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The X-ray emission from Nova V382 Velorum – II. The super-soft component observed with *BeppoSAX*

M. Orio,[1,2]★ A. N. Parmar,[3] J. Greiner,[4] H. Ögelman,[5] S. Starrfield[6] and E. Trussoni[1]

[1]*Istituto Nazionale di Astrofisica (INAF), Osservatorio Astronomico di Torino, Strada Osservatorio, 20, I-10025 Pino Torinese (TO), Italy*
[2]*Department of Astronomy, 475 N. Charter Street, University of Wisconsin, Madison, WI 53706, USA*
[3]*Astrophysics Division, Space Science Department of ESA, ESTEC, Postbus 299, 2200 AG Noordwijk, The Netherlands*
[4]*Astrophysical Institut, An der Sternwarte 16, 14882 Potsdam, Germany*
[5]*Department of Physics, University of Wisconsin, 1500 University Avenue, Madison, WI 53706, USA*
[6]*Department of Physics and Astronomy, PO Box 87150, Arizona State University, Tempe, AZ 85287-1504, USA*

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ABSTRACT

Nova Velorum 1999 (V382 Vel) was observed by *BeppoSAX* six months after optical maximum, and was detected as a bright X-ray supersoft source, with a count rate $3.454 \pm 0.002\,\mathrm{ct\,s^{-1}}$ in the Low-Energy Concentrator Spectrometer (LECS). It was the softest and most luminous supersoft source observed with this instrument. The flux in the 0.1–0.7 keV range was not constant during the observation. It dropped by a factor of 2 in less than 1.5 hr and then was faint for at least 15 min, without significant spectral changes. The observed spectrum is not well-fitted with atmospheric models of a hot, hydrogen burning white dwarf. This is due mainly to a supersoft excess in the range of 0.1–0.2 keV, but the fit can be significantly improved at higher energy if at least one emission feature is superimposed. We suggest that a 'pseudocontinuum' was detected, consisting of emission lines in the supersoft X-ray range superimposed on the thermal continuum of a white dwarf atmosphere. As a result, an accurate determination of the effective temperature and gravity of the white dwarf at this post-outburst stage is not possible.

Key words: stars: individual: V382 Vel – novae, cataclysmic variables – X-rays: stars.

1 INTRODUCTION

Nova Velorum 1999 (V382 Vel) was the second brightest nova of the last 50 yr ($V = 2.6$; Seargent & Pearce 1999). It was a 'fast O–Ne–Mg nova', with $v \simeq 4000\,\mathrm{km\,s^{-1}}$, $t_2 = 6\,\mathrm{d}$ and $t_3 = 10\,\mathrm{d}$ (Della Valle, Pasquini & Williams 1999; Shore et al. 1999). The nova was immediately declared a Target of Opportunity by the *BeppoSAX* Mission Scientist.

BeppoSAX carries instruments that cover the energy range 0.1–300 keV. The instruments used are the co-aligned Low-Energy Concentrator Spectrometer (LECS; 0.1–10 keV; Parmar et al. 1997), the Medium-Energy Concentrator Spectrometer (MECS; 1.8–10 keV; Boella et al. 1997), and the Phoswich Detection System (PDS; 15–300 keV; Frontera et al. 1991). The LECS and the MECS, used in this work, consist of grazing incidence telescopes with imaging gas scintillation proportional counters in their focal planes.

Novae in outburst have been observed to emit X-rays due to thermal emission of shocked ejecta (see Orio, Covington & Ögelman 2001a, and references therein). The outburst is normally due to a radiation pressure driven wind and not to a shock wave, but shocks can be produced in interacting winds, or in interaction between the ejecta and the circumstellar medium. After a few months, luminous 'supersoft' X-ray emission (luminosity of the order of 10^{37}–$10^{38}\,\mathrm{erg\,s^{-1}}$) has also been observed. The previous detections have been attributed to residual hydrogen burning in a shell on the white dwarf remnant (e.g. Ögelman et al. 1993; Krautter et al. 1996; Orio & Greiner 1999). We expect to detect in this case an atmospheric continuum at $T_{\mathrm{eff}} = 20$–$80\,\mathrm{eV}$ and the absorption edges of the white dwarf (or even emission edges if the effective temperature is extremely high).

