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# ULTRAVIOLET SPECTROSCOPY OF THE RECURRENT NOVA U SCORPII DURING OUTBURST

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## ABSTRACT

During its recent outburst, a series of ultraviolet spectra of the recurrent nova U Sco were obtained with the *IUE* satellite. The spectra consist primarily of emission lines; however, broad resonance absorption is also present during the first week after outburst. Analysis of the emission lines shows the nova ejecta to be very depleted in hydrogen relative to helium and to be rich in nitrogen, although the combined CNO abundance is probably essentially solar. A method for determining the masses of nova shells is derived which relates the mass directly to the optical depth of absorption lines, and a very small mass of $\sim 10^{-7}\ M_{\odot}$ is found for the ejected envelope; the mass ejected is thus significantly less than that typical of classical novae. A comparison between other properties of U Sco and classical novae further indicates that quantitative differences extend to virtually all aspects of the outburst. Optical spectra of U Sco were obtained after its return to quiescence and show predominantly He II emission lines, indicating that the preoutburst gas in the system was probably very helium rich and suggesting the presence of a highly evolved secondary star.

*Subject headings:* stars: individual — stars: novae — ultraviolet: spectra

## I. INTRODUCTION

U Scorpii is a recurrent nova, having undergone recorded outbursts in 1863, 1906, 1936, and, most recently, in 1979. Between outbursts, the nova is rather faint, with $m_v \gtrsim 18$, and the quiescent system was only recently identified by Webbink (1978). The maximum apparent magnitude achieved during outbursts has averaged around $m_v \approx 9$, and the declines in brightness following outbursts have been among the most rapid of any known nova ($t_3 \approx 6^d$). Because of its normal faintness and its extremely rapid rise to and decline from maximum, little is known about U Sco other than fragmentary data on its light-curve during previous outbursts.

In late 1979 June, U Sco was discovered near maximum light in one of its episodic eruptions. The nova was immediately declared to be a "target of opportunity" by the *International Ultraviolet Explorer* (*IUE*) Observatory, and we began a systematic series of UV spectroscopic observations of U Sco with the satellite. The observations were all made at low dispersion (resolution ≈6 Å) with both the short-wavelength and long-wavelength cameras during the period from June 28 (about 5 days past maximum) until July 11, when the nova had declined to $m_v \approx 14.3$, as determined by the *IUE* Fine Error Sensor. An attempt was made to acquire an additional spectrum in late August, when the nova was fainter than 16th magnitude; however, a 4 hour exposure recorded no detectable signal from the object. The short-wavelength UV spectra which were obtained of U Sco during the outburst are shown in chronological order in Figure 1. Spectra using the long-wavelength *IUE* camera were also taken; however, these scans are all extremely noisy, and they contain little information other than the fact that Mg II λ2798 emission was present and became weaker with time during the period in which U Sco was monitored. For reference, a light-curve of the visual brightness of the nova during this time, compiled from visual estimates by members of the AAVSO, is shown in Figure 2.

Initially, the U Sco spectrum was a mixture of both high-ionization and low-ionization lines, with resonance and intercombination transitions present—very similar to the emission spectra of high-redshift quasars (Baldwin and Netzer 1978). Resonance absorption from C IV λ1549 and Si IV λ1397 was seen through June 30, and N V λ1240 was probably also present; however, geocoronal Lyα emission dominated the N V absorption. After June 30, the line spectrum changed. The resonance lines became optically thin and the absorption disappeared because of the decreasing column density in the ejecta. In addition, the general level of ionization increased, and emission from most of the lower ionization lines disappeared, leaving only the higher ionization species prominent: N V

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λ1240, N IV] λ1486, C IV λ1549, and He II λ1640. The emission and absorption features were all very broad, characteristic of expansion velocities of up to 7500 km $s^{-1}$ for the ejected gas.

We did not obtain optical data during the outburst; however, U Sco was monitored regularly during the decline by Barlow *et al.* (1981), and they have presented an analysis of the outburst based upon optical spectra which is complementary to this study. The general pictures of the outburst deduced from both the optical and the UV data are quite similar.

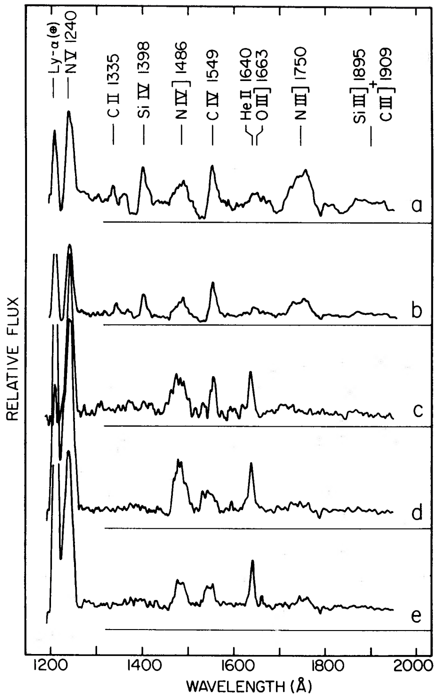

FIG. 1.—UV spectra of U Sco in the period following outburst. The dates for the *IUE* scans, together with the visual magnitude of the nova as determined from the Fine Error Sensor, are as follows: (*a*) June 28 ($V = 11.4$); (*b*) June 30 ($V = 11.9$); (*c*) July 2 ($V = 13.1$); (*d*) July 4 ($V = 13.8$); (*e*) July 11 ($V = 14.3$). The zero flux levels for the scans are given by the horizontal lines, and the emission-line identifications are shown at the top.

