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X-RAY EMISSION OF NOVA PUPPIS 1991: ACCRETION OR A SHOCKED SHELL?

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ABSTRACT

Nova Puppis 1991 (V351 Pup) was observed and detected in X-rays by the *ROSAT* Position Sensitive Proportional Counter 16 months after the visual maximum with a count rate of 0.223 ± 0.005 counts s^{-1}. With follow-up optical observations we determined the value $E(B-V) = 0.3 \pm 0.1$ for the interstellar absorption and $D = 4.7 \pm 0.6$ kpc as the distance to the nova. The best spectral fit to the X-ray data is a model of thermal plasma at temperature $kT \simeq 1.1$ keV and source flux $f_X \simeq 3 \times 10^{-12}$ ergs cm^{-2} s^{-1} in the range 0.2–2.4 keV, implying an X-ray source luminosity of 7.5×10^{33} ergs s^{-1}. The source brightness varied between the two *ROSAT* exposures taken 2 days apart. The X-ray emission could be due to restored accretion at a very high rate or to shocks in the ejected shell; it does not have the characteristics of a "supersoft" thermal X-ray source associated with nuclear burning on a white dwarf. Nova Puppis 1991 is the third classical nova that emits hard X-rays, among five that have been observed by *ROSAT* during outburst.

Subject headings: binaries: close — novae, cataclysmic variables — stars: individual (Nova Puppis 1991) — X-rays: stars

1. INTRODUCTION

Nova Puppis 1991 (V351 Pup) was discovered in outburst on 1991 December 27 (Camilleri 1992) and subsequently monitored in different wavelengths. From the IAU Circulars issued in the period of the outburst, t_2 and t_3, the times for declines of 2 and 3 magnitudes, respectively, were measured as 16 and 40 days. The ejection velocities were on average $\simeq 2000$ km s^{-1} (Sonneborn, Shore, & Starrfield 1992; Shore et al. 1992). These properties are consistent with a typical moderately fast classical nova outburst. The presence of strong neon lines in the optical and *IUE* spectra suggests that it was a neon nova (Saizar 1994; Pachoulakis & Saizar 1995).

Three basic mechanisms are thought to cause X-ray emission from novae in outburst and at quiescence: hydrogen burning on the remnant white dwarf after the outburst, shocks occurring in the ejected shell, and accretion. While *hydrogen burning* occurs, the theoretical simulations predict effective temperatures in the range 2.5×10^5–10^6 K, so a blackbody-like "supersoft" X-ray spectrum and a nearly Eddington luminosity would be detected (e.g., Prialnik 1986). The duration of hydrogen burning is proportional to the leftover envelope mass, which is in turn predicted to be inversely proportional to the mass of the white dwarf (e.g., Prialnik 1986; Starrfield 1989). According to the models, the length of the "supersoft" X-ray phase of novae after the outburst ranges from 1 to 100 yr, depending on the white dwarf mass and other physical assumptions (see Prialnik 1986; Orio, Trussoni, & Ögelman 1992b; Livio et al. 1990; Kato & Hachisu 1989, 1994). A goal of the X-ray observations of novae is to determine the duration of this phase *observationally*. Because the duration of nuclear burning indicates how much mass is added to the white dwarf, this phase is also related to the generation of Type Ia supernovae or neutron stars from accretion-induced collapse (e.g., Della Valle & Livio 1995).

The other two mechanisms produce a thermal bremsstrahlung X-ray spectrum. *Hot, shocked material around novae*, first hypothesized by Brecher, Ingham, & Morrison (1977), might explain the optical coronal emission lines in many nova spectra (Williams 1992), the radio continuum outburst at day 206 of nova QU Vul (Taylor et al. 1987), and the infrared high-excitation lines also observed for QU Vul by Greenhouse et al. (1990). A possible scenario that can explain the occurrence of shocks is a high-velocity wind colliding into a lower velocity wind emitted earlier (O'Brien, Lloyd, & Bode 1994). The predicted plasma temperatures are 0.2–10 keV (e.g., Lloyd et al. 1992; O'Brien et al. 1994), and the luminosity is $L_X \simeq 10^{33}$–10^{34} ergs s^{-1}.

