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MULTIWAVELENGTH OBSERVATIONS OF NOVA LMC 1990 NUMBER 2: THE FIRST EXTRAGALACTIC RECURRENT NOVA[1]

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ABSTRACT

We present *IUE* and optical observations of Nova LMC 1990 Number 2, the first recurrent nova to be observed outside the Milky Way. The earlier optical outburst of the nova was observed in 1968, when it reached a maximum of about $V = 10.9$. *IUE* spectra were obtained between 1990 February 16 and March 26, with 8 hr resolution during the first day of observations. The ultraviolet observations reported here caught the nova at UV maximum; no P Cygni profiles developed on the resonance lines, suggesting that very little mass was ejected and the outburst was not spherical. The integrated UV luminosity at UV maximum was 2.9×10^{38} ergs s^{-1}. Thus the luminosity exceeded the Eddington limit for a one solar mass white dwarf [assuming $E(B-V) = 0.15$ and a distance of 55 kpc to the LMC]. This is the first time that the luminosity of a recurrent nova has been directly obtained.

Subject headings: galaxies: Magellanic Clouds — stars: novae — ultraviolet: spectra

1. INTRODUCTION

Recurrent novae represent extremes of the nova phenomenon (Starrfield, Sparks, & Truran 1985; Starrfield, Sparks, & Shaviv 1988; Starrfield & Snijders 1989). As is the case with a classical nova, a thermonuclear runaway is initiated in hydrogen-rich material that is accreted from a secondary star. However, unlike the classical novae, the very short recurrence time scales require both a high-mass white dwarf and a high-mass accretion rate. The resulting outburst is predicted to reach *or exceed* the Eddington luminosity for the white dwarf. As a result, radiation pressure rather than a blast wave drives off the mass. Persistent uncertainties in studies of recurrent novae are the distance and, therefore, the total energy emitted during the outburst. For the first time, because Nova LMC 1990 Number 2 was at a well-determined distance, we can determine the total outburst energy and use this nova to improve our understanding of other recurrent novae.

2. ASTROMETRIC CONFIRMATION RECURRENCE

The optical outburst of Nova LMC 1990 No. 2 (hereafter LMC 2) was discovered on 1990 February 14.1 by Liller (1990) ($m_V = 11.2$ mag) as the result of photographic nova patrol observations. The position of the nova was determined with the 4 m telescope at CTIO to be $\alpha_{1950} = 5^h10^m41\overset{s}{.}8 \pm 0\overset{s}{.}5$, $\delta_{1950} = -71°43'27'' \pm 6''$. In his announcement, Liller suggested a correspondence in position between this nova and one reported in the LMC in 1968 (Sievers 1970) which reached a maximum visual magnitude of ~ 10.9 mag. We have remeasured the original plates plus more modern surveys of that region of the LMC, and the two novae coincide in position to within $2\overset{''}{.}4$ in right ascension and 6″ in declination. There are no other candidate stars at this location, and we therefore conclude that LMC 2 is the first extragalactic example of a recurrent nova.

3. CLASSIFICATION OF THE SECONDARY

Because a high mass-accretion rate is required to produce a short recurrent time, it has been assumed that the secondary is evolved rather than on the main sequence as found for the classical novae. This is certainly the case for some recurrent novae such as T CrB, RS Oph, and V745 Sco where the secondary is observed to be a giant. Compact secondaries have been inferred in two Galactic recurrent novae, U Sco and V394 CrA (Shaefer 1990), where the spectrum of the secondary is not seen but where eclipses have been detected. For LMC 2, plates taken at Mount John Observatory (New Zealand) before and after this outburst show nothing at the position of the nova to $V = 14$. Sanduleak (1990, private communication) reported no identifiable star at the nova position to $B = 16$, based on Curtis-Schmidt material and the Hodge-Wright charts. The ESO sky survey plates go deeper and are consistent with no remnant brighter than $B = 17$. Thus the probable luminosity of any red component in the system must be $M_V > -1.5$ mag. This is intrinsically fainter than the red giant companions of the Galactic recurrent novae V745 Sco, T CrB, and RS Oph and is consistent with a companion that is small in size. U Sco and V394 CrA, the two novae whose outbursts most closely resemble LMC 2, are Galactic recurrent novae that appear to have a small companion. However, we must emphasize that the secondary in both systems must be evolved in order to be accreting material as rich in helium as is observed. As we shall show, this nova is also transferring helium-rich material.

