The Astronomical Journal, 119:1359–1364, 2000 March

THE 1999 OUTBURST OF THE RECURRENT NOVA U SCORPII

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Received 1999 July 16; accepted 1999 November 29

ABSTRACT

The optical spectra of the recurrent nova U Sco obtained in five epochs 0.45–42.35 days after the 1999 outburst maximum are presented here. For the first time, an outburst spectrum of U Sco has been obtained as early as 0.45 days after maximum. The spectral evolution is broadly similar to the 1979 and 1987 outbursts. The mass of the ejected shell is estimated to be $\sim 10^{-7}\ M_{\odot}$. Based on the Mg I *b* 5174 Å and the Fe I + Ca I 5270 Å absorption indices in the late-decline phase spectrum of day 42.35, we estimate the secondary to be a K2 subgiant star.

Key words: novae, cataclysmic variables — stars: individual (U Scorpii) — techniques: spectroscopic

1. INTRODUCTION

Recurrent novae form a small, heterogeneous group of cataclysmic variables that undergo classical nova-like outbursts at intervals of the order of decades. The outbursts are explained by the thermonuclear-runaway theory, assuming a white dwarf at or near the Chandrasekhar limit (e.g., Starrfield, Sparks, & Shaviv 1988). Mass accretion rates of $\sim 10^{-6}\ M_{\odot}\ \mathrm{yr}^{-1}$ are required to explain the short recurrence intervals in U Sco. These objects are of particular interest, since they could be evolving into supernovae of Type Ia (see, e.g., Starrfield et al. 1988; Hachisu et al. 1999).

The recurrent nova U Sco underwent its sixth recorded outburst on 1999 February 25.2 (Schmeer 1999). The previous outbursts were recorded in 1863, 1906, 1936, 1979, and 1987, although only the 1979 and the 1987 outbursts were well studied (Barlow et al. 1981, hereafter B81; Williams et al. 1981, hereafter W81; Sekiguchi et al. 1988; Rosino & Iijima 1988). With an outburst separation of 8 and 12 yr between the previous two outbursts, this recurrent nova has the shortest recurrence period among the known recurrent novae.

The outbursts are characterized by a rise of $\gtrsim 10$ mag, with an extremely fast initial decline, at the rate of 0.67 mag per day (Payne-Gaposchkin 1957; Sekiguchi et al. 1988; Munari et al. 1999, hereafter M99). Outburst spectra indicate that matter is ejected in the form of a discrete shell at extremely high ejection velocities of $\sim 10{,}000\ \mathrm{km\ s^{-1}}$ (W81; B81; Sekiguchi et al. 1988; M99).

The 1999 outburst of U Sco was discovered by P. Schmeer when the nova was at a visual magnitude of 9.5 on February 25.154. The nova reached a peak of 7.6 mag on February 25.562 (Schmeer 1999) and steadily declined thereafter. M99 describe the photometric and spectroscopic development of U Sco during 0.64–22.55 days after the 1999 outburst maximum. U Sco has also been detected as a supersoft X-ray source about 19–20 days after the outburst maximum (Kahabka et al. 1999, hereafter K99).

At quiescence, U Sco has been detected to be an eclipsing as well as a double-lined spectroscopic binary (Schaefer & Ringwald 1995; Hanes 1985). The photometric orbital period is 1.230561 days, with m_V varying from 18.5 to 20 mag (Schaefer & Ringwald 1995). Attempts to estimate the component masses, in particular that of the white dwarf, have so far been unsuccessful. Johnston & Kulkarni (1992) derived a white dwarf mass well below the Chandrasekhar limit, while Duerbeck et al. (1993) do not rule out the possibility of a massive white dwarf. Phasing the available radial velocity data with the eclipse period, Schaefer & Ringwald (1995) find that the data show a large scatter in the emission- and absorption-line velocities, which have significantly different averages. They conclude that a reliable estimate of the masses is not possible with the radial velocity curves. The detection of U Sco as a supersoft X-ray source constrains the white dwarf to be very massive ($>1.2\ M_{\odot}$; K99).