V382 Vel was observed with *BeppoSAX*, *ASCA* and *RossiXTE* two weeks after the outburst (Orio, Torroni & Ricci 1999a; Orio et al. 2001b; Mukai & Ishida 1999, 2001) as a hard X-ray source (with plasma temperature $kT \simeq 7\,\mathrm{keV}$). It cooled rapidly in the first two months after outburst to $kT \simeq 2.4\,\mathrm{keV}$ (Mukai & Ishida 2001). In a recent paper (Orio et al. 2001b; hereafter, Paper I) we attributed the initial X-ray emission to shocks in the nebula. As the initially very large intrinsic absorption of the ejected nebula was thinning out, the equivalent $N(\mathrm{H})$ decreased rapidly (Mukai & Ishida 2001). Thus, in the second *BeppoSAX* observation we hoped to detect the supersoft X-ray emission with the LECS and derive

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★E-mail: orio@cow.physics.wisc.edu

useful information on the nature of the white dwarf. The peak temperature of the hot white dwarf remnant, and the absorption edges that indicate the underlying chemical composition, are extremely important in order to constrain the physical models. In addition to this, the length of the constant bolometric luminosity phase is an essential parameter in order to understand whether the nova retains accreted mass after the outburst and is therefore a candidate Type Ia supernova (or, even, a candidate neutron star formed by accretion induced collapse).

2 THE SUPERSOFT X-RAY SOURCE

In the second *BeppoSAX* observation on 1999 November 23, the actual length of the LECS exposure was 12.4 ks, over a total of about 16 hr in 11 time intervals, each lasting for $t \leq 1200$ s. The MECS exposure time was 25.9 ks during the same 16 hr. The count rate measured with the LECS was extremely high, $3.4540 \pm 0.0021\,\mathrm{ct\,s^{-1}}$ in the 0.1–4.0 keV range, due to the emergence of supersoft X-ray emission (Orio, Parmar & Capalbi 1999b). This high count rate was not unexpected, and it would be equivalent (assuming for simplicity a blackbody at 40 eV and $N(\mathrm{H}) = 2 \times 10^{21}\,\mathrm{cm^{-2}}$) to $\approx 50\,\mathrm{ct^{-1}}$ with the *ROSAT* PSPC. A count rate of $75\,\mathrm{cts\,s^{-1}}$ was measured for V1974 Cyg at maximum with the PSPC (Krautter et al. 1996). In the 0.8–10.0 keV range the count rate was only 0.1030 ± 0.0038, consistent with the MECS count rate $0.0454 \pm 0.0015\,\mathrm{ct\,s^{-1}}$ (more than a factor of 3 lower than in 1999 June). There was no PDS detection with a 2σ upper limit of $0.080\,\mathrm{ct\,s^{-1}}$ in the 15–50 keV range. We have already discussed the evolution of the hard X-ray emission (Paper I). We found that more than one component was necessary to fit the LECS spectrum, however we also concluded that there was no component with a higher plasma temperature than $\simeq 1$ keV, that $N(\mathrm{H})$ was consistent with the interstellar value and that the supersoft portion of the flux was dominant.

Remarkably, the supersoft X-ray flux (0.1–0.7 keV) was variable. No significant variability was detected at higher energy. Overall, there was irregular flickering with time-scales of minutes, and as Fig. 1 shows, in the ninth observation (after ≈ 13 hr from the beginning of the exposures) the background-subtracted count rate decreased dramatically, by approximately a factor of 2. This low state lasted during the whole LECS coverage of 15 min, spaced about 5000 s from two observation in which the average count rate was twice as high. Close to the end of the ≈ 16 hr of intermittent observations, the count rate decreased again in the few minutes (see bottom panel of Fig. 1). If we missed other episodes of this type, they must have been shorter than the 4000–5000 s that elapsed between the observations. One possible explanation for the sudden decrease in count rate is of course that a dense clump intervened along the line of sight. However, the spectrum was definitely supersoft during the whole observation and became slightly softer during the dip. Instead, the additional absorption of a thick clump would absorb the softer portion of the spectrum more and produce an apparently ‘harder’ spectrum.