[1] This paper is dedicated to the memory of Nicholas Sanduleak (1933–1990).

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TABLE 1

IUE SWP OBSERVATIONS OF NOVA LMC 1990 NUMBER 2

SWP	Day[a]	F(SWP)[b]	F(1250 Å)[b]	F(Si IV)	F(N IV)	F(C IV)	F(He II)	F(N III])	F(1900)[c]
38199	47.02	1.54-10	4.00-11	8.48-12	2.98-12	2.57-11	7.31-12	4.69-12	8.08-12
38200	47.07	1.46-10	3.65-11	7.59-12	3.82-12	2.46-11	7.57-12	4.62-12	8.33-12
38202	47.51	1.39-10	2.72-11	6.38-12	3.54-12	2.53-11	8.46-12	3.12-12	6.08-12
38204	47.77	1.83-10	3.61-11	6.33-12	4.48-12	2.30-11	8.18-12	3.34-12	4.04-12
38209	48.95	1.26-10	2.31-11	3.94-12	3.48-12	2.05-11	7.20-12	1.78-12	2.51-12
38214	50.85	5.09-11	9.65-12	1.17-12	1.85-12	1.08-11	3.65-12	6.7-13:	7.0-13:
38229	54.04	1.59-11	2.83-12	...	7.42-13	1.69-12	1.16-12	...	...
38231	54.75	1.62-11	2.66-12	...	3.72-13	1.24-12	1.00-12	...	...
38284	61.07	6.30-12	7.18-13	...	...	2.2-13:	3.2-13:	...	...
38394	79.30	3.15-12	3.10-13	...	...	1.1-13:	<3.2-13	...	...
38439	85.17	1.65-12	1.77-13	...	...	1.1-13	5.2-14:	...	...

NOTES.—Units are ergs cm^{-2} s^{-1}. Fluxes give the exponent as the second number

[a] Day number, 1990 (day 47 = Feb 16 UT).

[b] Total flux; all other fluxes are for emission lines only (net flux).

[c] Combined emission-line fluxes for Si III] λ1895 and C III] λ1910. These fluxes have not been corrected for the degradation of the SWP and LWP cameras, which increases the total flux by about 10%. The Eddington luminosity quoted in the text has been corrected (see § 5).

4. OBSERVATIONAL DETAILS

The ultraviolet spectra reported in this paper were obtained with the *International Ultraviolet Explorer* satellite (*IUE*) using the low dispersion mode and large aperture beginning on 1990 February 16.02 UT. These spectra cover the wavelength region 1150–2000 Å in the short-wavelength primary (SWP) camera and 2000–3300 Å in the long-wavelength primary (LWP) camera, with an approximate resolution of ~7 Å. The data were reduced using standard routines at the Goddard Space Flight Center (GSFC) Regional Data Reduction Facility (RDAF). Synthetic photometry was obtained using 50 Å bins centered at 100 Å intervals between 1200 Å (removing Lyα between 1200 and 1225 Å) and 3300 Å. The data were dereddened using the LMC extinction curve appropriate for regions distant from 30 Dor (Fitzpatrick 1986), assuming $E(B-V) = 0.15$ mag, the average LMC color excess outside of the 30 Dor region. This reddening is consistent with the He II λ1640/λ4686 ratio found in the nova. We have assumed a distance of 55 kpc to the LMC.