The quiescence spectrum is dominated by He II lines (Hanes 1985; Johnston & Kulkarni 1992; Duerbeck et al. 1993). The hydrogen lines are either absent or very weak and blended with the rather strong He II Pickering lines. Helium enrichment has also been estimated from outburst spectra. This is attributed to the accretion of helium-enriched material from an evolved secondary. An evolutionary scenario for this system assuming a secondary that experienced a helium accretion phase has been proposed by Hachisu et al. (1999). In their scenario, for such a system with mass transfer rates $\sim 10^{-6}\ M_{\odot}\ \mathrm{yr}^{-1}$, such as required for U Sco, the white dwarf burns hydrogen to form a helium layer and also experiences mass loss due to the white dwarf wind.

The earliest spectrum of the previous outbursts was taken ~ 4 days after the 1987 outburst maximum (Sekiguchi et al. 1988). The rapid notification of the discovery of the present outburst over the Variable Star Network (VSNET) has made it possible to study the spectral evolution during the immediate post-maximum phase of the present outburst (Niedzielski, Tomov, & Munari 1999; Zwitter & Munari 1999; Bonifacio, Molaro, & Selvelli 1999; M99). In this paper we present the spectroscopic data of U Sco obtained during the period 0.45–42.35 days after the outburst maximum. We also estimate the mass of the ejected shell and the helium abundance in the shell. The late-decline spectrum is used to estimate the secondary spectral type.

2. SPECTROSCOPY

2.1. *Observations*

CCD spectra of the nova were obtained from the Vainu Bappu Observatory, using the Cassegrain spectrograph at the 2.3 m Vainu Bappu Telescope (VBT; Prabhu, Anupama, & Surendiranath 1998), during the maximum and early and late decline phases on February 26.011 and 27.015, March 8.989 and 9.953, and April 8.925. The spectra were obtained in the wavelength range of ~4000–9000 Å. Table 1 gives the journal of observations. Also listed in the table are the corresponding days since outburst maximum, the visual magnitude, and the orbital phase from Schaefer & Ringwald (1995).

All spectra were reduced in the standard fashion. The data were bias-subtracted using a mean bias value and flat-field corrected. The one-dimensional spectra were then extracted using the optimal extraction option method, wavelength calibrated, and corrected for the instrumental response using spectrophotometric standards observed on the same night. The skies were nonphotometric during all our observations. Furthermore, the March and April data were obtained during bright moon phases and the spectra were contaminated by strong moonlight, which has been corrected for during sky subtraction. However, the higher sky background during these phases reduces the signal-to-noise ratio in the star spectrum. The average signal-to-noise ratio of the spectra, at continuum, are also listed in Table 1. A zero-point correction has been applied to the flux levels based on the *V* visual magnitude estimates reported in the IAU and VSNET Circulars and also in M99. Various tasks for spectroscopic data reduction under the IRAF package were used for the reduction of the data presented here.

2.2. *Description of the Spectra*

2.2.1. *1999 February 26–27*

The first spectrum on February 26.011 was obtained 0.45 days after the discovery. By this time, the nova had already declined to a visual magnitude of 8.5 mag from the maximum of 7.6 mag. Figure 1 shows the spectra obtained on February 26.011 and 27.015, 0.45 and 1.45 days after maximum, respectively. The spectrum is characterized by strong, extremely broad emission lines, which are blended. The lines, identified following B81 and Rosino & Iijima (1988), are predominantly due to N III, C III, the hydrogen Balmer series, and He I. Also present are lines of N II at 5700 Å, Mg II 7880 Å blended with O I 7774 Å, and N I 8200 Å, possibly blended with 8446 Å. The identification of the 8446 Å line is difficult, since it is at the edge of the spectrum. However, this line is clearly present in the spectra presented by M99. The line identifications are marked in Figure 1.

