n = 1 cm^{-3}).
- Shock temperature: $kT_s \sim 10.83[\delta V/3,000]^2$ keV — however, it take ions $nt \sim 10^{12}$ cm^{-3}s to reach appropriate ionization equilibrium.
- Bremsstrahlung cooling time: $1.3 \times 10^{14} kT^{1/2}/n$ s

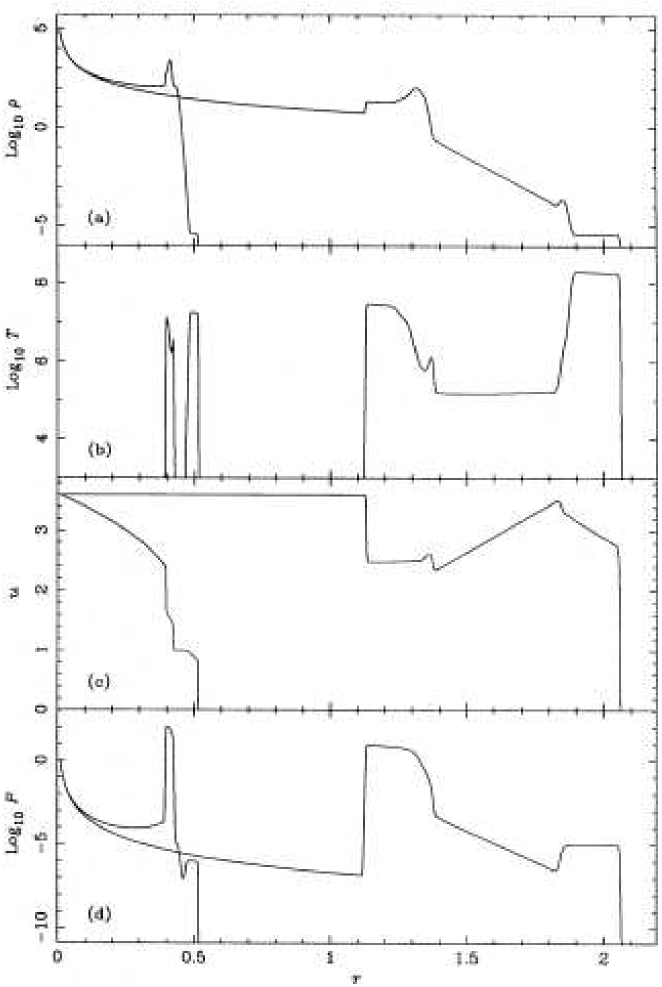


High kT Shock in Nova Sgr 2012 #1



- Nova Sgr 2012 #1 was undetected with *Swift* XRT on Day 1 and Day 5.
- Detection on Day 20. $kT > 23$ keV (Nelson et al.) or even $>$33 keV (Kim Page's analysis). δV is $>$4,400 or $>$5,200 km s^{-1}
- Esipov et al. (ATel 4094) estimated ejecta velocity of 6,500 km s^{-1}. There must be a $<$2,100 km s^{-1} ejecta ahead of this system.
- Despite the high shock temperature, Nova Sgr 2012 #1 was *not* detected with *Fermi* LAT.