Since novae are cataclysmic variables, eventually *accretion* onto the white dwarf will be established and will produce X-rays. Quiescent novae were observed in X-rays with *Einstein* and *ROSAT* some 50 years after the outburst, at low luminosities ($L_X = 10^{30}$–10^{33} ergs s^{-1}) and with plasma temperatures of at least 1 keV (e.g., Becker & Marshall 1981; Balman, Orio, & Ögelman 1995; Orio et al. 1992a; Ögelman & Orio 1995). However, because of the large interstellar absorption of the average classical nova lying in the Galactic plane at a distance of a few kiloparsecs, the X-ray data set to study accretion in old classical novae is still poor.

X-ray observations of novae in outburst, aimed mainly at studying the "supersoft" phase and the ejected shell, were first performed with *EXOSAT*. Three novae (GQ Mus, QU Vul, and PW Vul) were detected, but the *EXOSAT* instruments did not have the necessary spectral resolution to determine the type of X-ray emission (Ögelman, Beuermann, & Krautter 1984; Ögelman, Krautter, & Beuermann 1987). *ROSAT*, with its high sensitivity in the range of very

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soft X-rays and a modest spectral resolution with the PSPC instrument, is particularly well suited for monitoring novae. Although about 20 novae erupted shortly before or during the *ROSAT* Position Sensitive Proportional Counter (PSPC) lifetime, most of them were not observed, either because of observational constraints of the satellite or because of difficulties in scheduling targets of opportunity. Therefore, before Nova Pup 1991 only three novae were observed 1–2 yr after the optical maximum, while they were bright in the optical and UV and displayed high-excitation emission-line spectra. However, this early stage is critical for classical novae because all three mechanisms of X-ray emission can play a role. The central ionizing object is still very hot and luminous, so it is reasonable to assume that hydrogen is still burning. The rapidly expanding circumstellar shell of ionized ejecta is present, and high-velocity winds are likely (e.g., Williams 1994a). It is also possible that accretion might be resumed at an early stage after the outburst (Leibowitz 1993); knowing if and when this happens is extremely important for the nova theory.

The three recent novae observed by *ROSAT* while they were still bright in the optical and UV were Nova Her 1991 (V838 Her), Nova Cyg 1992 (V1974 Cyg), and Nova LMC 1992 (Orio, Ögelman, & Balman 1996; Ögelman & Orio 1996). The only other nova observed by *ROSAT* before its return to minimum, even if at a late postoutburst phase (9 and 10 yr after the eruption), was GQ Mus (Ögelman et al. 1993; Shanley et al. 1995). Surprisingly, only this nova and Nova Cyg 1992 appeared to be, as expected, "supersoft" X-ray sources. Another X-ray component, which was harder, had low luminosity, and was fitted with a Raymond-Smith plasma at temperatures of a few million degrees, was also detected for Nova Cyg 1992. This component was the only one detected for Nova Her 1991. For Nova Cyg 1992 it appeared in every observation following the first 2 months after the outburst (Krautter, Ögelman, & Starrfield 1992; Krautter et al. 1996) and for Nova Her 1991 at only 5 days after the outburst (Lloyd et al. 1992).

In this paper we introduce a new piece in the X-ray observational picture of classical novae by presenting the observation of Nova Pup 1991 obtained by *ROSAT* 16 months after the outburst. We also present follow-up optical spectroscopy and imaging aimed at better understanding the nature of this nova. In § 2 we examine the observations, in § 3 we combine the information from X-ray and optical data, and in § 4 we draw some conclusions.

2. OBSERVATIONS

2.1. *The ROSAT Observation*

Nova Pup 1991 was observed by *ROSAT* for a total time of 9554 s on 1993 April 30 and 1993 May 2, 16 months after the outburst. The nova was detected at an average count rate of 0.223 ± 0.005 counts s^{-1}. The observation lasted for 3750 s on April 30, and for 5804 s on May 2. The count rate was significantly different on April 30 (0.297 ± 0.012 counts s^{-1}) and on May 2 (0.204 ± 0.006 counts s^{-1}). This indicates that the source flux varied on a timescale of the order of a few days or smaller, but given the short intervals of the observation and the limited number of photons collected all together (about 2200), we could neither detect nor rule out any periodicity on shorter timescales.

