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THE ULTRAVIOLET AND X-RAY VIEW OF THE DEMISE OF NOVA V1974 CYGNI

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ABSTRACT

We present new data on the variations of the ultraviolet nitrogen lines during the late, optically thin stages of the outburst of V1974 Cygni. These show that, ~500 days after discovery, the ejecta reached maximum ionization and then started to recombine, coincident with the X-ray turnoff observed with *ROSAT*. We derive densities for the ejecta at this stage and use these to discuss the development of the ejecta. The decline with time of the UV emission lines, especially He II λ1640, shows that the ejecta must have a linear velocity structure. This agrees with models for the ejection by an explosion and models that we have previously published for the line profiles. We then model the variations of the X-rays from this nova. We show that the *ROSAT* rise can be modeled by assuming a constant-luminosity central source, at approximately the Eddington limit for a massive white dwarf and an effective temperature of $\sim 4 \times 10^5$ K, using only a decreasing X-ray optical depth within the ejecta, as previously noted by Krautter et al. This model can be generalized to explain the absence of X-ray emission during the early outburst stages of any nova. Last, we show that the final decline in the X-rays requires a substantial decrease in both the luminosity and temperature of the central star, in agreement with expectations for thermonuclear burnout on the surface of the white dwarf.

Subject headings: novae, cataclysmic variables — ultraviolet: stars — X-rays: stars

1. INTRODUCTION

V1974 Cygni 1992 has been the most thoroughly analyzed nova outburst of this century (see Starrfield & Shore 1995). Having been observed at virtually every part of the electromagnetic spectrum, this nova represents the fiducial object against which to compare interpretations of the phenomenology of the outburst. The purpose of this Letter is to present ultraviolet confirmation of the cessation of X-ray emission by the remnant central star and to describe a simple model that accounts for the observed turn-on of the X-rays detected by *ROSAT*, which has been described in a previous paper (Krautter et al. 1996).

2. ULTRAVIOLET SPECTROPHOTOMETRY

Observations of V1974 Cyg with the *International Ultraviolet Explorer* (*IUE*) have been obtained since the beginning of the outburst. The early spectrophotometry and high-resolution spectral development have been described elsewhere (Shore et al. 1993, 1994; Hauschildt et al. 1994). We report here only on the later observations obtained at low resolution ($R \equiv \lambda/\Delta\lambda \approx 300$) with the short-wavelength primary (SWP) camera (in the range 1200–2000 Å) with the large science aperture ($20'' \times 10''$) during the epochs that occurred immediately before and during the X-ray turnoff of the nova. The *IUE* low-resolution observations ended in 1995 May because the nova became too faint to detect.

The last spectrum we report in this Letter, however, was obtained on 1995 September 28 UT with the Goddard High Resolution Spectrograph (GHRS) on the *Hubble Space Telescope* at low resolution ($R = 2500$) using the G140L grating and the large science aperture ($2'' \times 2''$) centered on the central star. The point-spread function is much better than our initial, pre-COSTAR observations. We aimed at duplicating these earlier GHRS observations (Shore et al. 1993) as closely as possible, considering the faintness of the nova at the time of the observations. The detailed analysis of the GHRS data will be reported elsewhere (Shore et al. 1996).

In this study, we concentrate on the evolution of the emission lines of nitrogen, N III] λ1750, N IV] λ1486, and N V λ1240. The journal of our *IUE* and GHRS observations and integrated line fluxes is provided in Table 1. We also include the C IV λ1550 and He II λ1640 integrated fluxes. All data are uncorrected for reddening [which is $E(B-V) = 0.3 \pm 0.05$, following Austin et al. 1996 and references therein]. Upper limits for N III] λ1750 are also indicated in Table 1.

The ultraviolet nitrogen lines are extremely useful as indicators of the ionization and density structure of the ejecta. Three ionization stages are represented by resonance and intercombination transitions that have similar density and temperature dependences. All of the lines appeared early in the outburst, as soon as the veiling absorption from the iron peak (the "iron curtain" described in Shore et al. 1994 and Hauschildt et al. 1994) had dissipated. We know from the GHRS profiles obtained in 1992 September and 1993 April that the individual components of all the nitrogen emission multiplets had profiles identical to that of the optically thin recombination line He II λ1640 (see Shore et al. 1993). Thus, the three nitrogen ionization stages are likely probing the same gas. Although, earlier in the outburst, we had access to several ionization stages of carbon and oxygen, the C III] λ1909 and O III] λ1665 multiplets were too weak to be measured in the low-resolution *IUE* spectra by mid-1993, leaving only C IV λ1550 and O IV] λ1402.