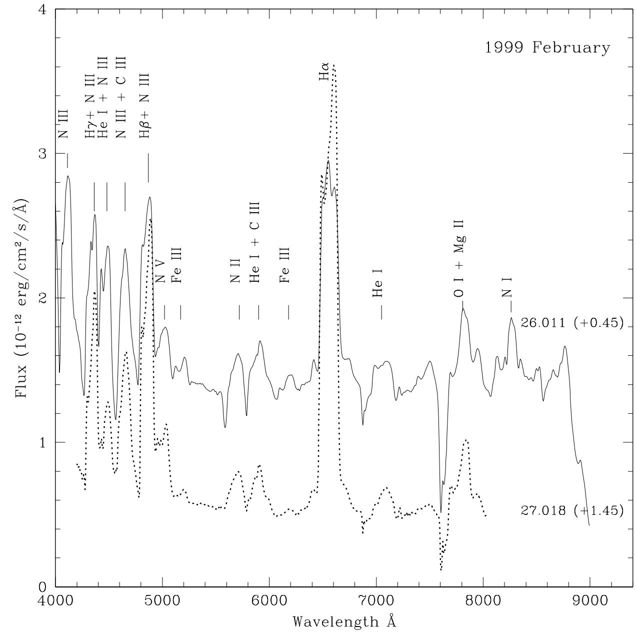

FIG. 1.—Optical spectra of U Sco during the immediate postmaximum phase in 1999 February. The dates of observations and time since maximum are marked. Also marked are the emission line identifications.

The FWZI velocities of the Hα line, corrected for instrumental profile, are 10,170 and 9530 km s^{-1}, respectively, on days 0.45 and 1.45. The Hα line shows a structured profile (see also Fig. 3 of M99).

2.2.2. *1999 March 8–9*

The spectra obtained during this period, corresponding to 11.41 and 12.35 days past maximum, are plotted in Figure 2. The ionization level has increased by this time, as indicated by the presence of strong 4686 Å and other He II lines. The strengths of the other emission lines have decreased, as have their widths. The Hα line has a FWZI velocity of 6875 km s^{-1} on day 11.41 and 6524 km s^{-1} on day 12.35. The FWHM velocity is ~1600 km s^{-1}. The width of He II lines are narrower, with a FWHM of 1100 km s^{-1}. The He I and other non-Balmer lines appear to have developed a triple-peaked profile similar to the Hα profiles beyond day 19 (see Fig. 3 of M99).

2.2.3. *1999 April 8*

U Sco had declined to below 17 mag on April 8.90, 42.35 days after the outburst maximum. The spectrum obtained on this day is shown in Figure 3. The spectrum is noisy, and the only emission lines clearly detected are Hα and He II 4686 Å. He II 5411 Å is weakly present. In addition, an

TABLE 1

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Date (1999)	Δ*t* (days)	Dispersion (Å pixel^{-1})	Resolution (Å)	Range (Å)	S/N[a]	m_{vis}	Φ[b]
Feb 26.011......	0.447	5.0	15.0	3800–9000	350	8.5	0.775
Feb 27.018......	1.454	2.5	7.5	4000–8000	120	9.5	0.593
Mar 8.978	11.408	5.0	15.0	3800–9000	75	13.1	0.682
Mar 9.953	12.348	5.0	15.0	3800–9000	40	13.3	0.446
Apr 8.897	42.353	5.0	15.0	4000–8000	25	17.1	0.829

[a] Average value.
[b] Orbital phase from Schaefer & Ringwald 1995.