Optical observations of the nova were obtained on 1990 February 23 (day 54) at CTIO with the 1.5 m telescope and Cassegrain spectrograph, using a bare, coated GEC CCD with enhanced blue response. The integration time was 15 minutes and the resolution was 16 Å over the spectral range 3200–7900 Å. The data were reduced at CTIO using IRAF. Additional analysis was performed using RDAF software at GSFC.

5. OBSERVATIONAL RESULTS

Table 1 provides the journal of the *IUE* observations along with the SWP photometry for LMC 2. Where available, we have included the LWP data in our analysis. The LWP data, however, are not as complete, and we shall concentrate on the SWP data for this paper. All fluxes given in the table are *uncorrected* for extinction. Figure 1 shows a gallery of the early SWP spectra.

Our principal result is that the luminosity in the ultraviolet between 1200 and 3300 Å during the first 2 days of the outburst was 3.1×10^{38} ergs s^{-1} or 7.8×10^4 $L_\odot$. This means that the bolometric luminosity, which is underestimated by the *IUE* observations, was greater than the Eddington luminosity, 3.1×10^4 $L_\odot$, for a 1.0 $M_\odot$ white dwarf, assuming a solar mixture of the elements and electron scattering as the primary source of opacity. As we shall discuss below, a helium-enriched mixture is more appropriate for LMC 2. For ejecta which are nearly pure helium, $L_{Edd} = 7 \times 10^4$ $L_\odot$ $M_\odot^{-1}$. The UV luminosity rapidly declined after the first day, which appears to have been at UV maximum. The optical outburst was discovered 2 days prior to the first *IUE* observation, which appears to have just preceeded UV maximum. The optical observations reported by Liller, Wells, & Heathcote (Liller 1990) suggest that this nova had already reached optical maximum when discovered. Thus, we see here the same pattern which has been observed in other novae, both classical and recurrent: the ultraviolet light maximum follows optical maximum (Austin et al. 1990). By February 23 (UT), ~1 week after UV maximum, the integrated luminosity (in this case SWP plus optical) had fallen to ~ 6300 $L_\odot$.

The ultraviolet spectral and temporal development of LMC 2 is similar in many ways to that of the Galactic recurrent nova U Sco during its 1979 outburst; the notable exception is the lack of P Cygni absorption on the strong resonance lines (see Shore et al. 1990). The light curve development was so close to that of V394 CrA during its 1985 outburst that we were able to use its light curve to predict exposure times during the decline of LMC 2 successfully.

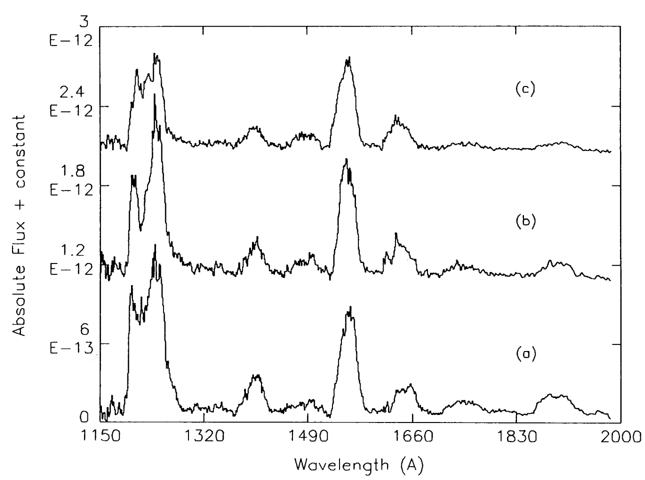

FIG. 1.—Gallery of early SWP spectra for Nova LMC 1990 No. 2. From bottom: (*a*) SWP 38200, (*b*) SWP 38204, and (*c*) SWP 38209.