kT in other novae

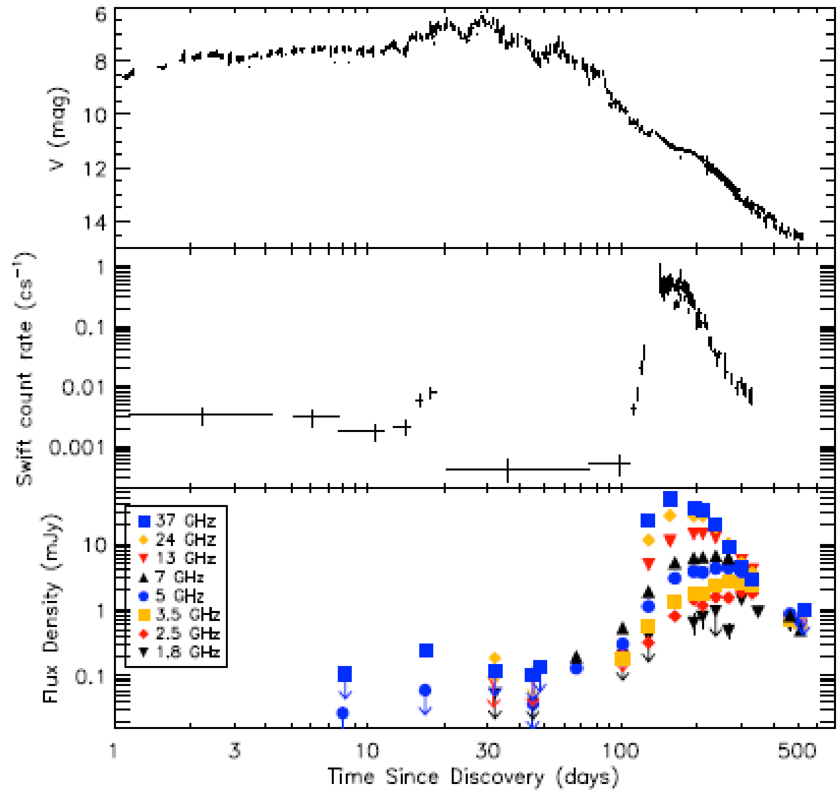


- Nova Sgr 2012 #1 is an extreme. However, typical kT at initial detection are often in 3 to 10 keV range.
- Longevity can be explained if post-shock density is low: $n \sim 10^7$ cm^{-3} leads to cooling time $\sim 10^7$ s.
- Data so far suggest kT highest at initial detection, with slow decline over time.
- Gradual increase in velocity (O'Brien, Lloyd, & Bode 1994, who assumed 1,000 km s^{-1} to 3,600 km s^{-1} during day 1–5) leads to an initial period of kT increase, which has not been seen to date.

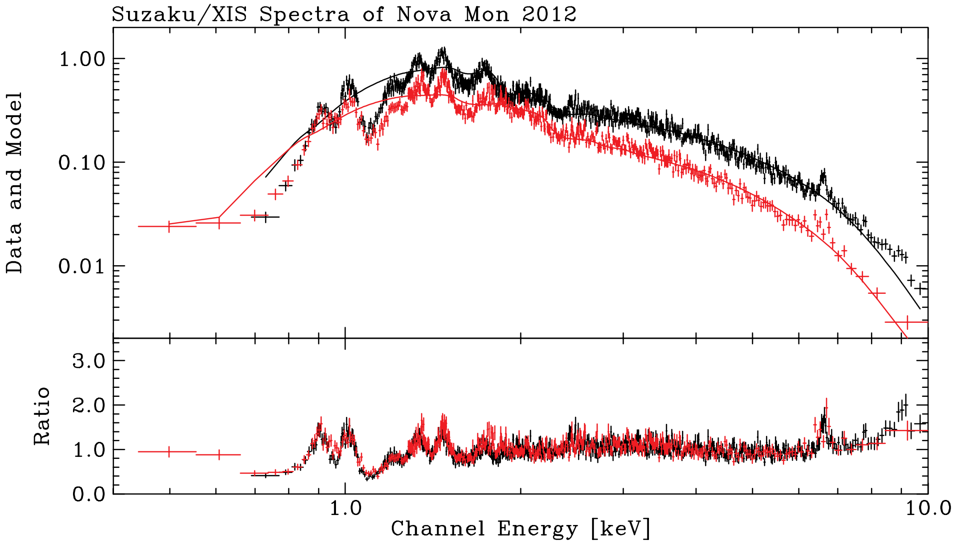
Teaser: T Pyx Results

- Main X-ray rise started around day 100, and most detected X-ray photons were from the shell. Increase in X-ray luminosity likely indicates more matter being shocked.
- Again, kT can be used to infer δV; the delayed onset of X-rays consistent with the delayed onset of the fast outflow.
- Gradual decline in X-ray flux can be due to density decrease, radiative cooling, and/or adiabatic cooling.

