Pre-nova X-ray observations of V2491 Cyg (Nova Cyg 2008b)

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ABSTRACT

Classical novae are phenomena caused by explosive hydrogen burning on an accreting white dwarf. So far, only one classical nova has been identified in X-rays before the actual optical outburst occurred (V2487 Oph). The recently discovered nova, V2491 Cyg, is one of the fastest (He/N) novae observed so far. Using archival ROSAT, XMM-Newton and Swift data, we show that V2491 Cyg was a persistent X-ray source during its quiescent time before its optical outburst. We present the X-ray spectral characteristics and derive X-ray fluxes. The pre-outburst X-ray emission is variable, and at least in one observation it shows a very soft X-ray source.

Key words. X-Ray Binaries – Novae

1. Introduction

Classical (and recurrent) novae are the third most energetic outbursts after GRB and SNe, but are much more common than either of those types of catastrophic explosions. They take place in binary systems in which mass is transferred from a low-mass secondary star onto a white dwarf. The accreted material gradually becomes degenerate, and when temperatures become high enough and the pressure at the bottom of the accreted envelope is sufficient, a thermonuclear runaway results. Enough energy is deposited in the accreted material to eject a fraction of the envelope of the white dwarf (Bode & Evans 2008).

Novae can be classified into two observational groups: Fe II and He/N, respectively, depending on the emission lines detected in their optical spectra (Williams 1992). Novae with prominent Fe II lines evolve more slowly, have lower levels of ionization, and show P Cygni absorption components. Novae with stronger lines of He and N have larger expansion velocities and a higher level of ionization, and the lines are more flat-topped with little absorption. Only a few X-ray observations of He/N novae exist and because of their rapid evolution little is known about them.

The nova V2491 Cyg (Nova Cyg 2008b) was discovered on 2008 April 10.8 UT at about 7.7 mag on unfiltered CCD frames (Nakano et al. 2008). Tomov et al. (2008a) found an optical V/R/I decline rate from -0.3 to 0.15 mag per day between t0 + 2.3 and t0 + 7.3 days. Assuming t0 + 0.6 and V = 7.54 mag for the maximum (Nakano et al. 2008), the time t2 in the V band is 4.6 days, where t2 is defined as the elapsed time to decrease 2 magnitudes in its visual luminosity. This t2 value makes V2491 Cyg a very fast nova, similar to V838 Her (O’Brien et al. 1994) and V2487 Oph (Hernanz & Sala 2002). Optical post-outburst spectra showed V2491 Cyg to be a nova in its early phase of outburst (Ayani & Matsumoto 2008, Lynch et al. 2008). The very fast decline and the optical spectral characteristics, such as extremely broad lines with complex profiles, and large expansion velocities (4000–6000 km s⁻¹), mark V2491 Cyg as a peculiar and extremely fast nova (Ashok et al. 2008, Lynch et al. 2008, Tomov et al. 2008). The object was fainter than 14 mag at t0+2 and t0+7 days, respectively. Taking the latter value and using the correlation between visual extinction, AV, and the dust (and hydrogen) column densities, assuming there is no intrinsic absorption (NHI [cm⁻²]/AV = 1.79x10¹⁰, e.g., Predehl & Schmitt 1995), and using AV = 3.1E(V-B), the optical reddening corresponds to N_dust/HI = 2.4x10¹² cm⁻². Using the reddening of E(B-V)=0.43 a distance of 10.5 kpc was estimated by Helton et al. (2008).

The object was fainter than 14 mag at t0+2 days (Nakano et al. 2008). Balman et al. (2008) did not detect the pre-nova
2. X-ray observations

A search through the X-ray catalogues (Available through Vizier at the Centre de Données de Strasbourg (CDS)) showed that the field of V2491 Cyg was observed at different epochs before the nova outburst by ROSAT, XMM-Newton and Swift. We determine the Swift position by combining all the data into one single image and using the \texttt{ximage} tool. In Table \ref{tab:positions} we list the positions and position errors of the candidate X-ray counterparts. In Fig. \ref{fig:swift/xrt_image} we show a Swift/XRT image with all the pre-nova X-ray counterpart uncertainties. The following paragraphs describe these satellites and the relevant instruments. The results are summarised in Table \ref{tab:positions}.