## II. ELEMENT ABUNDANCES

The time evolution of the spectrum, and the large widths of both the emission and absorption lines indicate that the line radiation is produced by expanding material ejected during the outburst. The presence of the N III] and N IV] intercombination lines, which are collisionally de-excited above electron densities $N_e \approx 10^{11}$ cm$^{-3}$, requires that the gas density in the shell be less than this value. On the other hand, the absence of any detectable optical forbidden lines during the entire decline period (Barlow *et al.* 1981), which is unusual for a classical nova outburst, indicates that the density in the ejecta must have exceeded values of $N_e \approx 10^8$ cm$^{-3}$. Thus, matter was ejected with unusually high velocity and gas density, as compared with a typical classical nova.

The source of the shell ionization is uncertain. It could be a relic of the ejection process, or due to photoionization from the nova continuum, or both. Since classical novae have been observed to be strong UV sources in the period immediately following the outburst

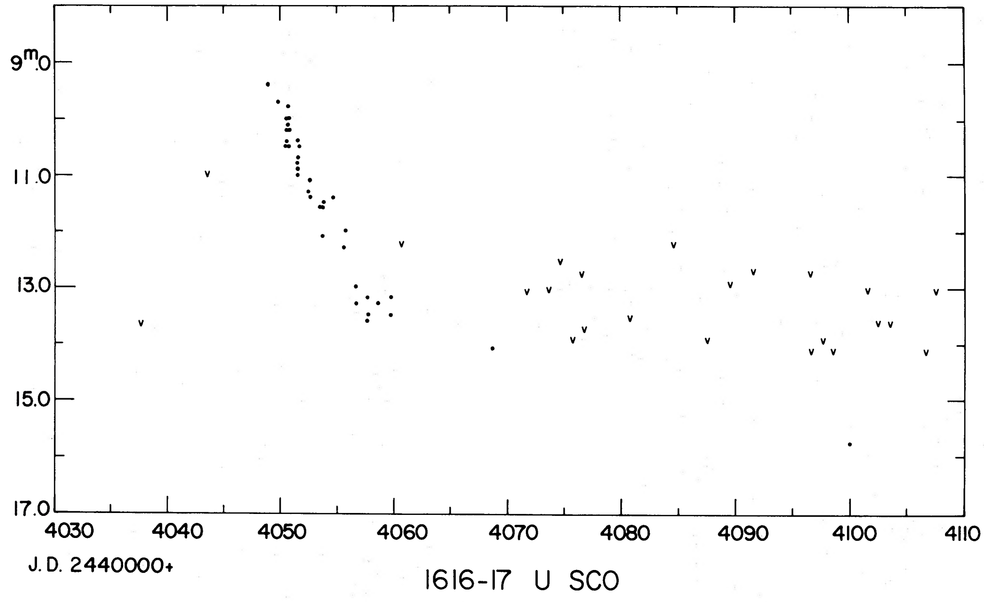

FIG. 2.—Visible light-curve for the 1979 outburst of U Sco, compiled from visual estimates of the nova brightness by observers of the AAVSO. These data may be compared with a similar curve presented by Barlow *et al.* (1981, Fig. 2).

(Gallagher and Code 1974; Wu and Kester 1977), this is possibly also the case here. The detailed ionization structure of the unresolved shell is also unknown; however, by analogy with other active objects which emit similar spectra, the ejecta most likely consist of large numbers of condensations and filaments which have some ionization stratification.

Without knowing the details of the geometry of the ejected gas and the ionization source, accurate element abundances cannot be derived, largely because of the uncertain ionization corrections for each emitting ion. However, rough calculations of the approximate composition may be derived by comparing relative intensities of lines which are formed by the same process and which originate from ions and levels having similar ionization and excitation potentials. This is particularly true for some of the later scans, where the low-ionization lines have disappeared and less stratification is evident.

In a highly ionized gas, both Lyα and He II λ1640 are formed by recombination, whereas the observed CNO lines are all collisionally excited. Consequently, a reliable He/H ratio can be found and, also, the abundances of C, N, and O relative to one another can be determined, independent of uncertainties in other parameters. However, the abundances of the CNO nuclei relative to H or He are sensitive to the electron temperature, and so there is less certainty in the determination of the absolute combined CNO abundance. In the case of the helium-to-hydrogen abundance, there is also the practical complication of having to disentangle geocoronal Lyα emission from that of the nova, and also of having to correct for the scattering of Lyα from U Sco by the intervening interstellar medium.