The averaged spectrum was examined with the EXSAS/MIDAS software (Zimmermann et al. 1993). Blackbody models fit the data if no lower limits for the source flux and no upper limits for the hydrogen column density are assumed; however, the blackbody temperature turns out to be always $T_{BB} > 120$ eV. No fit at a 3 σ confidence level or better is possible below this temperature. As mentioned in § 1, the models predict $T_{BB} = (2.5–10) \times 10^5$ K (e.g., Prialnik 1986; Starrfield et al. 1989), and the upper values of this range are reached only for white dwarfs of nearly Chandrasekhar mass. In addition, even the best blackbody fit we obtain, with a temperature $T_{BB} = 165$ eV for $N_H = 5.5 \times 10^{21}$ cm^{-2} and a bolometric unabsorbed flux $f_{bol} = 1.7 \times 10^{-12}$ ergs s^{-1} cm^{-2}, fits the data poorly with a χ^2 value of 2.3 per degree of freedom. We conclude that blackbody models are nonphysical for Nova Pup 1991.

The best fit to the data is obtained with a Raymond-Smith model of a thermal plasma. The quality of the fit is not sensitive to the choice of abundances, but since Nova Pup 1991 is known to be a neon nova (Saizar 1994; Pachoulakis & Saizar 1995), in Figure 1 we show the best fit with arbitrarily enhanced abundances of neon (assumed 10 times solar) and magnesium and helium (assumed 5 times solar). The plasma temperature kT, column density N_H, and source flux f_X are free parameters in the fit. We obtain $N_H = 1.3 \times 10^{21}$ cm^{-2}, $kT = 1.1$ keV, and an unabsorbed flux $f_X = 2.8 \times 10^{-12}$ ergs cm^{-2} s^{-1} in the *ROSAT* PSPC range 0.2–2.4 keV. The χ^2 value is 1.07 per degree of freedom. For comparison, assuming solar abundances, we obtain a best fit with the same χ^2, a slightly higher kT (by 10%), and a slightly lower f_X (by 5%).

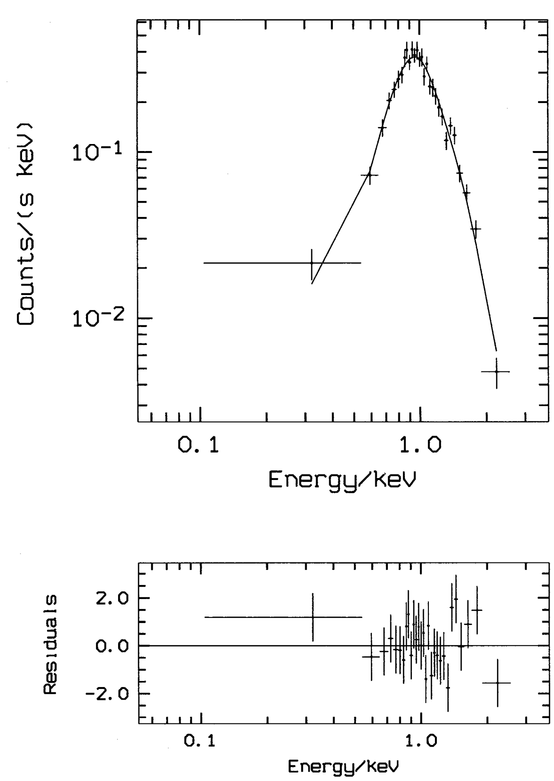

FIG. 1.—Observed spectrum of Nova Puppis 1991 with the *ROSAT* PSPC. The best fit to the spectrum is shown, with a Raymond-Smith model for a thermal plasma with Ne enhanced 10 times with respect to solar abundance, He and Mg 5 times solar, other abundances solar; source flux $f_X = 2.8 \times 10^{-12}$ ergs cm^{-2} s^{-1}, $kT_{BB} = 1.08$ keV, and $N_H = 1.34 \times 10^{21}$ cm^{-2}. We obtain $\chi^2 = 1.07$ per degree of freedom.

