

TWO INTRIGUING ERUPTING VARIABLES

OBSERVED WITH CHANDRA

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IM Nor

- IM Nor is a *recurrent nova* (RN). Outbursts were observed in 1920 and on January 3 2002 (Wood & Liller 1972, Liller 2002). It has a short orbital period (2.46 hours) and belongs to a sub-class of RN that *do not host a red giant companion*.
- Classical novae are thought to be recurrent over time scales ≥ 1000 years, but RN undergo interoutburst periods of ≤ 100 years. They are interesting as possible progenitors of type Ia Supernovae (e.g. Livio & Truran 1995, Della Valle & Livio 1996) and as a link between supersoft X-ray sources and novae.
- IM Nor was observed with *Chandra ACIS-S* 1 month after the outburst during the Director Discretionary Time. We observed it again 5 months after the outburst as part of a Target of Opportunity program for novae in outburst.

WHY ARE ERUPTING NOVAE X-RAY SOURCES?

Novae can be faint quiescent X-ray sources because of accretion, but after an outburst, the remnant white dwarf turns into a more luminous X-ray source, due to shocks in the ejected shell (e.g. in colliding winds, or phenomena between ejecta and circumstellar matter). Thermal bremsstrahlung emission is detected at temperatures in the range 0.1-10 keV, and emission lines are also detected in this energy range. The X-rays luminosity is $L_x = 10^{33-34} \text{ erg s}^{-1}$.

Rarer, but very interesting to understand the final fate of nova systems, is the luminous "SUPERSOFT" X-ray emission, due to residual hydrogen burning in a shell and observable when the ejecta become optically thin to supersoft X-rays. The central source is very luminous, with $L_x = 10^{36-38} \text{ erg s}^{-1}$. The atmosphere of a very hot WD with a "forest" of narrow and crowded absorption lines appears.

3 RN compared: IM Nor, CI Aql and U Sco

If the central WD is detected in supersoft X-rays, with atmospheric models we can derive the effective temperature, effective gravity and chemical composition of the underlying white dwarf. In addition, the length of the supersoft X-ray phase is an indication of the amount of hydrogen fuel left over after each outburst, hence the likelihood that the white dwarf mass grows towards the Chandrasekhar limit. If the WD mass grows after repeated outbursts, recurrent novae are the most likely progenitors of type Ia SN among novae and CV. There is also a second channel towards a type Ia SN explosion: accumulation of helium ashes in which explosive He burning could once be triggered (Fujimoto & Sugimoto 1982). The nature of type Ia SN progenitors is an open question. Both *single degenerate* close binary systems and *double degenerate* systems may contribute.

Della Valle & Livio (1996) argued that the contribution of RN to the type Ia SN rate is not high, but the recent discovery of two "different" RN, CI Aql and IM Nor (both with massive ejecta) may change their conclusions. The outbursts of these two newly studied RN, in 2001 and 2002 respectively, ejected a few $10^{-6} M_{\odot}$ and lasted for about 2 years for both, much longer than the one of the well studied RN U Sco that we take as a comparison. The decline of the optical light curve for U Sco was very rapid. U Sco is thought to have ejected only 1/10th of the mass ejected by CI Aql and IM Nor.

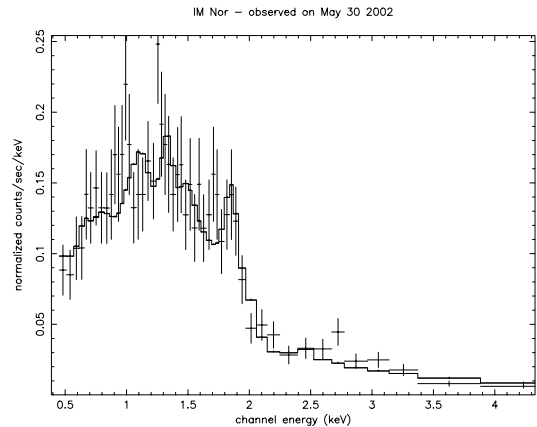
TOO EARLY OR TOO LATE?