It is straightforward to show that, when both lines are caused by electron recapture, the emitted fluxes of Lyα and He II λ1640 are related to the $He^{+2}/H^{+}$ ratio by the expression (Osterbrock 1974)

$$\frac{F(\lambda 1640)}{F(\mathrm{Ly}\alpha)} = \frac{N(\mathrm{He}^{+2})}{N(\mathrm{H}^{+})} \frac{2\alpha_{\mathrm{H}\alpha}(T_e/4)}{\alpha_B(T_e)} \frac{1216}{1640} = 2.4 \frac{N(\mathrm{He}^{+2})}{N(\mathrm{H}^{+})}, \tag{1}$$

and are virtually independent of temperature and density. On July 2, a spectral scan of U Sco was obtained during a period when geocoronal Lyα emission was relatively low, and, although the observed flux of the Lyα feature during the 27 minute exposure is consistent with an entirely geocoronal origin, it does enable a limit of $F(\lambda 1640)/F(\mathrm{Ly}\alpha) > 2.5$ to be set on the observed (uncorrected for Lyα scattering by the interstellar medium) U Sco shell emission. The resulting He abundance is quite high, $N(\mathrm{He})/N(\mathrm{H}) \gtrsim 1$, where both elements are assumed to be completely ionized.

The extent to which scattering of Lyα by the interstellar medium (ISM) diminishes the observed U Sco line depends upon the intrinsic width of the emitted line and the column density of neutral H along the line of sight to the nova. The wavelength interval over which the ISM is optically thick to Lyα can be determined from observations of distant early-type stars in the direction of U Sco, which is almost certainly at a distance which places it out of the galactic plane (Webbink 1978; Barlow *et al.* 1981). Jenkins, Morton, and Matilsky (1969) have observed $\beta^1$, $\delta$, and $\pi$ Sco in the UV from a rocket, and they found for the three stars, which all have distances of about 175 pc and lie within 10° of U Sco, that the width of Lyα absorption from the ISM is of the order of ~ 15 Å. Some indication of the intrinsic width of Lyα emission from U Sco is provided by the optical Balmer-line profiles observed during outburst by Barlow *et al.* (1981, Fig. 6), which show a narrow component with a half-width of the order of 1000 km $s^{-1}$ superposed on broader emission extending out to ~ 5000 km $s^{-1}$ on either side. Assuming the optical depth of the nova shell in Lyα is small because of the large expansion velocities, the Lyα profile should be similar to the Balmer lines. If so, then the narrow component will be scattered out of the line of sight before it reaches the Earth. However, the broad component should be detectable, and we find no evidence for it. The data are, therefore, indicative of relatively weak Lyα emission from the shell, but the large corrections required by both geocoronal emission and interstellar scattering make quantitative estimates of the H abundance based upon the UV data uncertain. Thus, our values are consistent with the results of Barlow *et al.*, who found $N(\mathrm{He})/N(\mathrm{H}) = 2$ from optical line strengths.

The emission lines of the heavy elements are all collisionally excited from the ground state. If the simplifying assumption is made that the ionizations of C, N, and O are similar, i.e., that $C^{+3}/N^{+3} \approx C/N$ and $N^{+2}/O^{+2} \approx N/O$, then approximate abundance ratios can be determined from the relative line strengths of C IV λ1549/N IV] λ1486 and N III] λ1750/O III] λ1663. The semiforbidden transitions in the U Sco spectrum tend to have greater widths than the permitted lines, and the broad feature at ~ λ1650 on June 28 is more likely to be O III] λ1663 than He II λ1640, which becomes stronger 4 days later and is distinctly narrower than any of the intercombination lines. Assuming that He II does not make a substantial contribution to the O III] line on June 28, the observed line ratio is $F(\lambda 1750)/F(\lambda 1663) = 2.3$. Similarly, on July 11, when no resonance absorption was present to modify the emission strength, the C IV to N IV] flux was $F(\lambda 1549)/F(\lambda 1486) = 0.8$. Using collision strengths computed by Jackson (1973) and Osterbrock and Wallace (1977) for these transitions, the expression for the emission coefficient of a collisionally excited line (Osterbrock 1974) leads to the relations

$$\frac{N(\mathrm{N}^{+2})}{N(\mathrm{O}^{+2})} = 0.51 \exp\left(-\frac{4305}{T_e}\right) \frac{F(\lambda 1750)}{F(\lambda 1663)}, \tag{2}$$

and

$$\frac{N(\mathrm{C}^{+3})}{N(\mathrm{N}^{+3})} = 0.20 \exp\left(-\frac{3942}{T_e}\right) \frac{F(\lambda 1549)}{F(\lambda 1486)}, \tag{3}$$

which are insensitive to temperature for normal values of $T_e$ because of the similar excitation potentials of the lines. Assuming $T_e = 2 \times 10^4$ K leads to the abundance ratios $C/N \approx 0.1$ and $N/O \approx 0.9$.

The abundances of the CNO nuclei relative to He can also be derived from the emission-line strengths; however, the resulting values have a sensitive dependence upon the electron temperature. The expressions used previously for the emission coefficients of recombination and collisionally excited lines can be shown to lead to the condition that

$$\frac{N(\mathrm{N}^{+4})}{N(\mathrm{He}^{+2})} = 1.65 \times 10^{-4} T_e^{-0.5} \exp\left(\frac{116100}{T_e}\right) \frac{F(\lambda 1240)}{F(\lambda 1640)}, \tag{4}$$