The ROSAT satellite (Trümper et al. \citeyear{1991A&A...247L..29T}) produced an all-sky survey (RASS) in the energy range 0.2–2.4 keV and covered about 25% of the sky during pointing observations with the PSPC camera (Voges et al. \citeyear{2000A&A...362L...1V}). Two X-ray sources in these catalogs have coordinates close to that of V2491 Cyg, i.e., the RASS source 1RXS J194259.9+321940 and the source 2RXP J194302.0+321912 (see also Table \ref{tab:positions} and Fig. \ref{fig:swift/xrt_image}). We have re-analyzed the 2RXP J194302.0+321912 observation using the HEASOFT (http://heasarc.nasa.gov/docs/software/heasoft) software suite. We filtered the ROSAT event list with XSELECT, down to $R=18.6\pm0.5$, 5–9 months prior to the outburst. However, the pre-nova was detected in archival plates spanning ~16 years showing a persistent source at $R\approx16.3$ (Jurdana-Sepic & Munari \citeyear{2008A&A...483..547J}). This indicates a dimming of the source by about 2 mag several months before the nova outburst. A search through archival X-ray data showed the presence of an X-ray source, before the nova outburst, at the nova position (Ibarra & Kuulkers \citeyear{2008MNRAS.384...89I}, Ibarra et al. \citeyear{2008MNRAS.390..440I}).

XMM-Newton (Jansen et al. \citeyear{2001A&A...380L..73J}) is performing a sensitive survey of the sky in the 0.2–12 keV energy band, when it slews between targets. A catalogue of slew point sources has been published by Saxton et al. \citeyear{2008MNRAS.384...89I}.

We report on XMM-Newton observations by the EPIC-pn camera (Strüder et al. \citeyear{2001A&A...374L..19S}) operating in full-frame mode with the medium filter during a slew performed on 2006 November 15 (OBSID. 9127000003). V2491 Cyg passed through the EPIC-pn field of view at a large off-axis angle such that an effective on-axis exposure time of 3.4 s was achieved. A source with 4 photons was detected in the full (0.2–12 keV) energy band of the EPIC-pn with a significance of 3.5$\sigma$ above the very low background (0.2 cts/arcmin$^2$) of the slew image. There were no XMM-Newton pointed observations of this field before outburst.

Six Swift observations were made of the V2491 Cyg field before the nova outburst, as part of a follow-up survey aimed at identifying the X-ray counterpart for sources discovered by the Burst Alert Telescope (BAT; Barthelmy et al. \citeyear{2005ApJ...627L..59B}). The survey (Tueller et al. \citeyear{2008A&A...480L..71T}) pointing was towards Swift J1942.8+3220 (Sect. 3.3).

The Swift X-ray Telescope (XRT, 0.3–10 keV; Burrows et al. \citeyear{2005ApJ...629.1206B}) detector was operated in photon counting (PC) mode, which provides two-dimensional imaging, spectral information, and 2.5 s time resolution. All the Swift/XRT data have been processed through \texttt{xrtpipeline} (Swift\_Rel2.8), with local-background subtracted spectra binned to $\gtrsim20$ cts bin$^{-1}$. One of the XRT observations was too short (20 s on 2007 July 15) to be useful, and has not been included in our spectral analysis.

No optical Swift/UVOT data were available. This is because the UVOT telescope was operated with BLOCKED filter due to the presence of a bright star in the field of view.

3. Results

3.1. The pre-nova X-ray identification

In Table \ref{tab:positions} we give the positions and source names of the X-ray sources we identify close to the optical position of V2491 Cyg. Based on the Swift/XRT observations, the pre-nova X-ray source has been designated as Swift J194302.1+321913 (Ibarra et al. \citeyear{2008MNRAS.384...89I}). The ROSAT/PSPC source, 2RXP J194302.0+321912, the

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{swift/xrt_image.png}
\caption{\textbf{Swift/XRT} X-ray image of the V2491 Cyg field of view. The big circle corresponds to the \textit{Swift}/BAT uncertainty and the zoomed view corresponds to the pre-nova X-ray counterpart uncertainties of Table \ref{tab:positions}. The cross corresponds to the optical coordinates.}
\end{figure}
Table 1. Pre-nova X-ray counterpart source identifications, coordinates, uncertainty, and offset (δ) from the position of the optical nova (19h43m01.96s, +32d19'13.8''; Nakano et al. 2008).

| name                  | position (RA,Dec; J2000.0) | error (2σ)  | δ     |
|-----------------------|-----------------------------|-------------|-------|
| 1RXS J194259.9+321490 | 19h42m59.9s, +32d19'40.5'' | 28''        | 3''   |
| 2RXP J194302.0+321912 | 19h43m02.0s, +32d19'12.0'' | 4''         | 1.9'' |
| XMM-SL J194301.9+321911 | 19h43m02.0s, +32d19'10.5'' | 12''        | 3.7'' |
| Swift J194302.1+321913 | 19h43m02.0s, +32d19'11.0'' | 3.7''       | 2.8'' |

XMM-Newton/EPIC-pn source XMM-SL J194301.9+321911, and the Swift/XRT source Swift J194302.1+321913 are all consistent with the optical nova coordinates (see also Ibarra & Kuulkers 2008; Ibarra et al. 2008). The ROSAT/SPC source 1RXS J194259.9+321490 is formally not consistent with the optical position (see Fig. 1) but due to its large uncertainty we consider that this is compatible with 2RXP J194302.0+321912. Based on the positional information, as well as the similar strength of the sources over time (see next subsection), we suggest that all the above mentioned X-ray sources are all the same source, and identify it as the X-ray counterpart to the pre-nova of V2491 Cyg.