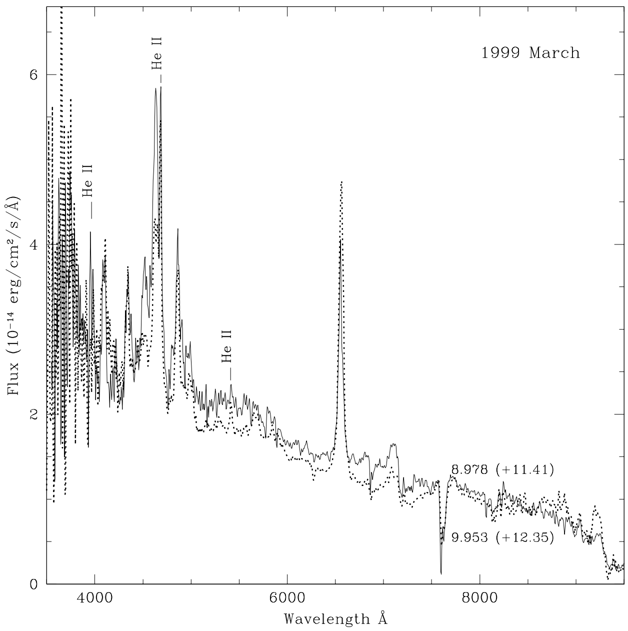

FIG. 2.—Optical spectra of U Sco during the early decline phase in 1999 March. The dates of observations and time since maximum are marked. The He II emission lines that have appeared by now are marked. All other identifications are the same as in Fig. 1.

absorption feature is clearly present at 5180 Å, which is identified with the Mg I *b* 5174 Å band seen strongly in stars of spectral type later than G0. This suggests that the secondary spectrum is also now contributing to the continuum. Na I D absorption could also be present. The apparent absorption feature at 5580 Å is due to a faulty subtraction of the night-sky [O I] emission. The spectrum appears quite similar to the late 1979 outburst spectra presented by B81.

3. SECONDARY SPECTRAL TYPE AND DISTANCE ESTIMATES

Previous estimates of the secondary spectral type have ranged from F5–G0 V to G6–8 III (Duerbeck et al. 1993; Hanes 1985; Webbink et al. 1987; Warner 1995). Based on the detection of the Mg I *b* absorption in the late 1979 outburst spectrum, K99 find the secondary to be consistent with a low-mass subgiant secondary of spectral type K2. The distance estimates vary from ≥ 3 to ≤ 18 kpc.

Although the spectrum of April 8.9 is noisy, the Mg I *b* 5174 Å blend can be easily identified. A comparison with standard spectra for K-type stars (Pickles 1998) indicates the presence of the Fe I + Ca I absorption feature at 5270 Å also (Fig. 4). Pritchet & van den Bergh (1977) have shown that the indices of these features can be used to estimate the stellar spectral and luminosity type. Following Pritchet & van den Bergh, we obtain the Mg I *b* index as 0.34 ± 0.07 and the Fe I + Ca I index as 0.09 ± 0.03. Comparing the absorption indices with those plotted in Figures 13 and 14 of Pritchet & van den Bergh (1977), we find that the Mg I index is consistent with that of a K2 III star, while the Fe I + Ca I index indicates a K2 V/K2 III star.

The apparent magnitude of $V = 20.0$ during eclipse minimum, together with the visual extinction $A_V = 0.6$ (B81), implies a distance of 60 kpc for a K2 III star and 3.6 kpc for a K2 V star. The former distance estimate is unlikely, and hence we rule out the possibility of a giant secondary. The 1.230561 day orbital period of U Sco is longer than the typical values for the nova systems with a main-sequence secondary. This period is, however, similar to that of GK Per (1.997 days), which has a K2 subgiant (Warner 1995; Anupama & Prabhu 1993). Thus, the Mg I *b* and Fe I + Ca I absorption indices together with the orbital period imply a spectral type K2 IV for the secondary in U Sco. This estimate is in agreement with the estimate of K99, based on the late 1979 outburst spectrum.