where we have assumed that case A conditions prevail because of the generally small masses and high expansion velocities of nova shells. The average of the ratio of N v to He II lines on July 4 and 11 is $F(\lambda 1240)/F(\lambda 1640) = 7.6$. If it is assumed that most, say 50%, of the N is $\mathrm{N}^{+4}$ because of the greater strength of N v λ1240 compared to that of the N III] and N IV] lines, and that all of the He is $\mathrm{He}^{+2}$ on these days, the N/He abundance follows for assumed values of the temperature. Using the C/N and N/O ratios previously derived, we have computed element abundances in the U Sco envelope relative to He for different temperatures, and these are given in Table 1. Independent of temperature, the He/H and N/CNO abundance ratios are higher than solar values, which is indicative of material that has experienced substantial CNO burning. For comparison we have also computed the relative abundances, by number, of nuclei in a solar mixture in which H has been largely converted into He, but the CNO have not been modified among themselves. It should be noted that the CNO/(H + He) ratio in the U Sco ejecta, if at $T_e \gtrsim 2 \times 10^4$ K, is not significantly different from the solar heavy element abundance, whether evolved or not.

### III. STRUCTURE AND MASS OF THE EJECTA

In classical novae, the mass ejection process usually occurs in two sequential phases, dynamic and continuous, which are driven by different mechanisms. Dynamic mass loss is an episodic event associated with the onset of the outburst. It is believed to be energized mechanically, and it generally produces a relatively distinct shell with its characteristic diffusion light-curve, e.g., V1500 Cyg (Sparks 1969; Gallagher and Starrfield 1978). Episodic ejection is usually followed by continuous mass loss in the form of an optically thick wind, which is presumably driven by radiation pressure (Bath and Shaviv 1978; Bath 1978) and is most important in slow novae such as DQ Her and HR Del. Winds can be more efficient than an ejected shell in interacting with the radiation from the underlying nova, and this can produce a slower spectroscopic evolution with less total ejected mass. Consequently, it is necessary to determine the dominant ejection process in U Sco if a reliable estimate of the ejected mass is to be made.

By analogy with classical novae, the very rapid optical decline of U Sco suggests that the primary form of mass loss was the ejection of a shell at the time of outburst. However, U Sco was not a classical nova, and there were several important differences between it and other novae regarding the time dependence of the UV spectrum, as illustrated in Figure 3. First, in U Sco, emission lines covering a range of ionization potential from 7.6 eV (Mg II) to 77 eV (N v) experienced similar declines in flux, while, in classical novae, the time variation of lines with differing ionization potentials is not similar (e.g., Meinel 1963; Ferland and Shields 1978). Second, there was no change in color temperature over the period covered by our observations. This is in distinct contrast to classical novae, which show a steady shift in energy toward the UV during the early postmaximum period as the underlying white dwarf radiation source is slowly unveiled. The observed U Sco continuum was relatively flat, with $F_{\lambda 1300}/F_V \approx 0.3$ when corrected for an extinction of $A_V = 0.6$ mag (Barlow *et al.* 1981). Therefore, although the evidence points to the discrete ejection of a shell of material in U Sco, there is some uncertainty which leads us to consider also the possibility that the UV resonance absorption was caused by a wind.

#### *a*) *Shell Model*

The mass of the ejected shell is an important parameter of the nova outburst; yet shell masses are not well determined. Optical observations of Balmer emission

TABLE 1

ABUNDANCES AND MASS OF U SCORPII SHELL

| ELEMENTS | $T_e$ (K) | | | | HYDROGEN-DEPLETED SOLAR MIXTURE (He/H = 2) |
|---|---|---|---|---|---|
| | 10,000 | 15,000 | 20,000 | 25,000 | |
| H | 0.5[a] | | | | 0.5 |
| He | 1.0 | | | | 1.0 |
| C | 0.3 | $5 \times 10^{-3}$ | $6 \times 10^{-4}$ | $2 \times 10^{-4}$ | $9 \times 10^{-4}$ |
| N | 3 | $5 \times 10^{-2}$ | $6 \times 10^{-3}$ | $2 \times 10^{-3}$ | $4 \times 10^{-4}$ |
| O | 3 | $5 \times 10^{-2}$ | $7 \times 10^{-3}$ | $2 \times 10^{-3}$ | $3 \times 10^{-3}$ |
| $\frac{\Sigma\mathrm{CNO}}{(\mathrm{H + He})}$ | 4 | $7 \times 10^{-2}$ | $9 \times 10^{-3}$ | $2 \times 10^{-3}$ | $3 \times 10^{-3}$ |
| $M_{\mathrm{shell}}(M_\odot)$ | $2 \times 10^{-10}$ | $1 \times 10^{-8}$ | $8 \times 10^{-8}$ | $3 \times 10^{-7}$ | |

[a] From Barlow *et al.* 1981.

