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LETTER

Letter to the Editor

LMC 1995, the third supersoft X-ray nova

M. Orio[1,2] **and J. Greiner**[3]

[1] Department of Physics, 1150 University Ave., Madison WI 53706, USA (orio@astrog.physics.wisc.edu)
[2] Osservatorio Astronomico di Torino, Strada Osservatorio 20, I-10025 Pino Torinese (TO), Italy
[3] Astrophysikalisches Institut, An der Sternwarte 16, D-14482 Potsdam, Germany (jgreiner@aip.de)

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Abstract. Nova LMC 1995 was detected with ROSAT as an X-ray source in repeated observations between 1995 and 1998, starting five months after the outburst. In February 1998, 3 years after the nova outburst, ROSAT PSPC data show that this is the only LMC post-nova – and one out of three among $\simeq$100 altogether – that appeared as a bright supersoft X-ray source after the outburst. The PSPC data are satisfactorily fitted with an LTE carbon-oxygen atmosphere model for a 1.2 $M_\odot$ white dwarf, resulting in an effective temperature about 30 eV. The X-ray flux increased in the last years and at present Nova LMC 1995 is about twice as bright as in a 1996 observation. We suggest that the photosphere is still shrinking and the remnant becoming hotter. Such a nova is a likely type Ia SN progenitor.

Key words: stars: binaries: close – stars: individual: N LMC 1995 – stars: mass-loss – stars: novae, cataclysmic variables – stars: white dwarfs – X-rays: stars

1. Introduction

Nova LMC 1995 was discovered in outburst in the Large Magellanic Cloud at the beginning of March 1995 (Liller 1995). It was probably a fast nova (Della Valle et al. 1995), however after the first IAU Circulars no additional information was ever published, so we do not even know the rate of decline of the optical light. This nova, however, has been brought to our attention by our discovery with the X-ray satellite ROSAT of luminous, supersoft X-ray emission, which makes it of exceptional interest for nova studies in general.

Classical novae are cataclysmic variables, that is close binary systems in which a white dwarf accretes matter from a companion filling its Roche lobe. Novae undergo outbursts of amplitude Δm=8–15 mag in the optical range; the total energy emitted is 10^{44}–10^{46} erg, implying it is the second most energetic phenomenon in the Galaxy. The outbursts are thought to be triggered by a thermonuclear runaway in the hydrogen burning shell at the bottom of the accreted layer. A subsequent shock wave might or might not ensue, and a radiation driven wind always follows, depleting all or part of the accreted envelope (see Kovetz 1998).

Residual hydrogen burning in a shell on the white dwarf should occur unless all the envelope is ejected after the outburst, while the atmosphere shrinks and the effective temperature increases. The post-nova should appear as a very hot blackbody-like object at effective temperatures 2.5–10 $\times 10^5$ K (Prialnik 1986), with $L_x \simeq 10^{38}$ erg/s (Eddington luminosity for a 1 $M_\odot$ star). Thus post-novae are predicted to be a sub-group of the *supersoft X-ray sources* (see Greiner 1996 and review by Kahabka and van den Heuvel 1997). The remnant is then detected in the very soft X-ray range for a time which is directly proportional to the leftover envelope mass (e.g. Kato & Hachisu 1994). If accreted mass is retained, the white dwarf mass increases towards the Chandrasekhar mass after a large number of outbursts in one system, eventually leading to a *type Ia supernova* event or to the formation of a neutron star by *accretion induced collapse* (AIC) (e.g. Della Valle & Livio 1996). Whether or not this occurs is a very important open question in modern astrophysics. So far, model predictions are very parameter dependent and contradictory (see Kato 1997, Kovetz 1998). The high flux in the supersoft X-ray range is the only clear indication of how long the hydrogen rich fuel lasts. A bolometric flux of few 10^{-7} erg cm^{-2} s^{-1} was indeed measured for two galactic novae.