The nitrogen-line variations are shown in Figure 1. For comparison, we include the He II λ1640 and C IV λ1550 lines. The *ROSAT* light curve, using the Position Sensitive Proportional Counter (PSPC) count rate for the energy range 0.1–

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TABLE 1

Integrated Emission-Line Fluxes for V1974 Cygni

SWP	JD	N v λ1240	N iv] λ1486	C iv λ1550	He ii λ1640	N iii] λ1750
45135	8818.17	4.08E−11	1.73E−10	4.94E−11	6.60E−11	2.53E−10
45310	8845.01	4.89E−11	1.62E−10	5.35E−11	6.22E−11	1.96E−10
45548	8873.04	8.02E−11	1.72E−10	5.05E−11	4.56E−11	1.43E−10
46064	8921.59	1.00E−10	1.37E−10	4.45E−11	2.60E−11	8.26E−11
46404	8960.86	8.47E−11	7.13E−11	2.55E−11	1.98E−11	3.55E−11
47027	9041.68	5.91E−11	3.21E−11	1.16E−11	6.96E−12	1.09E−11
47278	9061.47	1.86E−11	8.19E−12	2.98E−12	1.90E−12	2.86E−12
47416	9082.26	3.64E−11	1.62E−11	5.44E−12	3.67E−12	5.25E−12
47417	9082.31	3.92E−11	1.65E−11	5.91E−12	4.87E−12	6.00E−12
48026	9171.00	1.16E−11	3.97E−12	1.45E−12	1.28E−12	1.44E−12
48027	9171.07	1.36E−11	4.35E−12	1.66E−12	1.44E−12	1.55E−12
48028	9171.22	1.79E−11	5.39E−12	2.61E−12	2.21E−12	2.27E−12
48222	9192.83	8.80E−12	2.82E−12	1.20E−12	9.76E−13	9.80E−13
49321	9316.50	2.02E−12	1.61E−12	5.40E−13	7.54E−13	3.09E−13
50494	9449.61	3.21E−13	4.80E−13	1.28E−13	4.76E−13	1.01E−13
50941	9503.61	2.72E−13	3.35E−13	1.56E−13	4.49E−13	7.39E−14
51387	9543.82	1.98E−13	3.14E−13	8.54E−14	2.66E−13	6.30E−14
51983	9594.24	1.51E−13	2.55E−13	9.54E−14	2.94E−13	<1.88E−14
52846	9677.48	7.84E−14	2.47E−13	5.28E−14	2.71E−13	<4.66E−14
54430	9822.09	1.07E−13	1.75E−13	1.00E−14	1.81E−13	<7.22E−14
54795	9868.00	5.50E−14	6.39E−14	3.39E−14	1.35E−13	<3.00E−14
Z2YP	9982.00	4.86E−14	8.13E−14	3.45E−14	1.24E−13	1.23E−14

Notes.—Fluxes in ergs s^{-1} cm^{-2}. The last spectrum (Z2YP) was obtained using GHRS with the G140L low-resolution ($R \approx 2500$) grating and the large science aperture (2″ × 2″), with FP-SPLIT = 2 and quarter-diode stepping, centered on the central star. It is the composite of spectra Z2YP0106 and Z2YP0107, covering the region 1200–1780 Å (see § 2).

2.4 keV from Krautter et al. (1996), is shown in Figure 2. Until late spring 1993, we observed the behavior expected of the ionization of the ejected gas expanding with increasing ionization (see, e.g., Gallagher & Starrfield 1978). The central source was hot and the ionization of the gas was increasing, as indicated by an almost linear rise in the N v λ1240–to–N iv] λ1486 ratio. Nebular modeling of the ejecta indicated that this emission was likely coming from the denser knots moving with $v_{\rm exp} \approx 1800$ km s^{-1}, which, at the time of the N v peak, had an electron density less than 10^7 cm^{-3} (Austin et al. 1996). The