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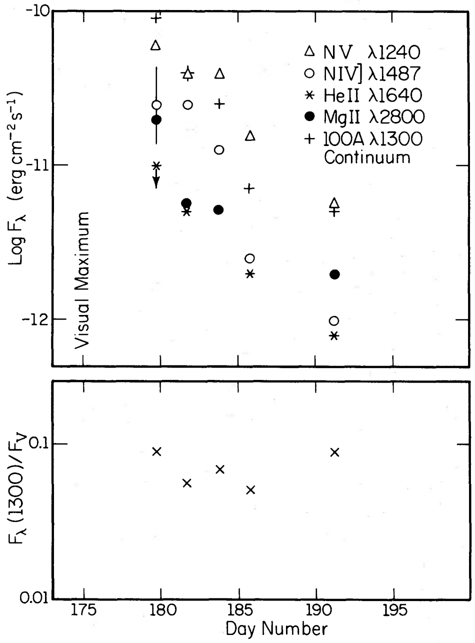

FIG. 3.—Integrated fluxes for the UV emission lines are plotted as a function of time in the upper panel, together with a 100 Å wide band of continuum. The early N v flux is uncertain because of strong P Cygni absorption, and He II could not be distinguished from O III] λ1663 in our first spectra. The bottom panel shows the UV to visual flux ratio with time, indicating that the observed $F_{\lambda 1300}$ is $\sim 0.1 F_v$. The abscissa is the number of the day in the year, e.g., day number 175 = 23 June.

lines have provided approximate masses if the gas density, distance, and filling factor $\epsilon$ can be estimated because the H$\beta$ flux of the shell varies as $F(\mathrm{H}\beta) \propto \epsilon N_e^2 R_s^3$. However, large uncertainties in these quantities have caused the derived masses to be unreliable by perhaps as much as a factor of 10 (see discussion in Gallagher and Starrfield 1978). The current capability of observing UV resonance absorption from novae after outbursts now enables a new method to be used to determine shell masses, since the mass can be shown to be directly related to the optical thickness of the shell along the line of sight, independent of the distance, density, or filling factor of the shell.

Consider a spherical shell of radius $R_s$ which consists of $n$ total clouds or filaments which are uniformly distributed throughout the volume, each having a representative size of radius $r$ and a number density of an absorbing ion $N_i$. If $a_0$ is the absorption cross section at line center per ion, then

$$a_0 = \frac{(\pi)^{1/2} e^2}{m_e c^2} \frac{f_i \lambda_i^2}{\Delta\lambda_\mathrm{D}} , \tag{5}$$

where $f_i$ and $\lambda_i$ are the oscillator strength and wavelength of the transition, and $\Delta\lambda_\mathrm{D}$ is the Doppler width of the line, including any mass motion, e.g., turbulence or differential expansion. Let $t_i$ and $\tau_i$ represent the optical depth in the center of a resonance line for an individual cloud and the entire shell respectively, where $t_i \approx N_i a_0 r$. If the fraction of the volume of the shell occupied by the clouds is given by the filling factor $\epsilon = nr^3/R_s^3$, then the mean free path between clouds is $l \approx r/\epsilon$, and the optical depth of the shell is given by

$$\tau_i = t_i(R_s/l) = N_i a_0 R_s \epsilon . \tag{6}$$

The mass of the ejected shell $M_s = \rho(\frac{4}{3})\pi R_s^3 \epsilon$, where the mass density

$$\rho = N(\mathrm{He}) m_\mathrm{H}(4 + 1/Y) , \tag{7}$$

and $Y \equiv N(\mathrm{He})/N(\mathrm{H}) \approx 2$ is the helium-to-hydrogen abundance, by number. Substituting for the filling factor $\epsilon$ from equation (6) yields an expression for the shell mass involving the optical thickness of the shell in a resonance line,

$$M_s = 6\pi m_\mathrm{H} \frac{N(\mathrm{He})}{N_i} \frac{\tau_i}{a_0} R_s^2 . \tag{8}$$

The most prominent resonance line appearing in the *IUE* spectra is C IV λ1549, which shows strong, deep absorption on June 28, but which is absent on the July 2 spectrum. On June 30, the broad C IV trough is present but at reduced strength. There is residual radiation even in the center of the line, indicating that $\tau(\lambda 1549) \approx 1$ on this date, 7 days after the outburst. From both the widths of semiforbidden lines such as N III] λ1750 and the blue wavelength limits on the resonance absorption features, the expansion velocity of the shell is deduced to be $V_s \approx 7{,}500$ km s$^{-1}$, leading to an outer shell radius of $R_s \approx 4.5 \times 10^{14}$ cm on June 30. On this date, the width of the C IV absorption is 40 Å, corresponding to an effective Doppler width of $\Delta\lambda_\mathrm{D} \approx 13$ Å. Adopting the C/He ratios presented in Table 1, and arbitrarily assuming that $\mathrm{C}^{+3}/\mathrm{C} \approx \frac{1}{4}$ because emission from a range of ionization states is observed on June 30 (C II through N V), leads to a shell mass of the order of $\sim 10^{-7} M_\odot$, as given at the bottom of Table 1. This value is much smaller than the typical mass of $\sim 10^{-4} M_\odot$ found for classical nova shells (Gallagher and Starrfield 1978). The corresponding value for the shell filling factor, assuming $N_e \gtrsim 10^8$ cm$^{-3}$ because of the absence of forbidden lines, is $\epsilon < 10^{-3}$, while the requirement for a covering factor over the shell of the order of $\sim 1$ most likely implies that the gas is in a large number ($\sim 10^6$) of condensations. We further note that any introduction of an inward radial increase in density, as might be expected in either Hubble-type flows or wind ejection (Starrfield, Truran, and Sparks 1978), will decrease the amount of ejected mass required (see below).