Is this phenomenon linked with orbital variability? Given the observed periodicity at optical wavelengths (Bos et al. 2001) the orbital period of V382 Vel is likely to be 3.5 hr. The time that elapsed between minima in the last observation span was a little over 3 hr. We folded the LECS light curve with the optical modulation period, and even if ≈ 70 per cent of the phase was covered, we could not detect any modulation in supersoft X-ray flux. We also note that the semi-amplitude of the optical modulation is only 0.02 mag, while the X-ray count rate has a large variation.

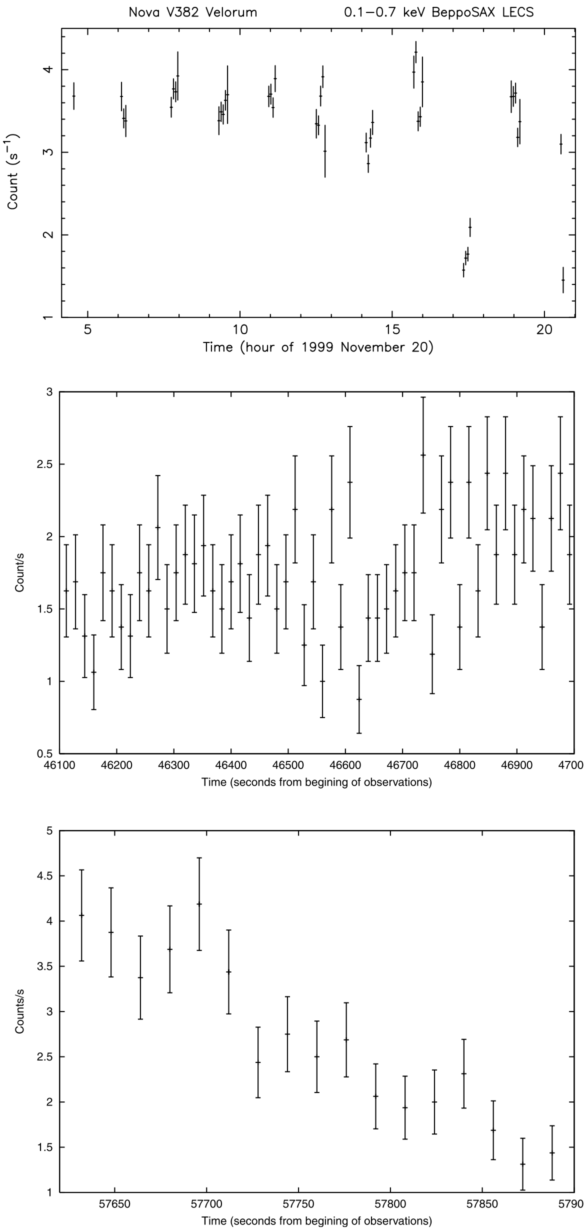

Figure 1. The LECS light curve in the range 0.1–0.7 keV with time bins of 100 s (top) and the 16-s binned light curve during the third-before-last (middle) and the last (bottom) of the observations performed during the 16 hr from the beginning to the end of the LECS exposure.

The time-scale of the phenomenon does not give very significant upper limits on the size of the obscuring region: the upper limit on the size of an obscuring clump in the nebula, assumed to be moving at $v = 4000\,\mathrm{km\,s^{-1}}$ for 5000 s, is 2×10^{12} cm (a small fraction of the nova shell radius at this epoch). Assuming some other type of phenomenon instead, connected with the possible orbital period, an upper limit on the size is obtained assuming the speed of light for the obscuring source: 1.5×10^{14} cm.