In the Galaxy only up to 20% of all classical and recurrent novae were observed as supersoft X-ray sources for more than few months. The supersoft X-ray phase lasts mostly for up to 2 years, although exceptions of order of 10 years have been found (GQ Mus, N LMC 1995: see Orio et al. 2001, Orio et al. 2003). U Sco, a non-red giant system RN, was a supersoft X-ray source already 20 days after the outburst (Kahabka et al. 1999). This fast evolution indicates a massive white dwarf, which ejects little accreted mass, but retains part of it after the outburst. CI Aql, also a non-red giant system, probably hosts also a massive WD but the optical light curve evolved very slowly. Therefore, X-ray observations of CI Aql were done only after more than a year after the outburst, with the working hypothesis that the evolution in X-rays would be as slow as the optical one. However, X-ray emission could only be detected from the ejecta and not from the central source (Greiner and Di Stefano 2002). Hachisu et al. (2003) argued that the supersoft X-ray emitting WD of CI Aql would have been detected only 6 to 9 months after the outburst. We asked that observation of IM Nor, (optically more similar to CI Aql than to U Sco), be performed at 1 and 6 months post-outburst.

- After one post-burst month, the upper limit on the ACIS-S count rate for IM Nor was 0.0014 cts s⁻¹ => $F^X < 10^{-14}$ erg cm⁻² s⁻¹ for a blackbody at T=30 eV and N(H)=10²² cm⁻², or $F^X < 4 \times 10^{-14}$ erg cm⁻² s⁻¹ for a thermal plasma at kT=3 keV and N(H)=10²¹ cm⁻².

- IM Nor turned into an X-ray source 5 months later, but not into a “super-soft” and luminous one. We concluded that we detected only X-ray emission from the ejecta. At this stage IM Nor was a harder X-ray source than CI Aql, as expected for a shell in an earlier cooling stage.

- Have we just observed IM Nor *too early* to detect the hot WD atmosphere, or there was no supersoft X-ray source because no H-burning mass was retained after the outburst? Was all the accreted envelope ejected? The second conclusion seems more likely, but the jury is still out. Full coverage of the X-ray lightcurve of a RN is desirable in the future, possibly with a short observations every 2 months for 2 years.



The X-ray spectrum of IM Nor observed with *ACIS-S* 6 months after the outburst. The measured count rate was 0.267 ± 0.008 cts s^{-1} , a factor of 30 higher than for CI Aql after 16 months from the outburst. We show the fit with two thermal bremsstrahlung components (“Raymond-Smith” model in *XSPEC*): a) $kT=370$ eV, $N(H)=3 \times 10^{22}$ cm^{-2} , absorbed flux 1.6×10^{-12} erg cm^{-2} s^{-1} , corresponding to unabsorbed flux $F_x=6.1 \times 10^{-11}$ erg cm^{-2} s^{-1} ; b) $kT \approx 6$ keV, $N(H)=9 \times 10^{20}$ cm^{-2} , $F_x=1.6 \times 10^{-12}$ erg cm^{-2} s^{-1} ($\chi^2=1.1/d.o.f.$)

Note that with this S/N and spectral resolution the spectrum may also be much more complex than this simple two-components model.