Of the various temperatures possible for the U Sco shell, we believe the higher values are more likely to pertain. The temperatures associated with highly ionized regions emitting C IV and N V in nebulae are usually of the order of $2 \times 10^4$ K. In the case of U Sco, which did not show forbidden lines, the gas has been deprived of the normal lower temperature ($T_e \approx 10^4$ K) cooling processes, so there is a particularly strong likelihood that the temperature is in the range of $T_e \approx 2\text{–}2.5 \times 10^4$ K. Consequently, the most likely composition of the shell is that for which the total CNO abundance does not differ significantly from a hydrogen-depleted solar mixture, and the mass of the ejected envelope is $\sim 1.5 \times 10^{-7}\ M_\odot$.

### *b) Wind Model*

If the mass loss from U Sco is in the form of a wind, an estimate of the total mass contained in the flow can be obtained from $\dot{M}(t)$. We assume that the flow accelerates from the scattering of resonance-line radiation (Cassinelli 1979), and that the wind velocity achieves its terminal value at the point where the lines become optically thin. It is straightforward to show from the equation of mass continuity that the radius where the optical depth in the center of a resonance line becomes unity into the flow is

$$R(\tau_i = 1) \approx \frac{N_i a_0 \dot{M}}{18\pi m_{\rm H} V N_{\rm He}}\,, \tag{9}$$

where $N_i$ is the absorbing ion number density and $V$ is the flow velocity, assumed to be constant outward. An observational limit on the value of $R(\tau_i = 1)$ can be set by the requirement that the maximum flux emitted by a collisionally excited line, such as C IV $\lambda$1549, cannot exceed the Planck function at the kinetic temperature of line formation, considered here to be $T \lesssim 25{,}000$ K. Then,

$$R(\tau_{\lambda 1549} = 1) \gtrsim D[F_{\lambda_0}/\pi B_{\lambda_0}(T)]^{1/2}\,, \tag{10}$$

where $F_{\lambda_0}$ is the observed flux in the center of the C IV $\lambda$1549 emission line and $D$ is the distance to U Sco. The distance is very uncertain (see Barlow *et al.* 1981 for a discussion), but if the luminosity at maximum light is assumed to exceed the Eddington limit for a 1 $M_\odot$ star, then $D \gtrsim 6$ kpc when a bolometric correction of 1 mag is assumed at visual maximum. Using the C IV flux observed on June 28, $F_{\lambda_0} = 2.4 \times 10^{-12}$ ergs cm$^{-2}$ s$^{-1}$ Å$^{-1}$ in the line center, the maximum radius for the C IV emission from the wind is then $R \gtrsim 2.8 \times 10^{11}$ cm. The corresponding mass loss rate for the wind on that date is $\dot{M} \gtrsim 7 \times 10^{17}$ g s$^{-1}$, for the C$^{+4}$/He ratio and wind velocity derived in § III*a*. The rapidly decreasing line fluxes lead to a diminished mass loss rate of the order of $\dot{M} \gtrsim 1 \times 10^{17}$ g s$^{-1}$ on July 11, when we last detected U Sco in the UV. These calculations suggest that the mass ejected from U Sco could have been as small as $\sim 10^{-9}\ M_\odot$ if it were lost in the form of a wind.

There are several features of the wind model for mass loss which cause us to question its importance in U Sco. First, the density of the wind at $\tau = 1$ during the first 2 weeks following outburst should have been $N_e \approx 10^7$–$10^8$ cm$^{-3}$, and, thus, forbidden lines should have been produced. Second, during the wind phase of classical novae, the lines with greatest width are formed deepest in the potential well, i.e., at the highest densities (Bath and Shaviv 1978). However, in U Sco, it is the intercombination lines which preferentially form in lower density regions, that have the largest velocity widths throughout our observations. For these reasons, we believe any continuous mass loss from a wind was a minor part of the mass ejection process. Given the observed characteristics of the outburst and the time dependence of the spectrum, the evidence favors the ejection near the time of maximum light of a discrete shell having a mass of $\sim 10^{-7}\ M_\odot$.

### *c) Comparison with Other Novae*

Both the ejected mass and the energy production of U Sco were $\lesssim 10^{-2}$ that of a typical classical nova, especially when the rapid shut-off is taken into account. A more specific comparison between the characteristics of U Sco and classical novae is given in Table 2. The mass ejection energy budgets are, in both cases, dominated by the binding energy to the white dwarf and thus are relatively unaffected by the final expansion velocities. In every respect, U Sco appears to be a more rapid type of event than a classical nova, particularly insofar as the constant luminosity phase is concerned, which seemed to be completely absent in U Sco (see Gallagher and Starrfield 1978). This burstlike characteristic may also account for the homologous development of virtually all parts of the spectrum during the mid-decline phase covered by our *IUE* observations.

The U Sco outburst not only differs from that of classical novae but also is apparently different in a number of ways from the T CrB and RS Oph type of recurrent novae. These latter two recurrents share the rapid optical decline and high ejection velocity characteristics of U Sco, but they produced different optical spectra having strong forbidden coronal emission lines. Whether or not this represents a fundamental distinction between two classes of recurrent novae is uncertain. The novae T CrB and RS Oph both have giant companions, while U Sco is probably a short-period binary containing a compact secondary (Webbink 1978). Giant stars are more likely to produce stellar winds of their own which could modify the development of the ejecta, and might provide an ideal medium for the propagation of a shock. Consequently, the lack of similarity between U Sco and T CrB or RS Oph may be more a reflection of different white dwarf circumstellar environments than an indication of two types of outburst mechanism.