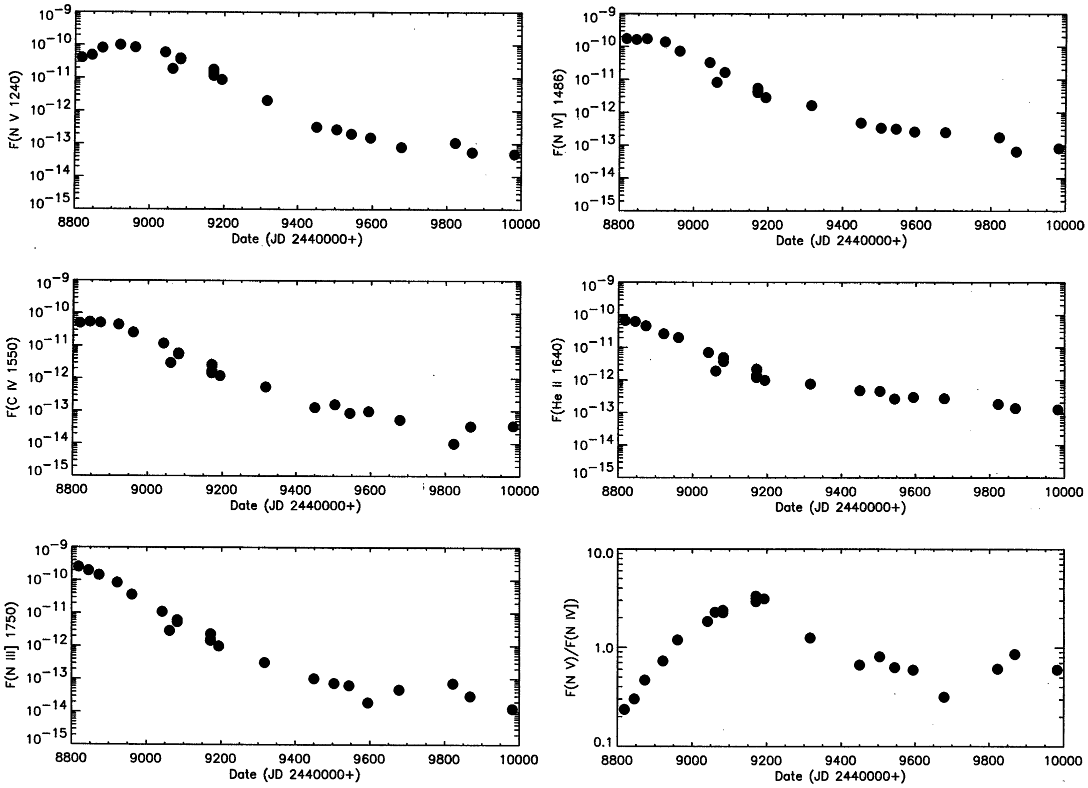

Fig. 1.—Variations of the integrated fluxes for the late stages of V1974 Cyg. All fluxes are in units of ergs s^{-1} cm^{-2}, and dates are Julian days. The bottom right panel shows the ratio of N v λ1240 to N iv] λ1486.

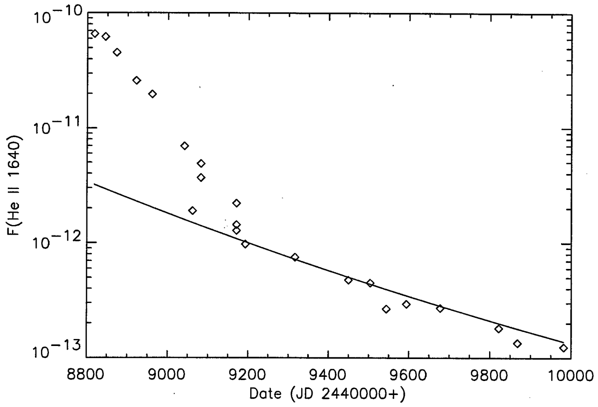

FIG. 2.—Variation of the He II λ1640 integrated fluxes plotted along with the recombination model discussed in the text (*solid line*). Units are as in Fig. 1.

N III] λ1750 multiplet also steadily weakened, confirming the increasing ionization. However, around 1993 July, the N V doublet began to fade with a slowing of the decline of the N IV line. In hindsight, we now recognize that this behavior occurred in the late spectra of QU Vul, taken in 1987 and 1988. However, it has not otherwise been seen in ultraviolet spectra of other novae we have observed with *IUE* during the past decade. The steady decline halted around JD 2,449,500 (day 920), when the ionization ratio of $N^{+4}/N^{+3}/N^{+2}$ reached an approximately constant value.

Based on the UV alone, we can say that the higher density knots, which dominated the integrated emission after about day 200, were recombining in response to a drop in the rate of EUV and X-ray illumination. The decrease in the N^{+4}/N^{+3} ratio had a characteristic timescale of ~100 days from the data in Table 1, which is approximately the recombination time, $(\alpha_4 n_e)^{-1}$, where α_4 is the N^{+4} recombination coefficient (R. Benjamin 1996, private communication; Aldrovandi & Péquignot 1973). The electron temperature was of order 10^4 K, so the electron density was $\sim 10^4$ cm^{-3} in the region of line formation. This was lower than in the knots and was likely located in the more diffuse, higher velocity ejecta. Since the N III λ1750 flux did not increase during this time, the central-source luminosity must have remained relatively high but had a lower effective temperature. We therefore interpret the initial decrease in the ionization fraction of the ejecta as a change in the photoionization rate from the central source.