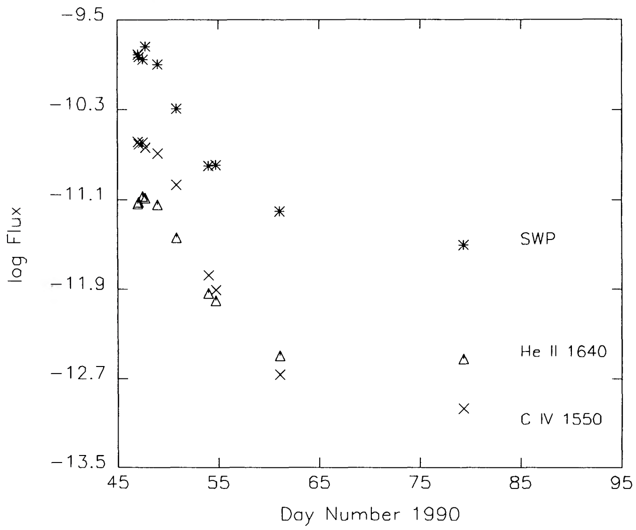

FIG. 2.—Variations in line and continuum fluxes during the outburst of Nova LMC 1990 No. 2. *Stars*: integrated flux from 1200 to 2000 Å (excluding Lyα, see text); *crosses*: C IV λ1550 emission-line flux; *triangles*: He II λ1640 line fluxes. No reddening correction has been applied.

Even in the earliest spectra, the resonance lines did not display P Cygni structure (see Fig. 1). This is in marked contrast to several other *recurrent novae* observed in the UV, such as U Sco 1979. The Mg II λ2800 doublet was extremely weak in the first spectra and faded rapidly thereafter. Interstellar absorption at Fe II λ2600 and Mg II was observed. Our spectra displayed only very high ionization states, N V λ1240, Si IV λ1400, C IV λ1550, and He II λ1640. The intercombination lines N IV λ1490, N III] λ1750, Si III] λ1895, and C III] λ1909 line were detected during the first week of observations. All lines were extremely broad. The mean velocity width of the lines (FWZI) was ~12,000 km s^{-1}, with FWHM of ~5000 km s^{-1}. The N V line appears blended with another line, likely Si III λ1206, and also shows complex structure after UV maximum.

The light curves are displayed in Figure 2. Although the major fraction of the energy losses occurred in the ultraviolet resonance lines, a weak continuum was present in the spectrum during the entire outburst. A flat LWP continuum is also present at a mean flux of $\approx 6 \times 10^{-14}$ ergs cm^{-2} s^{-1} $Å^{-1}$. The continuum was still rising at wavelengths shortward of 1150 Å and is consistent with a very hot source. In the earliest two *IUE* spectra, the continuum accounts for about three-fourths of the total flux in the range between 1200 and 2000 Å, and all of the flux in the LWP region. The total continuum flux is consistent with a temperature of $\approx 2 \times 10^5$ K, assuming that the radius of the remnant star is about 0.1 $R_\odot$ (see discussion in § 4, below).

Late developments in the line profiles showed what are probably multiple components, indicating that the ejecta rapidly developed an asymmetry. The C IV λ1550 profile displayed two components, at about −2300 and +1500 km s^{-1}. Gaussian fitting gives FWHM of ~2000 km s^{-1} for each component. The flux ratio of the approaching to receding components rose from about one-half to one over the course of ~1 week (from day 48 to day 55). Cross-correlation analysis shows that the C IV line becomes progressively more asymmetric with time, with the line centroid systematically shifting by 800 km s^{-1} to the blue, relative to the C IV line in SWP 38199, by day 85. The He II λ1640 line also shows multiple structures, with a narrow unresolved emission line superposed on a broader component developing by day 50.