GQ Mus ($\equiv$ N Muscae 1983), observed with the ROSAT PSPC, turned out to be a supersoft X-ray source 9 years after the outburst but the X-ray flux decayed towards "turn-off" in the following year (Ögelman et al. 1993, Shanley et al. 1995). The last part of the cooling curve was sampled in 1994 with the HST FOS (pre-COSTAR). At that time GQ Mus was already below the theshold limit for detection with ROSAT, since the temperature of the cooling remnant was only about 100000 K (Shanley et al. 1999). Nebular emission lines of a residual shell around the nova were not present any more already after 8–9 years despite the hot ionizing source (see Gonzalez-Riestra et al., 1998), so at the time of the ROSAT observations there was no intrinsic absorption by leftover material of the ejected shell. Nova Cyg 1992 ($\equiv$V1974 Cyg) (Krautter et al. 1996, Balman et al. 1998) was the only other supersoft X-ray source among the novae observed in X-rays. It remained close to Eddington

Send offprint requests to: M. Orio

Table 1. Observations of N LMC 1995 before the outburst. The equivalent PSPC count rate in brackets is converted as suggested for very soft flux (see text).

Observation dates	Obs-ID	Exposure time (s)	PSPC 3σ upper limit	HRI 3σ upper limit
Jun 21–23 1990	110181	1882	0.0092	
Mar 5–10 1992	300126	7649	0.0022	
Apr 4–14 1992	400148	6263	0.0031	
May 9–16 1992	300172	6372	0.0056	
Dec 18–26 1992	400298	2293	0.0070	
Mar 11–16 1993	400298-1	7502	0.0015	
Jun 15–27 1993	300172-2	7802	0.0023	
Aug 24 1993	141507	1332	0.0112	
Nov 4 1993	500141	5254	0.0034	
Mar 30 1994	141519	1101	0.0102	
Jun 2 1994	141542	1672	0.0091	
Aug 8 1994	201689	8463	(0.012)	0.0015

Table 2. Count rates or 3σ upper limit for ROSAT observations of N LMC 1995 after the outburst. We extrapolated the equivalent HRI count rate from the February 1998 PSPC observation.

Observation date	Obs.-ID	Exposure time (sec)	HRI count rate (cts/sec)
Jul 30-Aug 1 1995	400648	3154	$\leq$0.003
Aug 10–12 1995	201996	7162	$\leq$0.001
Sep 26 1995	201996	1730	0.006$\pm$0.002
Sep 27 1995	400648	1719	$\leq$0.003
Oct 22–24 1995	600782	12793	0.006$\pm$0.001
Sep 6–9 1996	600782-1	7542	0.004$\pm$0.001
Feb 21 1998	180255	9602	(0.008)

luminosity for more than a year despite the possible intrinsic absorption of a significant nebular remnant (emission lines in the UV were present until after X-rays turn-off, see Shore 1998). No supersoft emission was detected for about one hundred other novae observed in supersoft X-rays at different snapshots in post-outburst time (Ögelman & Orio 1995, Orio 1999 and Orio et al. 1999). Remarkably, this includes *all the other LMC novae* that had an outburst between 1987 and 1992 (Orio 1999). However, other types of supersoft sources are quite easy to detect in the LMC due to the low absorption.

2. The pre- and post- outburst ROSAT observations

We checked a number of serendipituous observations of the nova field done with the PSPC between June 1990 and June 1993 and the HRI observations until August 1994. *Before* the nova outburst we rule out the presence of an X-ray source at flux level comparable with the post-outburst observations. In Table 1 we show the 3σ upper limits for the PSPC count rates and for the last HRI observation before the outburst.

Observations of the LMC performed *after* the outburst with the ROSAT HRI instrument show that the nova was detected since September 1995. We found marginal (1σ) detections in July and August 1995 that we do not consider significant (we list only the upper limit in Table 2). In September of the same year the nova was detected at the 3σ level one day. However, an observation on the following day did not yield a significant detection and the two results overlap at only a 3σ level. In an exposure of October 1995, finally, we found a clear (7σ) detection and the flux level seems to have remained stable about one year later, in September 1996.