## IV. OPTICAL SPECTRUM AT QUIESCENCE

Our UV observations and the optical study of Barlow *et al.* (1981) indicate that the recent U Sco outburst resulted in the ejection at very high velocities of a helium-rich shell of very small mass. The chemical composition of the shell

TABLE 2

COMPARISON BETWEEN PROPERTIES OF U SCORPII AND TYPICAL CLASSICAL NOVAE

| Properties | Classical Novae | U Scorpii |
|---|---|---|
| Ejected Mass ................ | $10^{-4}$–$10^{-5}\ M_\odot$ | $10^{-7}$–$10^{-8}\ M_\odot$ |
| Active Phase Duration....... | $\gtrsim 1$ year | $\lesssim 1$ month |
| Maximum Ejection Velocity | 1500 km s$^{-1}$ | $\gtrsim 5000$ km s$^{-1}$ |
| Energy Budget: | | |
| Mass Motions ............ | $10^{46}$ ergs | $10^{43}$–$10^{44}$ ergs |
| Radiative.................. | $\sim 10^{45}$ ergs | $\gtrsim 10^{43}$ ergs |
| Total ...................... | $\gtrsim 10^{46}$ ergs | $\gtrsim 10^{44}$ ergs |
| He/H Ratio (by number) .... | 0.1–0.3 | 2: |

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can provide important clues to the source of energy for the outburst. The processes most likely to provide the necessary energy are either a thermonuclear runaway on the surface of a degenerate dwarf, as has been suggested for classical nova eruptions (see Starrfield, Truran, and Sparks 1978), or a rapid mass accretion event as has been suggested to explain outbursts in the recurrent nova T CrB (Webbink 1976) and dwarf novae (Bath *et al.* 1974). Existing theoretical calculations suggest that there may be difficulty in accounting for a thermonuclear runaway on the surface of a white dwarf in a time scale of roughly 40 years with an envelope mass of only $\sim 10^{-7}\ M_\odot$ unless special conditions prevail. One of the possible ways of discriminating between the thermonuclear runaway and mass accretion processes would be to determine the differences in composition of the preoutburst and postoutburst material, since a thermonuclear runaway would be expected to produce a substantial modification of abundances. It is generally believed that the gas ejected in nova outbursts originates from mass loss from a nondegenerate star in a close binary system, which is accreted onto the surface of a degenerate companion star. The dominant source of the visible light in quiescent nova systems is the accretion disk, and therefore the spectra of novae not in outburst should reveal something of the nature and preoutburst composition of the gas.

From the rate of its decline after outburst, U Sco should have returned to its preoutburst brightness within 4 months, and this is confirmed by the photometry of Barlow *et al.* (1981). Assuming that the shell continually expanded at constant velocity and mass, the emission lines should have continued to diminish in flux to the point where they would be substantially weaker than the quiescent continuum, at $m_v \approx 18$, after 1979 December. On 1980 March 12 and 13, spectrophotometry of U Sco was obtained by one of us (R. E. W.) with the Cerro Tololo Inter-American Observatory 4 m telescope in both the blue and red using the SIT Vidicon spectrometer, and these are shown in Figure 4. The continuum flux corresponds to a brightness of $m_v = 18.2$, indicating that the spectra are indeed representative of U Sco at its quiescent level.

The U Sco spectrum is very unusual for that of a cataclysmic variable in that the strength of the He II emission relative to the Balmer lines far exceeds that of any other known nova or novalike variable [although G61-29 is another example of a helium-rich cataclysmic variable, no He II is seen (Burbidge and Strittmatter 1971; Smak 1975)]. The blue scan shows only one definite strong line, at λ4684 and identified as He II λ4686, and two probable weaker lines at λλ3778 and 4200, which we identify as He II λ3781 and He II λ4200. The signal-to-noise ratio of the red scan is not very good, particularly in the Hα region, and the only obvious emission features are at λλ5410, 6250, and 6563. The proper identifications for two of these lines are undoubtedly He II λ5411 and Hα + He II λ6560; however, the λ6250 emission does not have a reasonable identification. The line has two peaks, but the longer wavelength emission component is too narrow to be attributed to U Sco. The profile and strength of the line may be complicated by poor sky subtraction of the [O I] λ6300 night-sky line. The apparent absorption at λ5577 is also due to faulty sky subtraction since the [O I] atmospheric emission was strongly saturated on all of our U Sco integrations.

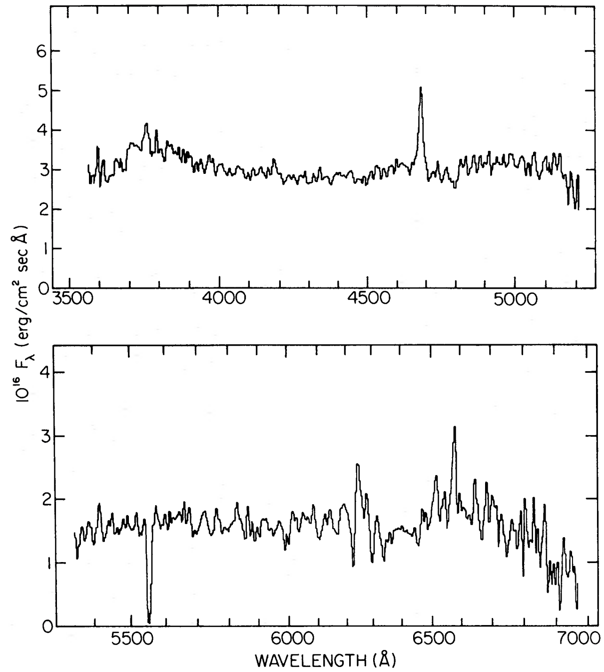

FIG. 4.—Optical spectra of U Sco obtained with the CTIO 4 m telescope using the SIT Vidicon system in 1980 March, after the nova had returned to quiescence.