The optical spectrum on 1990 February 23 has complex line profiles (see Figs. 3*a*, 3*b*). Both the He II λ4686 and Hβ lines display a broad (≈2000 km s^{-1}) component with a (probably unresolved) peak width ~250 km s^{-1}. Similar profiles were recorded by Dopita (1990). During this relatively late stage of the outburst, the Hβ flux was 1.22×10^{-13} ergs cm^{-2} s^{-1} (2.42×10^{-13} ergs cm^{-2} s^{-1} corrected for reddening). The dereddened Balmer decrement was 3.02:1.00:0.52. The He II λ4686 to Hβ ratio was 2.24, indicative of a large He/H ratio. In fact, only He II and hydrogen lines are present in the optical spectrum.

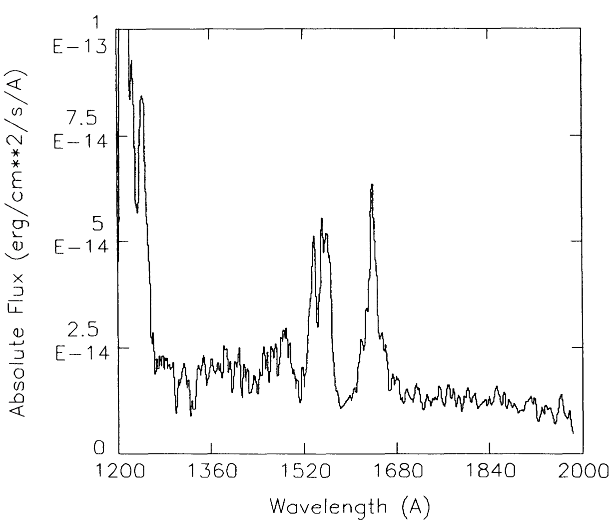

FIG. 3*a*

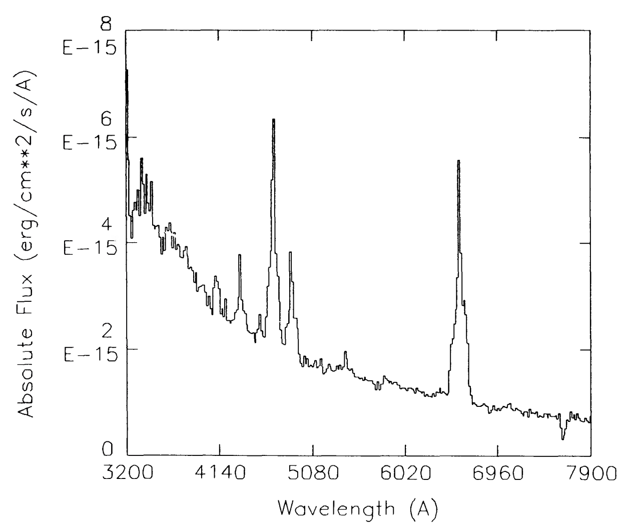

FIG. 3*b*

FIG. 3.—(*a*) SWP 38229, spectrum for Nova LMC 1990 No. 2 on 1990 February 23.7 UT. (*b*) CTIO optical spectrum taken on 1990 February 23, nearly coincident with the *IUE* spectrum. Note the complex structure of the line profiles and the He II λ4686/Hβ ratio of ~3. No reddening correction has been applied.