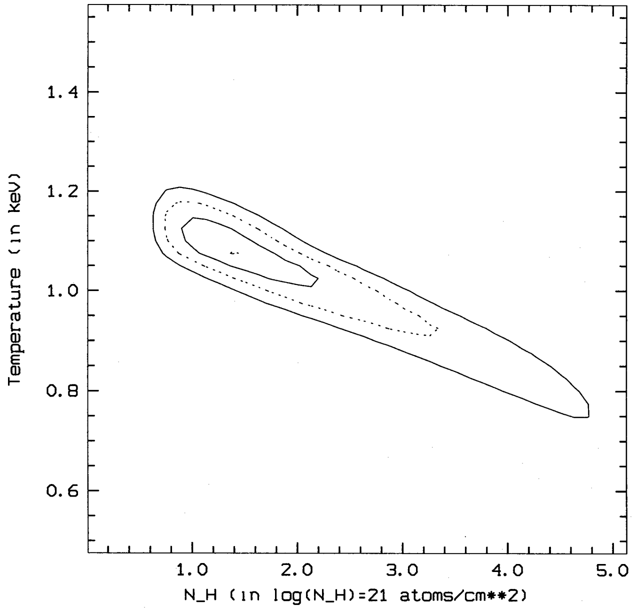

FIG. 2.—Grids of 1 σ, 2 σ, and 3 σ confidence contours in the T_{BB}-N_H parameter space for Nova Pup 1991. Here we assumed enhanced abundances as in Fig. 1.

Figure 2 shows the 1 σ, 2 σ, and 3 σ contours of all the acceptable Raymond-Smith model fits in the kT versus N_H plane. The allowed values are $N_H < 4.9 \times 10^{21}$ cm^{-2}, plasma temperatures 0.75 keV $< kT <$ 1.22 keV, and unabsorbed flux in the range $f_X = (0.96\text{–}6.4) \times 10^{-12}$ ergs cm^{-2} s^{-1}.

2.2. *Optical Observations: The Interstellar Absorption*

A good determination of reddening to this nova is very important to constrain accurately the column density N_H and thus the derived X-ray parameters. The only published determination of the interstellar extinction, $E(B-V) \simeq 0.85$, was obtained by Williams (1994a) with spectra taken within few months after the outburst. We monitored Nova Pup 1991 with ESO telescopes during the months following the *ROSAT* observation, and we use these data to improve the reddening estimate.

In 1994 March we obtained the spectrum shown in Figure 3 with the 3.6 m telescope and the imager/spectrograph EFOSC at ESO, La Silla. The slit was oriented to compensate for the atmospheric refraction. The detector used was a Tektronix 512 × 512 pixel CCD, with a projected pixel size on the sky of 0″.6. For a 1″.5 slit the resulting resolution is about 1 nm. Three 15 minute exposure spectrograms were obtained to cover the whole optical range, 380–720 nm. The interstellar extinction can be determined from this spectrum by comparing the expected Balmer decrement with the observed one. We measure an intensity ratio Hα/Hβ = 4.2, which, assuming an optically thin nebula, yields $E(B-V) = 0.34$. We thus adopt $E(B-V) = 0.3 \pm 0.1$.

This value for the reddening can be converted into a column density $N_H = (2.0 \pm 0.7) \times 10^{21}$ cm^{-2} following Ryter, Cesarsky, & Audouze (1975), in agreement with the results obtained in the X-ray spectral fits above. We attribute the much larger value of $E(B-V)$ reported by Williams (1994a) to variations of optical depths in the H Balmer lines in the ejecta (see Whitney & Clayton 1989). A decrease of the Hα/Hβ ratio with time has indeed already been observed for Nova Sct 1989 (Rosino et al. 1992; Anupama et al. 1992) and for Nova Cyg 1992 (Barger et al. 1993). Williams (1994b) obtained an unpublished spectrum also in 1993 April in which the line ratios are already about the same as in the spectrum observed by us 10 months later.