3.2. Pre-nova X-ray spectral characteristics

In Table 2, we list all X-ray pre-nova observations; for Swift/XRT we provide the background corrected count rates in two bands, and the 68% confidence Bayesian rate errors (Kraft et al. 1991) because of the low numbers of counts. The source is clearly variable. Based on the information in the two energy bands it changes dramatically in spectral shape between observations.

We find a persistent, but variable, and at least on one occasion very soft X-ray source present at the position of the nova V2491 Cyg from the ROSAT survey era up to 3 months before the nova outburst. This is only the second nova to be detected in X-rays before eruption (after V2487 Oph, Hernanz & Sala 2002). A hard spectral component is suggested by Swift/BAT survey catalog source Swift J1942.8+3220 has an estimated average flux of about 2×10⁻¹¹ erg cm⁻² s⁻¹ (14–195 keV; Tueller et al. 2008). Using public archival INTEGRAL/IBIS/ISGRI observations performed between March 2003 and December 2006 (for a total exposure time of about 620 ksec) we derive a 3σ upper limit (18–50 keV) of about 1×10⁻¹¹ erg cm⁻² s⁻¹ at the position of V2491 Cyg, more or less comparable with that derived for the Swift/BAT source.

Apart from Swift J194302.1+321913 there is another XRT source within the 5σ BAT error circle of Swift J1942.8+3220 (see upper part of Fig. 1): Swift J194245.9+322411 (RA = 19h42m45.9s, Dec = +32d24'10.7''), with 90% confidence error radius of 3.6''). This source has an absorbed AGN-like X-ray spectrum; a power-law fit gives Γ=1.5±0.3 and N_H = (2±1)×10²¹ cm⁻² with an unabsorbed 0.3–10 keV flux of 1.1×10⁻¹² erg cm⁻² s⁻¹. Our above described ROSAT and XMM-Newton identifications are not compatible with this AGN-like XRT source. The position of this source was covered by the XMM-Newton Slew Survey, but no source was detected with a 2σ upper limit of 2×10⁻¹² erg cm⁻² s⁻¹ (0.2–12 keV), assuming the AGN-like XRT spectrum. The AGN-like XRT source is not bright enough to account for the BAT detection, assuming it is constant, and so it is not likely to be the X-ray counterpart to the BAT source. If, on the other hand, we extrapolate the power-law fits of the Swift/XRT spectra of the prenova V2491 Cyg taken on 2007 July 17 and 2008 Jan 2 (i.e., when the source was hard) into the BAT band, we get fluxes which are more or less consistent with the BAT measured flux. If, however, the spectrum is assumed to be due to optically thin high-temperature emission, the extrapolated flux is a few orders of magnitude lower. It remains, therefore, uncertain whether the BAT source is related to the pre-nova.

4. Discussion

We find a persistent, but variable, and at least on one occasion very soft X-ray source present at the position of the nova V2491 Cyg from the ROSAT survey era up to 3 months before the nova outburst. This is only the second nova to be detected in X-rays before eruption (after V2487 Oph, Hernanz & Sala 2002). A hard spectral component is suggested by Swift/BAT, but the association with the pre-nova is not secure. V2487 Oph, also a fast nova (t2=6.3 days, see Hernanz & Sala 2002), was suggested to be a recurrent nova, because of both the rapid decline in the optical and the presence of a plateau.
phase during the decline (Hachisu et al. 2002). Pagnotta et al. (2008) discovered a previous outburst of V2487 Oph in 1900, confirming its recurrent nature. V2491 Cyg has been suggested to be a recurrent nova also (Tomov et al. 2008b).