The PSPC instrument aboard ROSAT, which possesses a moderate but important spectral resolution even at very low energies, was not working immediately after the nova outburst. However, it was used again with residual gas only for one week in February 1998, exactly three years after the outburst. LMC 1995 is close enough to other important targets to have been serendipitously observed and detected in an exposure performed on February 21, 1998, for a total time 9602 s. The vignetting corrected count rate is 0.061$\pm$0.003 cts/s, far above the pre-outburst limits and almost a 20σ detection thanks to the better sensitivity of the PSPC at the very soft energy range. And the source is *very soft*, as the spectrum (Fig. 1) shows. This PSPC count rate translates into an HRI count rate of 0.008 cts/s, a factor about 2 above the last HRI detections in 1995/96 (using a PSPC to HRI conversion factor of 7.8 for this soft spectrum; Greiner et al. 1996).

We examined the possibility that the variation in count rate in September 1995 indicates an X-ray eclipse or other type of intrinsic X-ray variability on a time scale shorter than a day. No clear variability appears however in the last two, longer HRI observations and in the PSPC one. Kolmogorov-Smirnov tests performed on the October 1995, September 1996 and February 1998 observations yield probabilities of variability of respectively 72%, 85%, and 76%, which might be interesting but is far from conclusive. It is on the other hand an important puzzle why the flux level increased from 1996 to 1998 (see below).

3. Spectral analysis of the PSPC data

We had to exclude about 40% of the nominal exposure time (17.6 ksec) from the February 1998 PSPC data due to problems with the PSPC high voltage supply. For the spectral analysis (using standard EXSAS procedures; Zimmermann et al. 1994) we have extracted source photons from within 100$''$ and the background from a concentric circle of radius 115–150$''$. Due to unstable gain during the observation we have conservatively ignored photons below channel 14 during the fit. We fitted the PSPC data interpolating from a grid of LTE atmosphere models of MacDonald and Vennes (1991) which were kindly provided to us. The models assume a 1.2 $M_\odot$ white dwarf with constant luminosity (4.2×10^4 $L_\odot$: about the Eddington value). The radius is proportional to the inverse of the effective temperature to the second power. The effective temperature, the column of neutral hydrogen and the distance of the source are given as parameters for the fit. Alternatively the distance parameter can be interpreted as a scaling factor for the flux (see below).

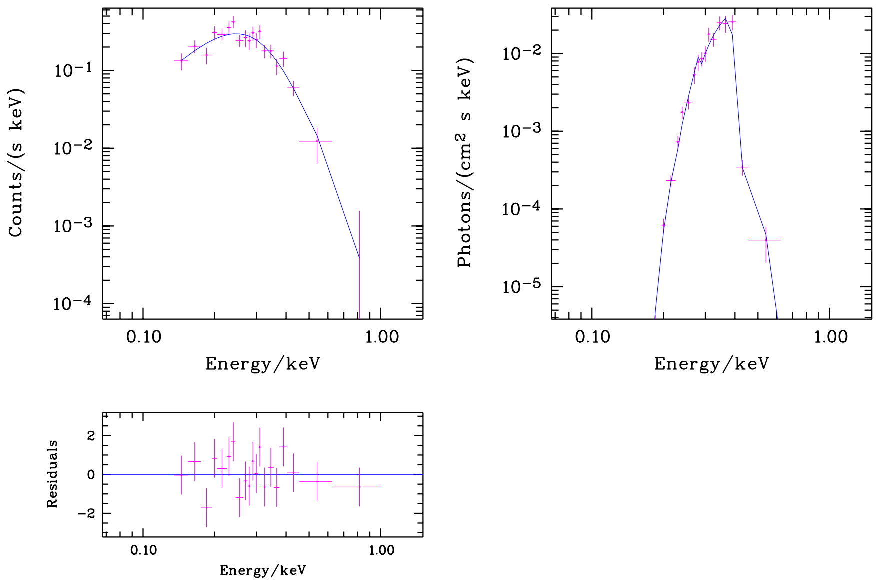

Fig. 1. The X-ray spectrum of N LMC 1995 as measured with the ROSAT PSPC on February 21, 1998. It is fitted with an atmosphere model for a CO white dwarf with an effective temperature of T_e= 31 eV, an interstellar absorbing column of N(H)= 1.4× 10^{21} cm^{-2} and a flux near the Eddington level for a 1 $M_\odot$ white dwarf, 5.1 × 10^{-10} erg cm^{-2} s^{-1}. The lower left panel shows the residuals between model and data in units of σ.