The He II λ1640 line is a clearer indicator of the change in the photoionization conditions in the ejecta than the nitrogen lines. There was a break in the rate of decline at about JD 2,449,200, after which the decline was much slower, with a characteristic decay time of ~1 yr. Assuming that the photoionizing source had turned off at time t_0, the emission measure varies as $\ln (j_{1640}/j_0) = \frac{1}{2}\alpha n_{e,0}\, t_0 [(t_0/t)^2 - 1]$, where $j_0 = 10^{-12}$ ergs cm^{-2} s^{-1} is the emission measure at time $t_0 = 9200$ days, α is the He II recombination coefficient (Osterbrock 1989), and $n_e \sim t^{-3}$ is the electron density in cm^{-3}. This last assumption is a consequence of the linear velocity law for the ejecta, as expected from a ballistic explosive outburst. The results from this model are compared to the He II λ1640 fluxes (see Fig. 2) assuming a recombination time of 350 days, which implies $n_{e,0} \approx 3 \times 10^5$ cm^{-3} for an electron temperature of $\sim 10^4$ K. This density indicates that the line was formed mainly in the knots, in agreement with the line-profile analyses. We note that our latest observation with GHRS, on 1995 September 27, showed that the O V λ1371 recombination line had increased since our last *IUE* observation, consistent with the extrapolated density to day 1300 of the outburst.

Thus, the ultraviolet emission line variations indicate that the hot central source, which dominated the early, optically thin evolution of the ejecta, had ceased to photoionize the gas by summer of 1993. The subsequent decrease in the recombination rate and electron density eventually froze the ionization fractions, by the beginning of 1994. Therefore, any further analysis of the physical conditions of the ejecta must assume that the effective temperature and luminosity of the central star at the "freeze-out" stage, around JD 2,449,500, set the physical conditions for the ejecta.

3. MODELING THE RISE IN THE *ROSAT* COUNT RATES

Krautter et al. (1996) used a simple model to determine the cause of the turn-on of the soft X-ray component. They assumed a constant bolometric luminosity from the underlying source and a decreasing column density $N_{\rm H}$. During the initial stages, the soft component is completely absorbed by the ejected shell. As the material expands, however, the density decreases and an ever-growing fraction of the soft X-rays can escape. They assumed that the spectral energy distribution of the underlying source was caused by thermal bremsstrahlung, which is probably not correct. Here we describe an independent analysis.

The model we employ for the ejecta is a uniform-density isothermal slab with solar abundances. We assumed that the central source maintained constant bolometric luminosity throughout the X-ray rise and that the ejecta simply extinguished the source with a variable optical depth τ. Absorption coefficients for hydrogen and helium were taken from Mihalas (1978). Those of the heavier elements were modified from routines available from the *EUVE* Data Reduction Facility programs (see Miller & Abbott 1995). We used a model atmosphere continuum supplied by K. Werner (1994, private communication), with $T_{\rm eff} = 4 \times 10^5$ K. The effective temperature was extrapolated from the analysis of the *IUE* and *Voyager* spectrophotometric variations, as discussed by Shore et al. (1994). Column densities were calculated using a similarity law for the expansion of the ejecta resulting from a linear velocity law (see Shore et al. 1993; Hauschildt et al. 1994), $N_{\rm H}(t) = N_{\rm H,0}[t/t(0)]^{-2}$. The initial column density $N_{\rm H,0}$ was varied between 10^{22} and 5×10^{22} cm^{-2} for day 40, $t(0)$, of the outburst. This is in agreement with the range derived by Hauschildt et al. (1994) for the optically thick stage of the outburst and also with estimates by Krautter et al. (1996) from the *ROSAT* count rates. Although we did not solve for the ionization balance within the slab as a function of time, we varied the helium ionization ratio. Figure 3 displays the results for $\mathrm{He}^+/\mathrm{He}^0 = 0.5$.

Figure 3 also shows the effect of the column density variation on the observed X-ray fluxes for the central star compared with the the *ROSAT* count rates taken from Krautter et al. (1996). The model was folded through the *ROSAT* PSPC and HRI point-source sensitivities.[6] Our models show that the *ROSAT* light curve is reproduced rather well, assuming that the X-ray turn-on was due entirely to the lifting of the ejecta's opacity, in agreement with Krautter et al. (1996). The initial column density is uncertain but appears to

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[6] These were derived from the figures in the NASA *ROSAT* Research Announcement.