More in Laura's talk.

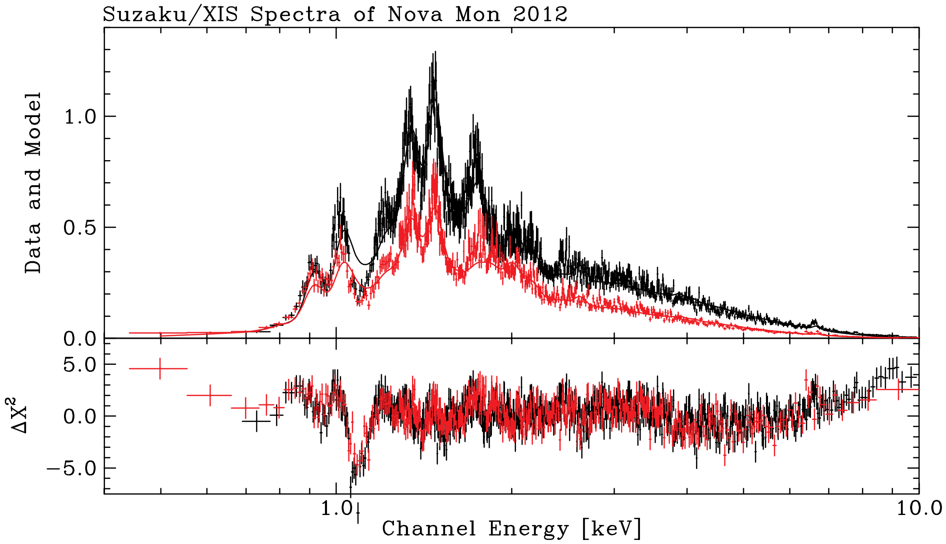


X-ray Spectra of Nova Mon 2012



- In addition to *Swift* XRT monitoring, we observed Nova Mon 2012 for ∼47 ks with *Suzaku* on 2012 Sep 25.
- By fitting the continuum above 2 keV, we obtain $kT_e = 4.8 \pm 0.2$ keV, or $\delta V \sim$ 2000 km s^{-1}.
- However, the Mg and Ne lines are both extraordinarily strong, and the ratio of the H-like and He-like lines indicates a much lower ionization temperature.

X-ray Spectra of Nova Mon 2012 (2)