The best-fit (Fig. 1) model parameters for an atmosphere composition typical for a CO white dwarf are: effective temperature $T_e = 31$ eV, (implying a radius of the remnant of $R_r = 3.9\times 10^9$ cm), N(H)=1.4 × 10^{21} cm^{-2}, and a distance 51 kpc yielding a flux of 5.1 × 10^{-10} erg cm^{-2} s^{-1}. The value for the neutral hydrogen column is in agreement with the value of the Galaxy towards the LMC (about 7 × 10^{20} cm^{-2} plus the intrinsic absorption in the LMC as evaluated by Luks' maps (1994), about 8 × 10^{20} cm^{-2}). The source distance is acceptable within the uncertainties both in the model and in the LMC distance as discussed in the literature (see Panagia et al. 1997, Stanek et al. 1998 and references therein). For comparison, the best fit obtained with a blackbody model has an effective temperature T_{BB} = 20 eV, an absorbing column of N(H) = 2.5 × 10^{21} cm^{-2} and an implied super-Eddington flux. Since the atmosphere model fits the data with the right value of the distance the white dwarf mass is consistent with being in a range close to 1.2 $M_\odot$. However, we tried to relax this assumption by exploring the whole parameter space. This is meaningful especially if we assume that the luminosity is scaled by a factor proportional to the mass of the white dwarf (M_{WD}), since in theoretical studies for masses greater than 0.6 $M_\odot$ the nova remnant is at L = A(M_{WD} -B) where B is a function of the chemical composition of the envelope, varying between 0.2 and ≃0.6 (e.g. Truran 1979). For a conservative estimate we can say that the peak luminosity does not vary by more than a factor of 10 (normally less, see Truran 1979). However, we allowed the distance to vary as a free parameter to explore even the unlikely possibility that the supersoft X-ray source is not associated with the nova. The result is shown in Fig. 2. The 3σ probability contours allow a narrow range of effective temperatures (18–42 eV) while N(H) must be larger than 5 × 10^{20} cm^{-2}, but the contours do not close for high values of N(H).

MacDonald and Vennes (1991) also calculated a sequence of models representative of a O-Ne-Mg white dwarf composition, Although the CO WD model fits the data slightly better, this does not discriminate the models well due to the low number of counts in the PSPC spectrum (only 525 photons above the background). However, the best fit with the O-Ne-Mg model, with parameters T_e=30 eV and N(H)=1.06 × 10^{21} cm^{-2}, has an intrinsically larger luminosity, and when scaled to the LMC distance d according to a factor 1/d^2 the relationship for L(M) places the white dwarf mass in the range 0.73–0.83 $M_\odot$, which is expected to be too low for a O-Ne-Mg white dwarf.

There is little doubt that a detailed atmosphere model allows a better fit to the data than a simplified blackbody model (e.g. Heise et al. 1994), and the only alternative to the LTE model we used would be a non-LTE model like those used by Hartmann & Heise (1997). These models avoid the sharp drop of flux at 0.49 keV, due to the C VI absorption edge (which is in emission instead in non-LTE). However, non-LTE effects are significant when the WD mass does not exceed 0.6 $M_\odot$, which is unlikely for classical novae - as a matter of fact the spectrum of LMC 1995 is much softer than that of the sources studied by Hartmann and Heise (1997).

4. Discussion and conclusions

Nova LMC 1995 became a supersoft X-ray source in the first months after the outburst and was still such in Feb. 1998. The effective temperature is only about 30 eV, and the best fit to the data is obtained with a 1.2 $M_\odot$ C-O white dwarf atmosphere model. The X-ray flux surged after about 200 days, which might imply a lower mass (Kato 1997, Kovetz 1998), however the nebular absorption might have shielded the central source (Yungelson et al. 1996). New observations are needed, however the evolution of the remnant does not seem as fast as for N Cyg 1992 – it is probably more similar to GQ Mus.