6. ANALYSIS OF THE OUTBURST

6.1. *Preliminary Constraints*

The optical depth in the ejected shell was clearly small at the time of the first *IUE* observations, based both on the lack of P Cygni absorption in the resonance lines and the strength of the He II λ1640 line. We assume that the hydrogen Lyman continuum was already optically thin, and that there was a strong ionizing source present from the exposure of the shell to the radiation from the postexplosion white dwarf. For simplicity, assume that the He II Lyman continuum was also optically thin. This provides a constraint on the electron density: $\tau \approx \kappa_{He^+} n_e \Delta r$, where Δr is the shell thickness, n_e is the electron density, and κ_{He^+} is the opacity at the He II photoionization edge (228 Å) (Osterbrock 1989). The condition that $\tau \leq 1$ gives $n_e \Delta r \approx 6 \times 10^{18}$. The He II λ1640 line is assumed to be produced by recombination, the lack of a strong O III λ3133 (which is pumped by He II Lyβ fluorescence) supports this assumption. Using the recombination rate from Osterbrock (1989), we obtain $j_{\rm He\,II\,1640} \approx 4.9 \times 10^{-24} n_e^2 R(t)^2 \Delta R$ ergs s^{-1}. Here $R(t)$ is the shell radius, given by the observed expansion velocity of $\sim 1.2 \times 10^4$ km s^{-1}. Using $j_{\rm He\,II\,1640} \approx 3 \times 10^{36}$ ergs s^{-1}, we get $n_e \approx 4 \times 10^{11}$ cm^{-3}, which is the upper limit to the electron density. The computed thickness of the ejecta is thus extremely small, $\sim 10^7$ cm. These estimates represent an extreme lower limit on the mass of the ejecta: $\sim 3 \times 10^{-10}$ $M_\odot$. However, the estimate of shell mass depends only on $\Delta M \approx \tau_{\rm He\,II\,LyC} R^2$ and is independent of the electron density if we take the He II λ1640 line to be due to recombination alone.

The high density is supported by the ratio of C III] λ1910/Si III] λ1895, which was ≈1, during the first 3 days of the outburst. The intercombination lines, including N III] λ1750 and N IV] λ1490, disappeared by day 51, 4 days into the outburst, indicating that the ejecta were by then completely optically thin and that the hot central source was by that time completely ionizing the ejecta.

Additional important constraints are provided by the LWP observations. The absence of Mg II at all stages of the eruption, even in the earliest observations, indicates that the shell is substantially ionized and therefore of very low mass. The last UV observations, taken some 40 days into the outburst, indicate that the central source is very hot and that most of the light is no longer coming from the lines but rather from the broad continuum. The fact that the N V and C IV resonance lines did not develop P Cygni structure suggests that the shell is neither spherical nor geometrically very thick. Within the limits of the parameters which can be explored in delimiting the properties of the shell, the best fitting models agree well with these constraints.

6.2. *Photoionization Modeling*

With these preliminary constraints in hand, we used the photoionization code CLOUDY (Ferland 1989) to perform a more detailed ultraviolet analysis of LMC 2. We assumed a hot central source, with a temperature of $\sim 2 \times 10^5$ K and a lower limit to the bolometric luminosity, based on the UV and optical observations, of 3×10^{38} ergs s^{-1}, as determined from the fluxes obtained with *IUE*. Models predict that the bolometric luminosity remains constant for at least several weeks after outburst for recurrent novae (Starrfield et al. 1985). Since detailed model atmospheres for such objects are not available, we assumed that the central body radiates like a blackbody, a minimal assumption which may overestimate the contribution of the He II Lyman continuum. A range of hydrogen densities between 10^8 and 10^{11} cm^{-3} were used, based on the initial assumptions just described. The radius was fixed for its approximate value for the first day of *IUE* observation, 2 days into the outburst: $R(t_0) = 2.5 \times 10^{14}$ cm. The shell thickness was varied between 10^6 and 10^{10} cm, and filling factors ranged from 10^{-4} to 1. The N/C ratio was assumed to be 30, in accord with results from galactic novae (Saizar et al. 1990) and U Sco (Williams et al. 1981). The abundances of all other metals were varied in the range from solar down to $\frac{1}{3}$ solar. For the final calculations, $Z = 0.3\, Z_\odot$, the value typical of the LMC.