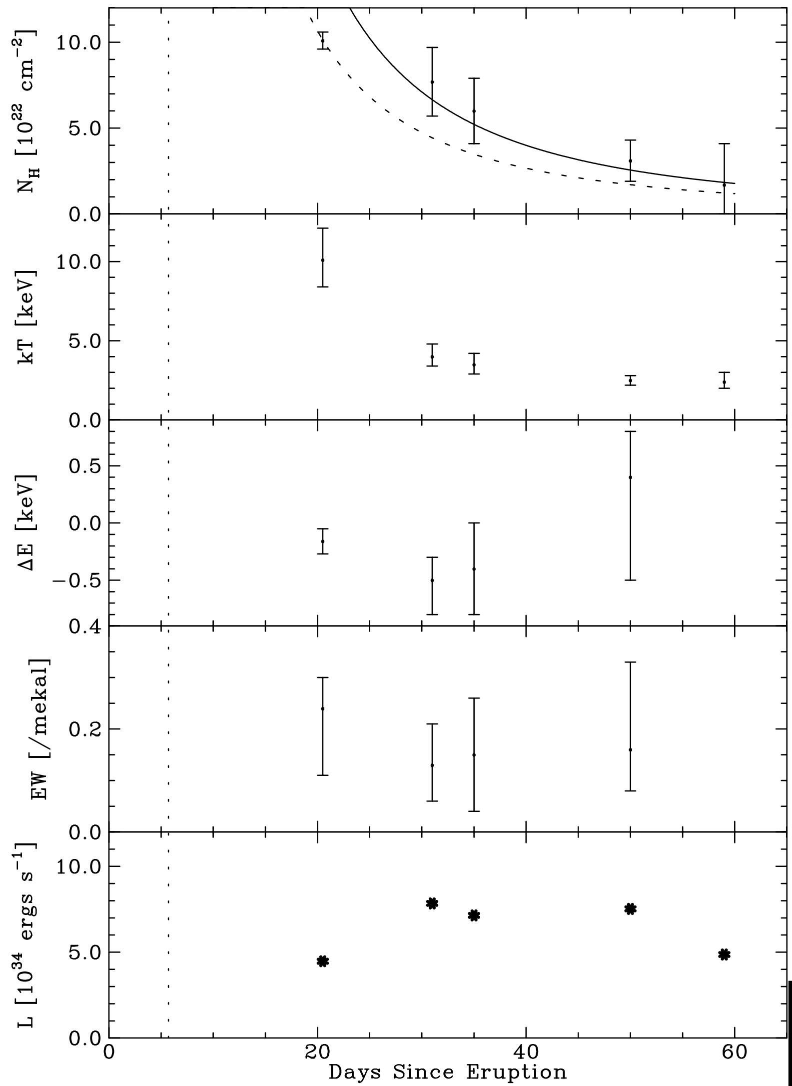


- Preliminary fit attempts suggest a strong (∼8–9) overabundance of Ne and Mg, as well as that of O.
- Early indications are that we need at least some of the emission to come from low ionization time ($n_e t \sim$ a few $\times 10^{11}$ cm^{-3}s) plasma.
- Assumption of collisional ionization equilibrium may lead to incorrect and/or inconsistent results.

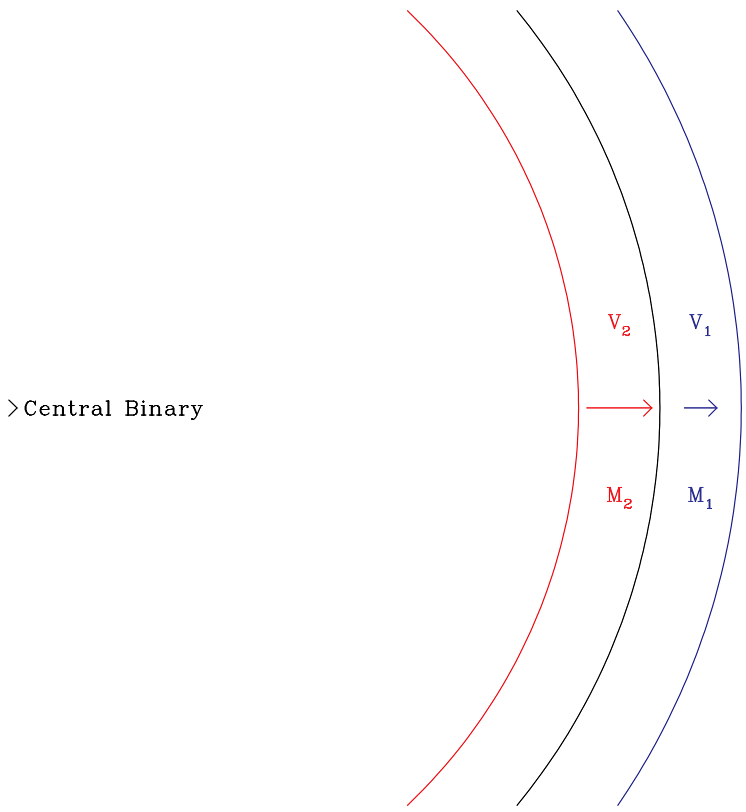
The Case of V382 Vel

- Early X-ray emission from V382 Vel was monitored using *RXTE*, *ASCA* and *BeppoSAX*.
- After an initial non-detection, hard X-ray emission was strongly detected.
- The spectral evolution was characterized by both a drop in kT and a drop in N_H.
- All the *RXTE* N_H points are consistent with a t^{-2} evolution.

We can explain this if the first, slower ejecta is much more massive (hence mostly remains unshocked), and was ejected at t=0 (its velocity can't have changed by the collision, since it has not been shocked).