Since the flux *increased* since the time of the HRI observations, there might have been some intrinsic absorption of the ejected shell and the source became more luminous in X-rays as the nebula thinned out. An alternative interpretation of the increase of the X-ray count rate between 1996 and 1998 could be

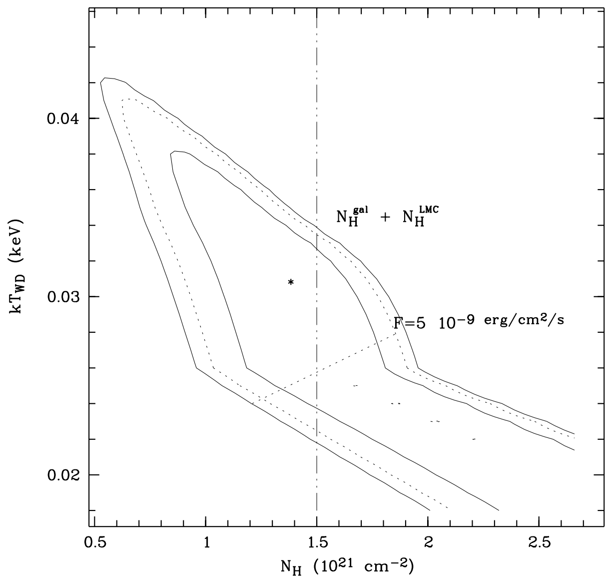

Fig. 2. The 1,2 and 3σ confidence contours obtained for the spectum measured with the ROSAT PSPC Feb. 21, 1998 in the N(H) vs. T_{BB} plane, fitting a CO WD atmosphere model at quasi-Eddington luminosity and allowing the distance parameter to vary as a free parameter. The solid-broken line shows the maximum value admitted for the Galactic+LMC-intrinsic photoelectric absorption. The dotted line on the right shows the loci of d=$\simeq$158 kpc for a 1.2 $M_\odot$ WD or flux$\simeq 5 \times 10^{-9}$ erg cm^{-2} s^{-1} (possibly scaling the WD mass).

the rise of the WD photosphere temperature from about $\simeq$20 eV in 1996 – already allowing a ROSAT detection – to $\simeq$30 eV in 1998. An additional point to remind is that the maximum effective temperature for a 1.2 $M_\odot$ post–nova white dwarf is expected to be in a range $\simeq$75–90 eV (MacDonald et al. 1985, Prialnik 1986). Since the models cannot reliably predict at which point in time the peak occurs, there is even the possibility that we missed the maximum between the last HRI observation and the Feb. 1998 PSPC one. However, the observations being less than 1.5 years apart, comparing with the evolution of GQ Mus and N Cyg 1992 we can probably rule out this possibility. If indeed the nova is moving leftwards in the HR diagram, while in the next few years the radius of the remnant shrinks and the effective temperature increases a larger portion of the Wien tail of the spectrum should be detected. Thus this nova will be a bright X-ray source and an important and promising target for future observations.

The ROSAT observations demonstrate that N LMC 1995 belongs to a quite exceptional small group of novae with hot, hydrogen burning remnants. *We need to study them in detail as possible progenitors of type Ia SNe or AIC neutron stars, and also to fully understand the inter-outburst evolution of nova systems*. The main point is understanding the difference between this group and other classical novae (the majority) for which no supersoft X-ray emission is detected after the outburst. Yungelson et al. (1996) attributed the difference to the mass of the ejected nebula and the time for it to become transparent to supersoft X-rays. The example of N Cyg 1992 discussed in the introduction shows that this point is far from being obvious. If the observed X-ray count rate increase is indeed due to the gradual thinning out of the ejecta, it would favour Yungelson et al.' s model, offering a logical explanation for the puzzle of the missing supersoft X-ray novae. If this is true, however, we have to admit that not very massive white dwarfs (M< 1.2 $M_\odot$), which would in time always appear as supersoft sources, must be very rare. It is not obvious at all why novae should occur only in systems with such massive white dwarfs.

Little is known about N LMC 1995 and new observations in X-rays to monitor the light curve and in the optical (mainly to determine the orbital period) are necessary to tighten the constraints on the system parameters.

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