This variability is a truly puzzling phenomenon which we do not fully understand. We note that also V1494 Aql (N Aql 1999 no. 2), which was observed with *Chandra* and also detected as a supersoft X-ray source, showed time-variability in supersoft X-rays: a flare (with increase of flux by a factor 6) that lasted for about 15 min and pulsations every 42 min (Starrfield et al. 2001). Even for this nova, the supersoft X-ray variability time-scale was very short.

3 SPECTRAL ANALYSIS AND INTERPRETATION

In Paper I we made the working hypothesis that the supersoft flux observed in November 1999 was entirely due to the central hot white dwarf remnant. Neglecting the LECS flux below 0.8 keV we simultaneously fitted the LECS and MECS spectra with a MEKAL model of thermal plasma (included in the software package XSPEC, see Arnaud 1986) with parameters: $N(\mathrm{H}) \simeq 2 \times 10^{21}\,\mathrm{cm}^{-2}$, $kT \simeq 700\,\mathrm{eV}$, and unabsorbed flux $\simeq 10^{-12}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ (the reduced χ^2 was ≈ 1.2). In this work we analyse instead the properties of the supersoft X-ray flux. The spectral distribution observed for V382 Vel, shown in Fig. 2 in the range 0.1 – 1.1 keV, is strikingly different from the one observed with the *BeppoSAX* LECS for three non-nova supersoft X-ray sources: Cal 87 (Parmar et al. 1997), Cal 88 (Parmar et al. 1987) and RX J0925.7-4758 (Hartmann et al. 1999). The LECS spectra are shown in fig. 7 of Hartmann et al. (1999) and fig. 3 of Parmar et al. (1997). V382 Vel is much more luminous than the other observed sources, it appears to have additional, harder spectral components and above all it is very luminous also in the very soft range, 0.1 – 0.2 keV. It is the only object of this kind ever studied with the LECS.

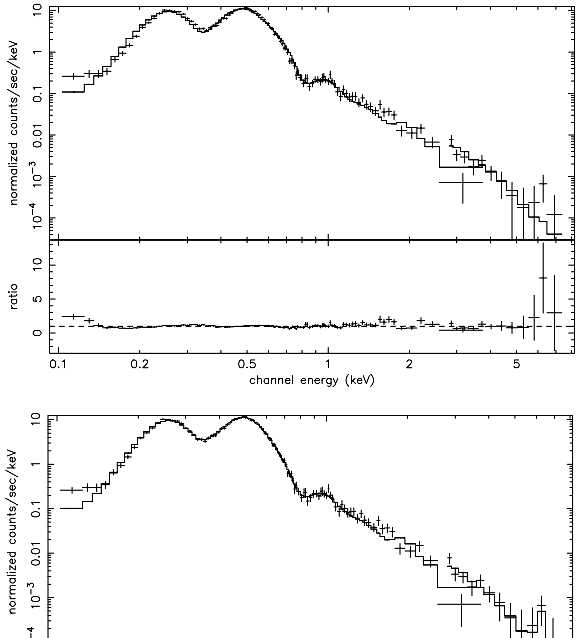

Figure 2. Spectra observed in the 0.1 – 8 keV range with the *BeppoSAX* LECS and MECS in 1999 November and (above) the best fit with model A (MEKAL + NLTE model atmosphere for $\log(g) = 8.5$ and cosmic abundances) and (below) with model C, which includes also three superimposed emission lines, at 0.243 keV, 0.449 keV and 6.4 keV). The first fit is not acceptable, and this is due in a large portion to structured residuals in the range 0.1 – 0.2 keV. The second fit is much better overall, but the residuals in the soft range are still large. The lower panel in each plot shows the residuals, as a ratio of observed over predicted counts per energy bin.