For the first UV observations, the derived electron density is $n_e \approx 10^{10}$ cm^{-3}. The electron temperature obtained for the ejected material is 4×10^4 K. The analyses of the optical spectra agree with this value (M. Dopita 1990, private communication). The primary stage of ionization weighted by volume is He II, Mg III, and N IV. This agrees with the strength of the N IV λ1490 line. The helium to hydrogen ratio is $0.3 < \mathrm{He/H} \leq 1$. The He II optical and UV lines and the He II λ4686 to Hβ ratio cannot be reproduced with any lower value of He/H than unity. A similar result has been obtained for U Sco (Barlow et al. 1981). In general, however, it is impossible to produce precise matching of all of the lines, but the agreement with the best fitting set of abundances is within a factor of 2. In Table 2 we compare our best fitting model with the observations from the first *IUE* spectra.

The mass of the ejecta yielded by these models is $10^{-7.3 \pm 0.5}$ $M_\odot$, in agreement with determinations for other recurrent galactic novae. Taking this figure for the mass ejected during the 1990 outburst and the interval of 22 yr between successive eruptions of LMC 2, we derive a mass accretion rate $\dot{M}_{\rm acc} \geq 10^{-8.6 \pm 0.5}$ $M_\odot$ yr^{-1}. The total kinetic energy of the shell at UV maximum was $\sim 10^{43}$ ergs, comparable to the energy radiated during approximately the first half-day of the outburst.

The white dwarf temperature is also well determined by

TABLE 2

COMPARISON OF OBSERVED AND MODEL LINE LUMINOSITIES[a]

Line Luminosity	N V λ1240	C IV λ1550	He II λ1640	He II λ4686	Hβ
Observed[b]	37.98	37.47	36.89	...	...
Model[c]	37.63	37.12	36.91	35.94	35.89

[a] All luminosities are quoted as logarithms.

[b] Combined values for SWP 38199 and SWP 38200, corrected for $E(B-V) = 0.15$ and $D = 55$ kpc.

[c] Model parameter values are $\log L = 38.5$, $\log T_{\rm eff} = 5.5$, $\log n_p = 10$, He/H = 10, nitrogen abundance = 30 $N_\odot$, $\log R(t) = 14.4$ and $\log \Delta R(t) = 11$. Luminosity is in ergs s^{-1}, temperature is in kelvins, density is in cm^{-3}, and radii are in centimeters.

these observations. The N v $\lambda1240$ line is an excellent thermometer, being extremely sensitive to the flux emitted in the Lyman continuum. These calculations show that decreasing $T_{\rm eff}$ of the ionizing source from 2×10^5 K to 10^5 K decreases the N v line strength by more than an order of magnitude. Consequently, for temperatures below 2×10^5 K, no reasonable match can be obtained with either the observed N v line strength or for the N v/N IV ratio for any consistent set of abundances.

In a subsequent paper, we shall report on the detailed analysis of this system and compare it to the other Galactic recurrent novae observed with *IUE*.

7. SUMMARY

The explosion of a recurrent nova in the LMC has provided us with an unparalleled opportunity to understand the outbursts of these enigmatic objects. As a direct result of knowing the distance to the LMC, we can firmly state that the peak luminosity of this nova exceeded the Eddington limit for a 1 $M_\odot$ white dwarf with solar abundances. This nova's luminosity becomes less super-Eddington if we note that the ejected abundances were not solar but that helium (He/H $\sim$ 1) and nitrogen ($N \sim 30 \times$ solar), at least, were enhanced over an equivalent solar mixture by large factors. The optical depth in the He II Lyman continuum was, however, great enough during the first stages of the outburst that electron scattering certainly underestimates the opacity and makes the nova considerably more super-Eddington for a 1 $M_\odot$ white dwarf. Thus the mass of the progenator may have been closer to the Chandrasekhar limit than we have estimated here. We find that the ejected mass was $\approx 5 \times 10^{-8}$ $M_\odot$ which is similar to the value determined for U Sco. Until this nova returns to minimum and observations are obtained of the secondary it will not be known if it is a giant, subgiant, or condensed object. However, the large amount of helium ejected during the outburst certainly argues for an evolved secondary.

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