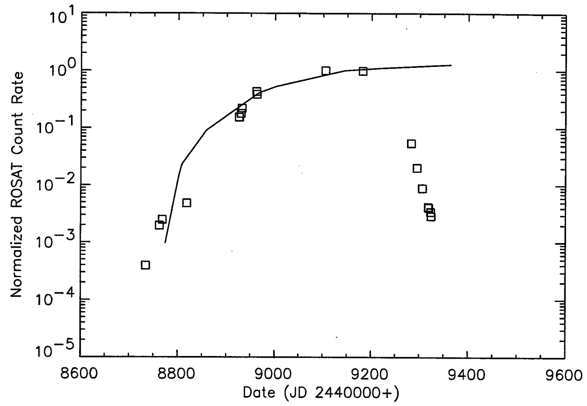

FIG. 3.—Comparison between *ROSAT* 0.1–2.4 keV PSPC count rate and the model discussed for the ejecta's optical depth variations. A constant-luminosity 4×10^5 K white dwarf model was used for the calculation. The steep decline in the *ROSAT* counts occurred at the same time as the change in the rate of decline of the He II λ1640 flux, shown in Fig. 2. The model assumes a neutral-hydrogen column density of 3×10^{22} cm^{-2} on day 40 (see § 3 for discussion).

be $\sim 3 \times 10^{22}$ cm^{-2} during 1992 April, at the epoch of the first detection.[7] Subsequently, the progressive decrease in the opacity of the ejecta produced an almost exponential increase in the observable X-ray counts that matches the observations rather well. Thus, the underlying star was maintaining roughly *constant* bolometric luminosity throughout the period 1992 April–1993 July, and the final decline in the *ROSAT* count rates means it must have actually turned off after that time.

Since we could not include the effects of variable temperature in these computations, it is possible that the temperature of the source decreased along with its luminosity. Our most recent GHRS observations reveal a stellar continuum with a Lyα absorption line similar to standard DA2 white dwarf spectra (Shore et al. 1996) with a bolometric luminosity of order 100 $L_\odot$ in late 1995. This agrees with the extrapolations, based on model calculations for the cooling of the white dwarf, outlined in Krautter et al. (1996) The final decrease in the luminosity of the central star was very fast, as discussed by Krautter et al., and accounts for the deviation of the models from the observations after 1993 September.

This model can be applied to other novae. For instance, a hydrogen column density for the ejecta of order 10^{22}–10^{23} cm^{-2} is sufficient to extinguish the soft X-ray emission from the central star of any nova, regardless of the interstellar absorption. A recent study of the ONeMg nova Pup 1991 (Saizar et al. 1996) obtained electron densities of order 10^8 cm^{-3} as late as 400 days after outburst, which argues that the column density was still rather high and likely sufficient to block the underlying source. Similarly, QU Vul, a slower ONeMg nova, also maintained high densities well into its expansion. In contrast, the very rapid expansion of the ejecta from V838 Her 1991 would have permitted earlier visibility of the X-rays from the central star, which appears to have turned off almost immediately. Therefore, the absence of X-rays during the early stages of nova outbursts can likely be attributed to the large column densities of the ejecta and argues in favor of high masses for the expelled gas.

4. SUMMARY

We have presented *IUE* data obtained during the phase of X-ray turnoff of Nova V1974 Cyg 1992 that serve as a calorimeter for the central source. These data show that maximum ionization of the ejecta was reached at the time of the peak soft X-ray flux and that the ionization then decreased as the X-rays declined. Our analysis indicates that the decline in X-rays was caused by the turnoff of thermonuclear burning on the central star, which produced a decrease in both its luminosity and effective temperature. We also performed new modeling of the turn-on of the soft X-ray component using an input model atmosphere spectrum and were able to show that it was caused by a reduction in the column density of the expanding ejecta. Application of these results to other novae, such as V351 Pup 1991, suggests that no soft X-ray source should have been detected from this nova.

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[7] Krautter et al. found a minimum value for the column density of $N_{\rm H} \approx 2 \times 10^{21}$ cm^{-3} from their fits to the *ROSAT* light curve after day 200. Although higher than indicated by the Lyα profile, this value is consistent with the interstellar contribution. The leveling off of $N_{\rm H}$ as a function of time indicates the change in the optical depth of the ejecta and the increasing ionization of the gas.

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