2.3. *Optical Observations: The Distance*

The other important point is to estimate the distance to Nova Pup 1991. The best estimates of the distances to Galactic novae are obtained via nebular parallaxes. After the *ROSAT* observation we performed narrowband filter imaging of Nova Pup 1991 twice from ESO at La Silla. The

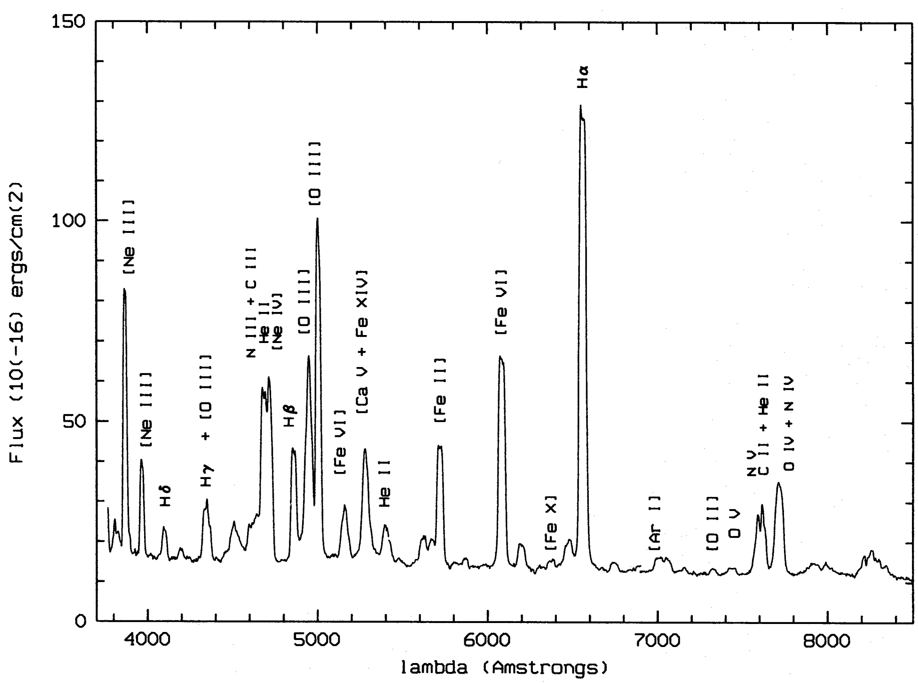

FIG. 3.—Optical spectrum of Nova Pup 1991 as observed in 1994 March with the 3.6 m ESO telescope and the EFOSC imager spectrograph

second set of images, in which the shell was detected, was recently taken in the framework of an ongoing collaboration with a Padua group (Della Valle et al. 1996). Three 10 minute Hα exposures were obtained at La Silla with NTT on 1995 March 3, with seeing $\simeq 0''.70$, and a structure was resolved that was larger by $\approx 10\%$, in both X and Y, than the point-spread function of eight field stars. Assuming an average expansion velocity of the ejecta of ≈ 2000 km s^{-1} (Sonneborn et al. 1992), the derived distance is $d = 4.7 \pm 0.6$ kpc. This value, assumed in the rest of the article, is in agreement with the approximate estimate given by the maximum absolute magnitude versus rate of decline relationship for classical novae (following Della Valle & Livio 1995). We also remark that at a distance of 4.7 kpc and at the Galactic latitude of Nova Pup 1991 the height above the Galactic plane is 60 pc (i.e., it is a disk nova according to the definition of Della Valle et al. 1992).