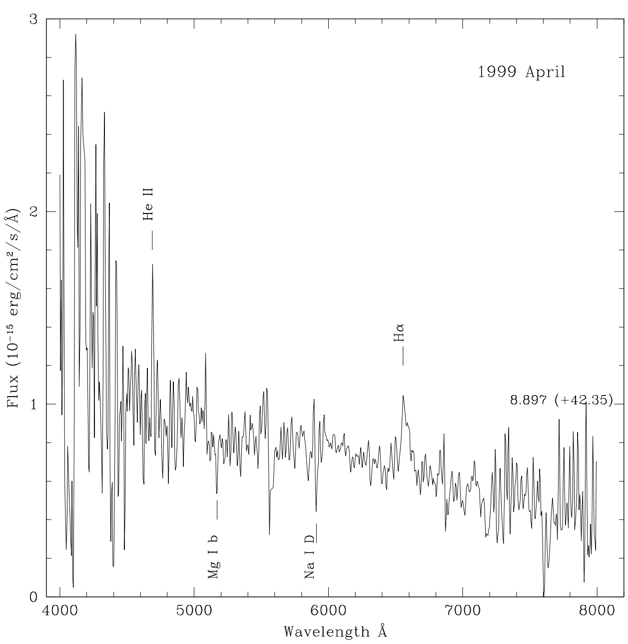

FIG. 3.—Optical spectrum of U Sco in the late decline phase in 1999 April. The date of observations and the time since maximum, in days, are marked. Note the absence of emission lines except those of He II 4686 Å and Hα, which are marked. Also marked are the Mg I *b* absorption blend and the Na I D absorption, both from the secondary.

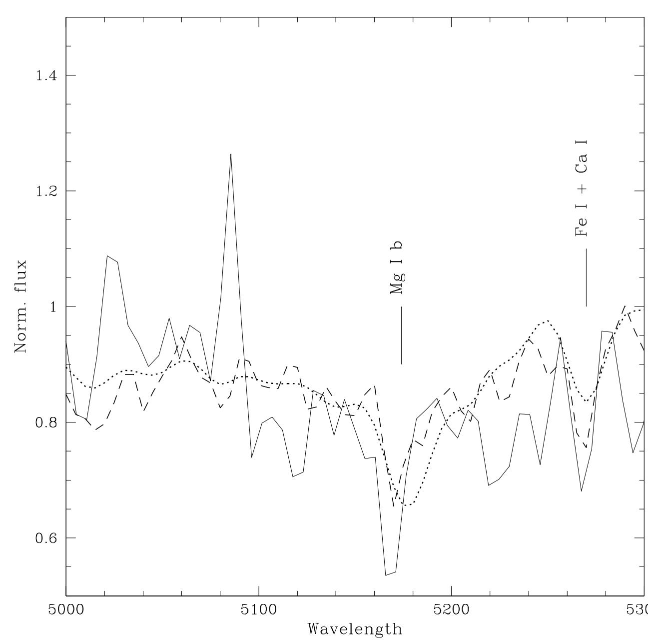

FIG. 4.—Late-decline (day 42.35) spectrum of U Sco (*solid line*) in the 5000–5300 Å region, showing the Mg I *b* and the Fe I + Ca I absorption features. Also plotted, for comparison, are the standard spectra for K2 V (*short-dashed line*) and K2 III (*long-dashed line*) stars from Pickles (1998).

Following K99, we assume the distance to U Sco to be 14.0 kpc.

4. THE EJECTED SHELL

4.1. *Mass*

The observed fluxes in the Balmer lines can be used to obtain a rough estimate of the mass of the ejected shell. The blending of lines on days 0.45 and 1.45 makes estimation of the fluxes of the Hα and Hβ lines quite difficult. The lines are narrower on days 11–12, and the He I 6678 Å line is separated from Hα. On day 42, the Hα line is available, but the spectrum is quite noisy and the fluxes are not very accurate. Furthermore, the He II Pickering line could be blended with Hα. We hence use only the data from days 11–12 to estimate the shell mass. The observed average fluxes of Hβ and Hα during this phase are 6.12×10^{-13} and 1.51×10^{-12} ergs cm^{-2} s^{-1}, respectively. Assuming case B recombination, uniform density, and a temperature for the emitting gas of 2×10^4 K (following W81) and using the recombination coefficients given by Hummer & Storey (1987), the mass for the ionized gas, M_s, can be estimated as