We tried to fit the whole LECS and MECS spectra in the 0.1 – 10 keV range adding the MEKAL model used for the hard flux to (i) a blackbody, (ii) a blackbody with absorption edges (included in XSPEC), and (iii) more detailed model atmospheres (see Hartmann & Heise 1997; Hartmann et al. 1999). The latter models were used to fit the non-nova supersoft X-ray sources and very reasonable results were obtained. We expected that the blackbody would not give a perfect fit (because white dwarf atmospheres resemble blackbodies only in first approximation) but we thought that it would provide an approximate estimate of the luminosity, of the range of effective temperatures, and indicate whether absorption edges must be included. Adding absorption edges to the black-body (the most likely seemed C VI at 0.49 eV, but we also tried N VI at 0.55 keV and 0.67 keV, O VIII at 0.87 keV) did not improve the fit.

We also found that a reasonable fit to the supersoft portion of the spectrum could not be obtained with any of the atmospheric models we tested, in local thermodynamic equilibrium (LTE) and in NON-LTE (hereafter NLTE), developed by Heise, van Teeseling & Kahabka (1994), Hartmann & Heise (1997) and Hartmann et al. (1999). For the NLTE case, we tested four small grids of models with $\log(g)$ between 8 and 9, with four different set of abundances. The first set had cosmic abundances (developed primarily for galactic sources, hereafter NLTE-1 models), in the second set of abundances the abundances were depleted to 0.25 times the solar value (developed for LMC sources, here after called NLTE-2 models), and in the third and fourth group of models the abundances were enhanced in C, N and O and in Ne, O and Mg, respectively. These models include line opacities. The two grids with enhanced abundances are still unpublished (Hartmann, private communication). With either models in LTE and NLTE we could *not* obtain a good fit by, for instance, decreasing $\log(g)$ and 'tuning' the MEKAL component accordingly. In Table 1 we give the best-fitting parameters the NON-LTE model atmospheres with $\log(g) = 8.5$ and a MEKAL bremsstrahlung component. The value $\log(g) = 8.5$ does not give an acceptable value of χ^2, but it is smaller than for other values of $\log(g)$. The only reason for also testing the NLTE-2 LMC-type models was that we could not obtain a reasonable fit with the other available models and wanted to experiment with all the available grids. We concluded that no model is acceptable: with the best NLTE-1 model, model A in the table, we obtain $\chi^2 = 4.5$ for 105 degrees of freedom. The fit to the data, shown in the upper part of Fig. 3, predicts counts at energies higher than 200 eV that differ from those observed by more than 5 per cent, which is the likely uncertainty in the knowledge of the LECS spectral response. Apart from what can be interpreted as an iron line at ≈ 6.5 keV, at low energies (< 0.2 keV) the predicted counts exceed those observed by at least 100 per cent (see Fig. 2). However, the uncertainty in the low-energy LECS response in this range is estimated not to exceed $\simeq 20$ per cent (Parmar et al. 1997).

In a *Chandra* HRC-S + LETG observation of V382 Vel carried out in 2000 March by one of us (SS), the HRC-S + LETG spectrum, which is to be described in detail in a forthcoming paper (Starrfield et al., in preparation) is very different from another nova which also appeared as a supersoft X-ray source, V1494 Aql (N Aql 1999 no. 2, see Starrfield et al. 2001). The main difference is the lack of conspicuous continuum for V382 Vel in 2000 March: it was instead an emission line spectrum, with many high ionization emission lines in the supersoft range. These lines presumably have an origin in the ejected nebula. The *BeppoSAX* instruments would

Table 1. Spectral fit parameters obtained applying two NLTE models with $\log(g) = 8.5$ and different abundances (25 per cent of the cosmic value, NLTE-1, and depleted LMC-like, NLTE-2), plus MEKAL and lines, to the *BeppoSAX* LECS and MECS spectra of Nova Vel observed in 1999 November. The absorption, N(H), is in units of 10^{22} atom cm^{-2}. $T_{\rm eff}$ is the white dwarf atmospheric temperature, kT the MEKAL plasma temperature (of the ejecta), $F_{\rm a}$ is the absorbed flux and $F_{\rm x}$ is the unabsorbed flux, χ^2/dof is the reduced χ^2, and dof is the number of degrees of freedom.