A Schematic Model of N_H Evolution



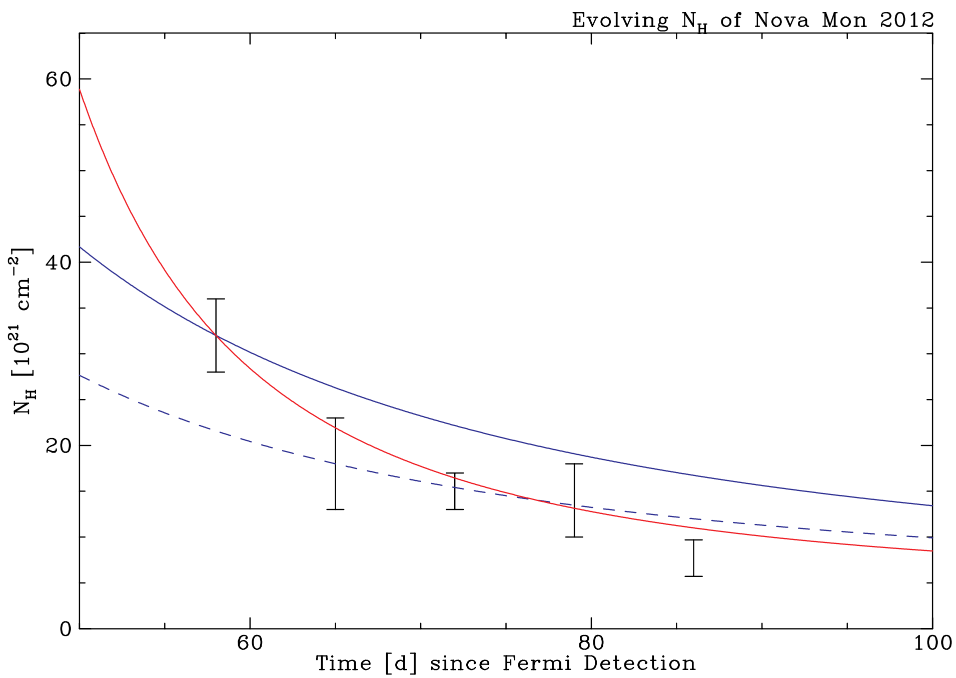
- Under the assumption that the outer, slower layer is much more massive, it will remain largely unshocked for a long time.
- Further assuming no acceleration/deceleration of this layer, X-ray column density should be inversely proportional to the square of time since ejection of this layer.
- There is also complications due to the geometry of the shocked region.

$$N_H \sim 2.4 \times 10^{25} [t/1day]^{-2} cm^{-2}$$

for a 1,000 km s^{-1}, $3{\times}10^{-5}$ $M_\odot$ ejecta (Recall Henze's argument on the unveiling of SSS).

N_H Evolution of Nova Mon 2012

- First several *Swift* XRT spectra show a rapid drop in N_H.
- The t^{-2} law assuming ejection at the time of Fermi discovery (blue) results in a shallower slope at this time.
- The same law with a ~30 day delay (red) follows the observed trend muchmore closely.
- Is this delayed ejection view true?



Current and Future Insights

Frequent detections of hard X-rays in unembedded novae implys that internal shocks are common (universal?); total kinetic energy of ejecta can easily power all the observed X-rays and more.

- The measured kT values imply large velocity differentials.
  - Non-equilibrium ionization needs to be considered in fitting data, because of low density.
  - The same modest density also implies long cooling time, easily of order years.
- The measured evolution of N_H is broadly consistent with expanding outer ejecta.
  - It's hard to imagine that the velocity of the outer ejecta was already modified before it gets shocked.
  - N_H evolution shows it was ejected during the observed nova event, but with a delay for Nova Mon 2012.
- There is always a delay before X-ray emission is detected.
  - Time for shock to develop? But what about prompt GeV emission?
  - Initial N_H too high for X-rays to escape? Can this also explain Nova Sco 2012?