Assuming a distance of 10.5 kpc (Helton et al. 2008) and using the power law fit results, we derive 0.2–10 keV X-ray luminosities ranging from about 1 × 10^{34} to 4 × 10^{35} erg s^{-1}. This is comparable to that derived for V2487 Oph, about 3 years after the outburst, i.e., 8 × 10^{34} erg s^{-1} (0.2–10 keV; Hernanz et al. 2008) assuming a distance of 10 kpc (but note that the distance is rather uncertain, see Hernanz & Sala 2002). It is, however, orders of magnitude higher than that seen for the recurrent nova RS Oph about 2 years after the 2006 outburst (5 × 10^{33} erg s^{-1}, Nelson & Orio 2008 using a distance of 1.6 kpc, Mason et al. 1987). Bode et al. 2008. This is compatible with the fact that in general fast novae appear to be brighter than slow novae, when they are at quiescence (e.g., Becker & Marshall 1981 Orio et al. 2001).

Our X-ray luminosity estimates imply inter-nova mass accretion rates in the range 10^{-9} – 10^{-8} M_\odot yr^{-1}, for a 1 M_\odot white dwarf. These rates are around an order of magnitude lower than those required (judged from the models of Yaron et al. 2005) to fuel the novae outbursts of RS Oph, which are recurrent on a ~20 year period. This would imply that, even with a massive white dwarf, the recurrence timescale for novae in V2491 Cyg would be ~> 100 yrs, similar to V2487 Oph.

The soft spectra observed with ROSAT/PSPC and Swift/XRT resemble those of the post-outburst super-soft state (Page et al. 2009, in prep.), but are much fainter. This, and the fact that the Swift/XRT observation was taken less than a year before the nova outburst, suggests that the spectra were not obtained during a super-soft state after a previous nova outburst or accretion driven nuclear burning, in agreement with our relatively low mass transfer estimates. The Swift/XRT observations show that V2491 Cyg changes spectral state on at least a 4-day time scale.

Magnetic CVs in quiescence show harder spectra than their non-magnetic equivalents (e.g., Barlow et al. 2008 Landi et al. 2009). If the BAT source is the same as that seen at ≤10 keV, V2491 Cyg may be magnetic. Polars, for example, are known to change from hard to soft states as the white dwarf rotates (e.g., Heise et al. 1985), which could explain the X-ray spectral evolution we observe. However, we do not see evidence for short-term (~hour) orbital related variations. Moreover, in general polars are rather weak X-ray sources (see King & Watson 1987). Additionally, at ≤10 keV the spectrum is not unlike that seen in non-magnetic CVs (e.g., Baskill et al. 2005). This brings into doubt a magnetic interpretation.

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table 2. Observation log of the ROSAT, XMM-Newton and Swift pre-nova observations. Apart from the exposure time the count rates in different energy bands as well as the absorbed fluxes are given (see text for more details). For the second ROSAT observation, the XMM-Newton and the first two Swift observations, the flux was calculated using a power-law with _G_ between 1.3 and 5.2, and _N_H_ = 2.2 × 10^{21} cm^{-2}.

| Date         | Days before outburst | Instrument          | Exposure time (ks) | Count rate 0.3–1.0 keV (cts/ks) | Count rate 1.0–8.0 keV (cts/ks) | Count rate 10–10 keV flux absorbed (10^{-12} erg cm^{-2} s^{-1}) |
|--------------|----------------------|---------------------|--------------------|---------------------------------|---------------------------------|---------------------------------------------------------------|
| 1990-10-19   | 638                  | ROSAT/PSPC[1RXS]    | 0.39               | 28±11                           | 12±2                            | 8±2                                                            |
| 1993-10-05   | 5302                 | ROSAT/PSPC[2RXP]    | 4.3                | 22±3                            | 4.3 ± 0.8                       | 3.2 ± 0.4                                                      |
| 2006-11-15   | 517                  | XMM-Newton/EPIC     | 3.43×10^{−3}       | 1.173 ± 0.13                    | 32 ± 2                         | 10.7 ± 10                                                     |
| 2007-05-25   | 322                  | Swift/XRT          | 0.97               | 41±7                            | 19±3                           | 1.6 ± 0.5                                                      |
| 2007-06-07   | 306                  | Swift/XRT          | 3.82               | 37±3                            | 19±3                           | 1.6 ± 0.5                                                      |
| 2007-07-17   | 269                  | Swift/XRT          | 4.87               | 27±3                            | 19±3                           | 1.6 ± 0.5                                                      |
| 2007-07-21   | 265                  | Swift/XRT          | 5.65               | 24±3                            | 19±3                           | 1.6 ± 0.5                                                      |
| 2008-01-02   | 100                  | Swift/XRT          | 2.65               | 24±3                            | 19±3                           | 1.6 ± 0.5                                                      |

Note 1. Energy bands: ROSAT/PSPC, 0.2–2.0 keV; XMM-Newton/EPIC, 0.2–12 keV; Swift/XRT, 0.3–10 keV.
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