$$M_s = 8.943 \times 10^{10} \frac{f_{\mathrm{H}\beta}}{N_e} \left(\frac{d}{\mathrm{kpc}}\right)^2 M_\odot$$

and

$$M_s = 3.337 \times 10^{10} \frac{f_{\mathrm{H}\alpha}}{N_e} \left(\frac{d}{\mathrm{kpc}}\right)^2 M_\odot ,$$

where f is the observed flux in the Balmer line, N_e is the electron number density in units of cm^{-3}, and d is the distance to U Sco.

The electron density, N_e, can be estimated using the observed Balmer line fluxes by assuming that the ejected material is expanding uniformly and that the shell is radiation-bounded, using $f \propto \epsilon N_e^2 R_s^3/d^2$, where ϵ is the filling factor. Assuming the shell to be expanding with a uniform velocity of 5000 km s^{-1} and $\epsilon = 10^{-3}$ (W81), and using the observed Balmer line fluxes corrected for extinction using $A_V = 0.6$, we obtain a shell density of $N_e \sim 2 \times 10^8$ cm^{-3}. This estimate for N_e is consistent with the absence of forbidden lines in the spectrum and also with the estimates of N_e at similar phases during the 1979 outburst (B81; W81). With this estimate of the density, the mass of the ejected shell is $M_s \sim 10^{-7}\ M_\odot$, similar to the estimates during the 1979 and 1987 outbursts.

4.2. *Helium Abundance*

The helium abundance can be estimated using the plasma diagnostic method (Osterbrock 1989), assuming pure radiative recombination. In this approach, the electron temperature and density are assumed to be constant throughout the ejected material. Schwarz et al. (1997) have shown that such an assumption can underestimate the derived abundance by a factor of 10%. The total helium abundance,

$$\frac{\mathrm{He}}{\mathrm{H}} = \frac{\mathrm{He}^+}{\mathrm{H}} + \frac{\mathrm{He}^{++}}{\mathrm{H}} ,$$

is estimated using the observed ratios of the He I and He II lines to the Balmer lines.

Following the arguments mentioned in the previous section, we use the spectra obtained on March 8–9 for the estimation. The observed, dereddened flux ratios are $f_{4686}/f_{\mathrm{H}\beta} = 1.48$, $f_{5411}/f_{\mathrm{H}\beta} = 0.16$, $f_{6678}/f_{\mathrm{H}\beta} = 0.06$, $f_{4686}/f_{\mathrm{H}\alpha} = 0.73$, $f_{5411}/f_{\mathrm{H}\alpha} = 0.08$, and $f_{6678}/f_{\mathrm{H}\alpha} = 0.03$. The ratios of He I 5411 Å and 6678 Å lines to the Balmer lines give the He$^+$ abundance, and the ratio of the He II 4686 Å line to the Balmer line gives the He^{++} abundance. Using the above-mentioned flux ratios, the He I emissivities from Brocklehurst (1972) corrected for collisional effects following Clegg (1987), and the He II and hydrogen emissivities from Hummer & Storey (1987), we obtain an average helium abundance of He/H $\sim 0.4 \pm 0.06$. This estimate is lower than the estimate of He/H = 2 made during the 1979 outburst (B81; W81). Even the expected 10% underestimate due to the method employed here does not account for the large discrepancy with respect to previous estimates. We discuss the possible causes of the discrepancy in more detail in the next section.

5. DISCUSSION

The observations of U Sco presented in this paper begin much earlier than those presented during the previous outbursts, and a few hours earlier than those presented by M99.