Model	N(H)	$T_{\rm eff}(\times 10^5\,{\rm K})$	kT (keV)	$F_{\rm a}$	$F_{\rm x}$	χ^2/dof	dof
A: NLTE-1 + MEKAL	1.38	5.6	0.896			4.53	105
B: NLTE-1 + MEKAL + L(0.449 keV)	2.03	4.0	0.801			1.70	102
C: NLTE-1 + MEKAL + L(0.243 keV + 0.449 keV + 6.4 keV)	2.07	4.0	0.836	1.6×10^{-9}	6.1×10^{-6}	1.67	96
D: NLTE-2 + MEKAL	1.56	5.3	0.069			12.66	122
E: NLTE-2 + MEKAL + L(0.453 keV)	1.98	5.2	0.826			1.57	117
F: NLTE-2 + MEKAL + L(0.491 keV + 6.52 keV)	1.98	5.2	0.813	1.6×10^{-9}	1.2×10^{-6}	1.62	112
G: NLTE/CNO + MEKAL	1.68	4.8	0.063			15.81	106
H: NLTE/NeOMg + MEKAL	1.69	5.0	0.068			10.73	105

have detected a blend of such lines as a featureless ‘pseudocontinuum’. Emission lines in the supersoft range may well have existed even at the earlier epoch of our *BeppoSAX* observations. These lines may have been due to shock ionization in the ejecta, rather than to photoionization by the central source.

Even if the spectral resolution of the *BeppoSAX* LECS and MECS is not sufficient to detect lines, we tried to determine which emission lines may explain the observed X-ray spectrum and what constraints we could derive on the level of the continuum. In model C of Table 1 we added not only the bremsstrahlung continuum at the harder energy ($kT = 0.84$ keV) and a line at $\approx$6.5 keV (which is necessary but is not in the range where the bulk of the flux is emitted), but also one or more ‘softer’ spectral features in emission. As an experiment, we obtained best fits with $\chi^2 = 1.6$–1.7 adding such lines to both NLTE-1 and NLTE-2 models with $\log(g) = 8.5$ (see Table 1). For the NLTE-1 model, in the best fit the added Gaussian feature has to be at 449 keV. It could probably be C VI (perhaps a blend of the C VI triplet at 27–28 Å). We tried to add additional lines and improved the fit only marginally, although another emission line at 243 eV may be present (probably the Fe XV line at 50.5 Å), and a narrow iron line at $\approx$6.4 keV is needed to explain the excess at this energy (model C). This fit is shown in Fig. 2 (lower panel).

With the NLTE-2 model we obtained model F with $\chi^2 = 1.62$ adding a line (perhaps N VI) at $\approx$490 keV, and again an iron line for the excess at $\approx$6.5 keV. The total unabsorbed flux in the lines in these two models is a negligible fraction of the total bolometric flux – less than 1 per cent. However, the flux in the line at $\approx$450 or 490 keV would be about 30 per cent of the absorbed flux in the *BeppoSAX* LECS range. In model C, the bolometric luminosity at a distance of 2 kpc (Della Valle et al. 1999) is 6.8×10^{38} erg s^{-1}. This value is higher, but not much in excess of the model predictions for a $\approx 1\,{\rm M}_\odot$ white dwarf emitting at Eddington luminosity.

The main problem in determining the white dwarf parameters accurately is the excess at low energy ($kT < 200$ eV), which cannot be fitted with one or more narrow lines. Around 150 eV, several transitions exist due to Fe, Si, Mg and Ni that could produce an intricate pattern, which must be heavily absorbed, and that cannot be resolved with the spectral resolution of the *BeppoSAX* LECS. By the time this nova was observed with the *Chandra* LETG, it had become much less luminous and the spectral structure had definitely changed. We only remark that a complicated multi-temperature structure most likely existed in the ejecta, and that continuum and emission lines with different origins (white dwarf for the first and nebular for the latter) can explain the complicated spectrum we detected with the *BeppoSAX* LECS and MECS. We rule out that our determination of effective temperature and gravity of the white dwarf can be accurate if nebular lines overlap with the white dwarf continuum. It is only clear that at this stage the atmosphere of the central source was still the dominating component of the X-ray flux.