The only certain line identifications in the optical spectrum of U Sco are due to He II since the λ6563 emission may have a substantial contribution from He II. There is no detectable H emission from Hβ or any of the other higher Balmer lines. The conditions under which the optical spectrum is formed are not known; however, it seems likely that the gas is very poor in H (or rich in He). If the emitting material is part of an accretion disk, the evidence then points to the existence of a highly evolved secondary companion, perhaps a He core. In this case, the high He abundance of the ejecta of U Sco may not be due to nuclear reactions occurring during the outburst, but rather it may simply be a relic of the large He/H ratio of the accreted gas from an evolved secondary star.

## V. DISCUSSION

The nature of the outburst mechanism(s) for members of the class of recurrent novae remains to be established. Guided by considerations of overall time scales and energetics, recurrent novae have been viewed historically as bridging the gap between dwarf novae and classical novae. We now strongly suspect that dwarf novae and common novae are, in fact, the result of different physical phenomena; dwarf nova outbursts are generally assumed to be powered by accretion, while numerical hydrodynamic studies have established that a thermonuclear runaway is the mechanism responsible for the outbursts of classical novae. Consequently, alternative models based upon either episodic accretion events or thermonuclear runaways have been proposed and examined and have had varying degrees of success in reproducing the observed features of the recurrent novae. It now appears likely that the recurrent novae constitute a "class" of cataclysmic variables of quite diverse physical characteristics.

Such observational studies of recurrent novae in outburst as we report in this paper serve to provide clues to and restrictions upon theoretical models. Unfortunately, the accumulated observations of U Sco do not yet allow a definitive statement to be made regarding the physical nature of the outburst. Some features are suggestive of a nuclear-powered event—a scaled version of a fast nova (see Table 2)—particularly the rapid development of the visual light curve, the high velocities, the ejection of a distinct "shell" of matter, and the enrichment of N relative to C and O in the ejecta. One feature of the thermonuclear runaway studies (see Sparks, Starrfield, and Truran 1978; Starrfield, Truran, and Sparks 1978) is the achievement of an essentially Eddington luminosity at maximum light. For U Sco, this requires that the distance be $\gtrsim 5$ kpc; a reliable distance estimate could therefore serve to provide a stringent test of this criterion.

While the N enrichment may be interpreted as evidence for a thermonuclear event, this finding itself is not free of ambiguity. We note, in particular, that the He/H ratio determined from our data and from Barlow *et al.* (1981) indicates a substantial He enrichment. An overabundance of He and N is to be expected from a thermonuclear runaway; however, the presence of strong He II emission features in the spectrum we have obtained at quiescence suggests that this enrichment may instead reflect the composition of the matter transferred from the companion. For such hydrogen-depleted material, one also expects to find a significant N anomaly; redistribution of the abundances as a direct consequence of CNO hydrogen burning in the companion could explain our observations. Thus, there exists no compelling evidence in support of a thermonuclear runaway interpretation.

The rapid development of the visual light-curve for U Sco is similar to the behavior observed for two other recurrent novae: T CrB and RS Oph. The spectral evolution of U Sco differed quite significantly from these objects, however, particularly in that it exhibited none of the intense forbidden-line emission so evident for both T CrB and RS Oph. This distinction may be related to the fact that both T CrB and RS Oph are systems with giant companions, while a late-type companion is more compatible with current observations of U Sco (Barlow *et al.* 1981). Thus, there are no obvious grounds on which an accretion event of the general type proposed by Webbink (1976) can be excluded. There seems to be no obvious preference for either an accretion event or a runaway event implied by these considerations.

## VI. CONCLUSIONS

Observations of the recurrent nova U Sco during the 1979 outburst have been obtained with the *IUE* satellite. The spectral evolution has been found to differ from that of other recurrent novae. The spectra are dominated by emission lines, though broad resonance absorption is present during the first week after outburst, and the strong forbidden-line emission characteristic of seemingly similar systems such as T CrB and RS Oph is conspicuously absent. A method for determining the masses of nova shells is outlined, and a mass $\sim 10^{-8}$–$10^{-7}$ $M_\odot$ is inferred for the ejecta. Analysis of the emission lines reveals the nova ejecta to be rich in He relative to H and shows an enrichment in N relative to C and O (although the total concentration of CNO nuclei appears to be essentially solar). Optical spectra of U Sco obtained following its return to quiescence show predominantly He II emission lines, suggesting an enrichment of the preoutburst gas in He and thus the presence of a highly evolved companion. The available data are insufficient to allow conclusions to be drawn concerning the nature of the outburst mechanism—accretion powered or nuclear powered. Observations capable of providing a realistic distance estimate remain critical.

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