The spectral evolution during the present outburst is quite similar to that in the 1979 and 1987 outbursts (B81; Sekiguchi et al. 1988). The spectrum is characterized by broad emission lines emitted by material moving at a very high initial velocity of $\sim$10,000 km s^{-1}. The width of the emission lines decreased with time. The decrease in the Hα velocity is almost linear with time (M99). Deceleration of the ejecta has also been observed in the recurrent nova RS Oph and other recurrent novae with giant secondaries, and has been attributed to a shock interaction of the ejecta with the circumstellar material (Bode & Kahn 1985; O'Brien, Bode, & Kahn 1992). We here discuss the possibility of a similar interaction in U Sco. Following the model of Bode & Kahn (1985), we find that there was very little deceleration in the velocity in the first few days, and the deceleration proceeded with a $t^{1/2}$ dependence later (Fig. 5). The deceleration beyond 4.4 days implies that the remnant was in phase II during the period of our observations and interacted with a preoutburst wind with a mass-loss rate of $\dot{M}/u = 4 \times 10^{10}$ g cm^{-1}, where u is the terminal velocity of the wind. The expected X-ray flux due to such an interaction is $L_{\mathrm{X}} \sim z 10^{30}$ ergs s^{-1}, where z is the factor by which the metal content of the gas exceeds the solar composition. The mass of the gas that gives rise to the X-ray flux would then be $\sim 10^{-8}\ M_\odot$. It is thus apparent that although the interaction causes a detectable deceleration of the ejecta, it does not produce strong X-ray emission or coronal lines. The preoutburst wind from the U Sco system was very tenuous and could produce significant deceleration only because of the low mass and high velocity of the nova ejecta.

The X-ray observations presented by K99 about 20 days after the optical maximum indicate the presence of a supersoft component as well as an additional hard component. The supersoft component is consistent with a thermonuclear-runaway outburst on a white dwarf close to the Chandrasekhar limit. The hard X-ray component is explained as due to emission from a postoutburst strong shocked wind from the white dwarf.

At a mass accretion rate of $\sim 10^{-6}\ M_\odot$ yr^{-1}, as required by the thermonuclear models to explain the outbursts of U Sco, $\sim 10^{-5}\ M_\odot$ of matter is accreted between the 1987 and

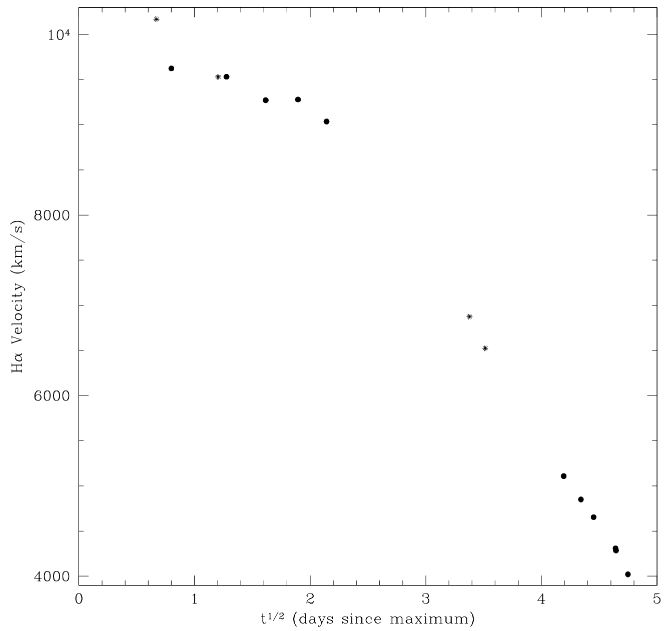

FIG. 5.—Hα FWZI velocity dependence on $t^{1/2}$. The values from M99 (*filled circles*) are plotted along with those presented in this work (*stars*).