4 CONCLUSIONS

The observation of V383 Vel made six months after the outburst revealed a very luminous supersoft X-ray source, comparable in luminosity only with V1974 Cyg at maximum. The details of this observation raise new, unexpected and very interesting questions. We observed irregular variability on a time-scale of minutes in the supersoft flux of V382 Vel. The lack of energy dependence of the variability measured below 0.7 keV seems to rule out the ejection of an obscuring clump, yet other considerations seems to rule out orbital variability as well.

Moreover, the *BeppoSAX* spectrum of V382 Vel in 1999 November appears much more complex than the expected thermal continuum of a hot white dwarf plus a residual thermal component from the nebula. We cannot justify this spectrum without invoking emission lines in the supersoft range (which were indeed observed shortly after this observation with *Chandra*), so we suggest that the observed ‘supersoft X-ray source’ in V382 Vel is characterized by unresolved narrow emission lines superimposed on the atmospheric continuum. We found that even a contribution of the lines of less than 1 per cent to the total bolometric flux can significantly change the shape of the stellar continuum, and make the task of determining the white dwarf temperature and effective gravity impossible with the resolution of the *BeppoSAX* instruments.

However, we conclude that the bulk of the X-ray flux was still due to the atmospheric continuum and not to lines at this epoch, unlike in the later observation performed with the *Chandra* LETG (Starrfield et al., in preparation).

Emission from classical novae in outburst can be quite complex and different from one nova to another. The X-ray spectra of N LMC 1995 (Orio & Greiner 1999) and of the recurrent nova U Sco (Kahabka et al. 1999) could be fitted well with model atmospheres, although U Sco also required a nebular component at higher energy. We caution, however, that the spectral structure may be as complex as the one observed for Cal 83 by Paerels et al. (2001), when observed with higher resolution.

The situation was more complex for V1974 Cyg, where a model atmosphere *and* a hotter thermal component were necessary to fit the spectrum. The relative importance of the two components seemed to vary in each observation (see Balman, Krauter &

Ögelman 1998) and the interplay between them was rather complicated, which was also due to the lower energy resolution of the PSPC compared to the LECS (a factor of 2.4 less) and limited energy range of the PSPC (which could not cover the harder component well, at least at the beginning). We wonder whether the spectrum of V1974 Cyg also had superimposed nebular emission lines that made it appear hotter than it was, because a lower effective temperature ($\leq 20\,\mathrm{eV}$) of the post-nova white dwarf atmosphere may explain a puzzling fact. An ionization nebula was detected only in Hα for N Cyg 1992 (Casalegno et al. 2000) while *other ionization lines* (indicating a higher ionization potential) *were not present* in the nebula. We speculate therefore that in V1974 Cyg the white dwarf (Krautter et al. 1996; Balman et al. 1998) might have been *cooler* than it appeared by fitting the *ROSAT* PSPC spectrum with just a two-component model.

We note that even the spectrum of a non-nova super-soft X-ray source, the Galactic MR Vel, shows non-atmospheric emission lines, attributed to a wind from the source (Bearda et al. 2002). Instead, in classical novae in outburst emission lines in the soft X-ray range could be produced by shock ionization within the nebula. Shocked, X-ray emitting material seems to be present since the beginning of the outburst (Krautter et al. 1996; Orio et al. 2001b). The *BeppoSAX* LECS and the *ROSAT* PSPC do not resolve narrow emission lines. For novae, prominent nebular emission lines in the supersoft X-ray energy range indicate interesting possibilities, especially if they could be observed with *Chandra* or *XMM-Newton* in the future. We face new questions. Are these lines at times due to collisional excitation, do shocks occurs in the nova wind even many months after the outburst? Should we consider a line-driven wind at different velocity colliding into the initial radiation driven wind? The nova theory must become more detailed and refined once the X-ray spectrum is known in detail for a statistically meaningful sample of objects. The gratings in the new X-ray observatories are opening new and exciting possibilities for nova studies.

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