3. COMBINING THE X-RAY DATA WITH THE OPTICAL INFORMATION

3.1. *The X-Ray Luminosity and the Emission Measure*

The value obtained for the interstellar extinction confirms the range of N_H derived from the 1 σ confidence level fits of an optically thin thermal plasma Raymond-Smith model to the X-ray data (see Fig. 2). It is important to notice that the distance estimate gives additional evidence against the blackbody model for Nova Pup 1991, because the unabsorbed bolometric luminosity is orders of magnitude too low for a hydrogen-burning white dwarf, $L_{bol} \simeq 4.5 \times 10^{33}$ ergs s^{-1}. Assuming the Raymond-Smith model, the distance estimate implies that the X-ray luminosity at the time of observation was $L_X \simeq 7.5 \times 10^{33}$ ergs s^{-1}. The emission measure (EM) obtained for this X-ray luminosity is 3.5×10^{55} cm^{-3}. Since EM $\simeq n_e^2 V$, where n_e is the electron density and V the volume of the emitting region, assuming that X-rays are emitted in a spherical volume with the radius of a nebular shell that expanded at the average velocity of 2000 km s^{-1} for 16 months, $R_s = 1.3 \times 10^{14}$ cm, we obtain $n_e \simeq 2 \times 10^6$ cm^{-3}. This is typical for a nova shell at this stage (e.g., Saizar & Ferland 1994; Contini, Orio, & Prialnik 1995). If instead the central source, and not the nebula, is emitting the X-rays, the electron density and volume of the emitting plasma are not well known. However, such a high X-ray luminosity is sometimes observed for magnetic accreting cataclysmic systems (Cropper 1990; Patterson 1994).

3.2. *The Missing Blackbody: Upper Limits on Its Temperature, and Indications of Cooling*

The failure to detect a supersoft source does not imply that the central source has necessarily switched off, but it gives upper limits on its blackbody temperature (see Shanley et al. 1995 for discussion of the GQ Mus case). Having determined the reddening and the distance to the nova, we derived a limit for the temperature of the blackbody source by fitting a double component spectrum, a thermal plasma plus a blackbody for the soft part of the X-ray counts distribution. This procedure yielded $T_{BB} \simeq 20$ eV as a 3 σ upper limit to the blackbody temperature of a white dwarf at an unabsorbed bolometric luminosity $L_X \geq 10^{36}$ ergs s^{-1} (1/100 the Eddington value for a 1 $M_\odot$ star). We notice that both the luminosity and the temperature are lower than the range estimated in the models for nuclear-burning white dwarfs in postnovae.

With the help of the optical data we also examined the possibility that at the time of the observation the supersoft X-ray source had *not yet* emerged. The nova was still surrounded by the ejected nebula, which seems to be more massive than in most other novae (Williams 1994a) and might have absorbed the soft X-rays of the central source. In the case of GQ Mus, the supersoft source emerged while the nova was still in outburst, and it lasted almost 10 years, by which time the nebular shell emission lines had substantially declined (González-Riestra, Orio, & Gallagher 1996). For Nova Cyg 1992, however, the supersoft source emerged and faded while the nova was still active and the nebular lines were clearly present (Shore et al. 1994).

The nebular spectrum in Figure 3 and the previous optical spectroscopic observations show the physical conditions of the ejected shell. We see in Figure 3 that coronal lines of [Fe X] and perhaps [Fe XIV] are present. If these lines are produced by photoionization from the central source, the temperature of the white dwarf photosphere at the time of the optical observation must have been at least 100 eV, although the exact value depends on the electron density and on the ionizing source spectral energy distribution. However, these lines might have been produced instead by photoionization in a region of shocked nebular ejecta, so the central source photospheric temperature might have been lower than estimated above. From the strong [Ne III] lines, we derive a temperature of $(2–3) \times 10^5$ K, which is consistent with the upper limit for the blackbody temperature. Thus it is possible that Nova Pup 1991 was luminous in the extreme UV, but not in the soft X-ray range covered by *ROSAT*.

We also compared the spectrum in Figure 3 with previous nebular spectra of the nova, still unpublished and kindly provided to us by R. Williams. A critical diagnostic to understand whether a hot photosphere is gradually emerging or whether instead the central source is cooling down is the evolution of the ratio of the line He II λ4686 to Hβ. For Nova Pup 1991 this ratio was decreasing at the time of the *ROSAT* observation, while for GQ Mus it kept on increasing while the nova was bright in soft X-rays (Krautter & Williams 1989). We thus conclude that the central source in Nova Pup 1991 was probably already *cooling* in the period of the *ROSAT* observation, so we estimate that nuclear burning probably ceased within 2 years from the outburst. According to the numerical models, this short turnoff time implies at least a moderately massive white dwarf, of $M \geq 0.9$ $M_\odot$ (Kato & Hachisu 1994).