V838 Mon

This object was the most intriguing erupting variable of the last 20-30 years. V838 Mon “made it” to the cover page of *Nature* in virtue of its extended light echo (Bond et al. 2002, and see Fig.2). A summary of the outburst characteristics can be found in Munari et al. (2002), Crause et al. (2003), Wisniewski et al. (2003). The characteristics of the outburst were unusual:

- A progenitor at $B=15.85$ brightened by about 5 magnitudes in a few days, showing an absorption line spectrum.
- After a month from the initial outburst, a new brightening by 2.7 mag occurred, with gradual appearance of an emission line spectrum (Balmer lines, BaII, LiI, and other *s*-elements) with P-Cyg profiles indicating expansion velocities of up to 500 km s^{-1} .
- After an increase in luminosity to $V=6.7$, there was a gradual decline with oscillations, and the emission line spectrum gradually disappeared.
- The IR spectrum became much later that of an extremely cool supergiant (Evans et al. 2003). A hot binary companion of B3V spectral type was also detected (Munari and Desidera 2002).
- There is significant dust around the star and ≈ 2 months after the outburst an intriguing light echo appeared, expanding at 0.44 arcsec day^{-1} .

Four models have been proposed to explain this unusual outburst, but the rapid cooling is difficult to justify:

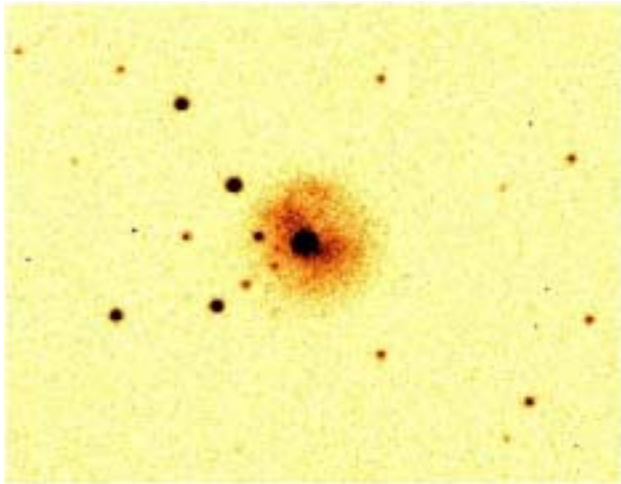
- It could have been a mild thermonuclear runaway (probably in a symbiotic binary, containing a WD and a red giant), or like the TNR event modelled by Iben & Tutukov (1992) .
- It may also have been a “born-again” AGB (the last He flash), but this interpretation is definitely not consistent with the rapid expansion and cooling (Evans et al. 2003).
- It could have been due to the merger of two main sequence stars (Soker & Tylenda 2003).
- The last model is that of an expanding giant that swallowed planets (Retter & Marom 2003).

THE CHANDRA RESULT

The star was not detected in the 0.2-10 keV band with ACIS-S with a firm 3σ upper limit of 1.5×10^{-3} cts s^{-1} pixel $^{-2}$. Thus the count rate upper limit is 1.42×10^{-3} cts s^{-1} for a point source (6 arcsec extraction radius). The flux upper limits in both blackbody and thermal bremsstrahlung case are $F_x < \text{a few } 10^{-14}$ erg cm^{-2} s^{-1} (see IM Nor, page 6).

Distance estimate vary between ≈ 670 pc and 3 kpc (Bond et al. 2003). With this distance range and even taking a larger extraction radius (for an emitting extended shell instead of assuming a point source), the upper limits on L_x are absolutely *not consistent* with observations of post-TNR symbiotics. Like for novae (see Page 6), X-rays are always detected from the ejecta, and often, supersoft X-rays with high luminosity are detected from the central WD (details can be found in Mürset et al. 1997). A symbiotic at $V=6.7$ in outburst *would have later been detected in X-rays*, and so would any similar system after a TNR.

We have ruled out one important possibility for the outburst of V838 Mon. An alternative likely scenario is the “merger” model of Soker and Tylenda, but the red, cool remnant is also difficult to explain in this model. The model of Retter and Marom explains the cooling better, but what role did the hot companion play in the eruption? The mystery has not been solved yet.... we are approaching a solution by ruling out one model at a time.



The image of the light echo of V838 Mon in the OIII filter, obtained in April of 2002 with the WIYN 3.5 m telescope (Orio et al. 2002). The diameter was about 35 arcseconds.

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