4. CONCLUSIONS

We have shown that the X-ray emission of Nova Pup 1991 is not associated with a supersoft X-ray source, but rather is produced by either of the other two mechanisms outlined in § 1, shocks or accretion. We cannot distinguish between these two models on the basis of model fits to the *ROSAT* PSPC spectrum.

If the X-ray flux is powered by accretion which resumed at such a short time after the outburst, the accretion rate required to provide a match between the boundary-layer luminosity and the observed L_X is $\dot{M} \geq 10^{17}$ g s^{-1} (Patterson & Raymond 1985). The observed ratio L_{opt}/L_X is higher than in most cataclysmic variables, and resembles magnetic systems for which higher X-ray luminosities versus accretion rates are measured (e.g., Cropper 1990;

Patterson 1994). An independent argument in favor of this possibility is the variability reported in § 2.1. In intermediate polars the X-ray flux is often modulated with the spectroscopic period (e.g., Balman et al. 1995); the nova might have a long orbital period (i.e., several hours) and have been observed at two different orbital phases.

Shocks in the ejected shell have already been considered as a viable explanation for the two other novae with a hard X-ray component in the *ROSAT* range, Nova Her 1991 (Lloyd et al. 1992; O'Brien et al. 1994) and Nova Cyg 1992 (Krautter et al. 1996). The simulations of the outburst (see review by Starrfield 1989; Shara & Prialnik 1994), reproduce many details of the observations but do not show that the velocity of the wind varies as required in the model of O'Brien et al. (1994). However, it has long been known that nova spectra show a range of wind velocities (e.g., Payne-Gaposchkin 1957), and the structure of the ejected gas is complex and thus difficult to model (Gallagher 1995). Mass loss through a line-driven wind might become important, and it has not yet been treated in the current models (Starrfield 1994). The observed coronal lines in the optical spectrum, at a time when other evidence points to a modest photospheric temperature of the stellar remnant, seem to indicate that some shocks did occur. We have to assume, however, that the different count rates measured in two exposures about 48 hours apart are due to emission from two different, inhomogeneous shocked regions. These regions cannot be in the outer shell if they move from the line of sight in less than 2 days. This is also consistent with the wind luminosity, $10^{-4}L_{\rm bol}$, higher than for O stars in which shocks in the wind are well known to occur. There might be a difficulty in reconciling the production of X-rays in an inner shell with the value of the emission measure while also keeping n_e in the observed range for novae. However, quantitative limits require a detailed numerical model, which is beyond the scope of this observational paper.

Perhaps the puzzle of the X-ray emission of Nova Pup 1991 will be solved by new observations. Observations in all wavelengths can tell us whether the nova has resumed accretion. A pointing with *ASCA* might detect the Ne x line if the X-ray emission indeed originates in shocked ejected material of the circumstellar shell, which should be enriched by the nucleosynthesis of the neon nova.

Finally, we compare Nova Pup 1991 with GQ Mus, Nova Her 1991, Nova Cyg 1992, and Nova LMC 1992, namely, the other classical novae observed in X-rays by the PSPC of *ROSAT* (for which we have some spectral information), before the return to minimum in the optical and UV spectral region. The supersoft X-ray component was present for GQ Mus and Nova Cyg 1992, but the harder component in the X-ray flux was detected in three out of five novae. This raises the question whether the hard X-ray emission is a common phenomenon in postoutburst novae or whether it occurs instead in a particular nova subclass. While Nova Her 1991 was an extremely fast nova, the other two objects can be classified as only "moderately fast." Nova Pup 1991 is the only "disk nova" (see definition of Della Valle et al. 1992). However, there is a common property of the three novae that showed the hard X-ray component: they have all been classified as "neon novae." It is still too early to draw conclusions with this limited data set, but in future years it will be meaningful to look for a correlation between neon novae and hard X-ray emission from classical novae soon after the outburst.

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