1999 outbursts. Part of the accreted material is lost due to the white dwarf wind at a rate of $\sim 6 \times 10^{-7}\ M_{\odot}\ \mathrm{yr}^{-1}$ (K99). The amount of matter ejected during the recent outburst is $10^{-7}\ M_{\odot}$. This, together with the mass loss due to wind, implies that about 70% of the total matter accreted during the outbursts remains behind on the white dwarf, allowing it to increase in mass and evolve into a supernova of type Ia.

The helium abundance estimated here, He/H = 0.4, is much lower than the value of 2 estimated previously (B81). The width of the He II lines are narrower than the Balmer lines. It is hence quite likely that they arise from different regions, with the He II lines arising predominantly from the shocked wind. On the other hand, both the Balmer and the helium lines could have a broad as well as a narrow component, with the latter being stronger in the He II lines. The resolution of our data is insufficient to distinguish the components. Assuming such a two-component profile and deblending, we estimate the flux in the narrow component in Hα to be 6.6×10^{-13} ergs $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$. Using this flux estimate, the helium abundance increases by nearly a factor of 2. The helium abundance estimate of 0.4 is thus a lower limit.

As mentioned earlier, the only prominent emission lines in the quiescence spectrum are the He II lines. The hydrogen lines are either absent or very weak and blended with the rather strong He II Pickering lines. This is attributed to the accretion of a helium-enriched material from an evolved secondary. Alternatively, the helium lines seen at quiescence could arise mainly from the optically thick white dwarf wind, which could also be responsible for the suppression of hydrogen lines arising from the accretion disc around the white dwarf. Prialnik & Livio (1995) have shown that the erosion of the helium layer on the white dwarf does produce helium-enriched wind. The helium enrichment observed in U Sco may also be due to this wind, without requiring the secondary to be helium enriched.

The origin of the helium emission lines in the white dwarf wind could possibly explain the large scatter observed in the emission-line radial velocity curve. It could also explain the observation made by Schaefer & Ringwald (1995), which showed the emission lines not reliably tracing the white dwarf's orbital velocity.

The secondary spectral type K2 estimated here based on the Mg I *b* and Fe I + Ca I absorption indices and the orbital period is later than the previous estimates, which range from F5 to G6. The late-outburst spectrum following the 1979 outburst also implies a K2 subgiant (K99). Similar discrepancies in the secondary spectral type estimates also exist for the recurrent novae with giant secondaries. The estimate for the secondary spectral type based on a spectrum obtained during the late-outburst phase following the 1985 outburst of RS Oph is M2, while the quiescence data imply K5–M0 (Dobrzycka et al. 1996; Anupama & Mikołajewska 1999). The increased contribution to the continuum through the reestablishment of the accretion process onto the white dwarf, and also the reestablishment of the envelope due to the stellar wind from the red giant in these systems, causes a dilution in the absorption bands, leading to an earlier spectral type estimate during quiescence. A similar effect, caused by the reestablishment of the circumstellar wind, could also be present in U Sco, in which case the estimate of the secondary spectral type based on the late outburst spectra would be more reliable.

6. SUMMARY

The optical spectra of the 1999 outburst of U Sco during 0.45–42.35 days after optical maximum are presented here. It is the first time that spectra have been obtained so close to the outburst maximum. The spectral evolution during the present outburst is broadly similar to the previous outbursts.

We estimate the mass of the ejected shell to be $10^{-7}\ M_{\odot}$, and observe helium to be overabundant, similar to the previous outbursts.

Based on the indices of the Mg I *b* 5174 Å absorption band and the Fe I + Ca I absorption feature in the late-decline spectrum, and on the orbital period estimates, we estimate the secondary to be a K2 subgiant.

We thank the VSNET network for an immediate notification of the outburst, which enabled us to obtain spectra just a few hours from maximum. We acknowledge the help of the assistants at the 2.3 m VBT during observations. We thank K. P. Singh and T. P. Prabhu for useful comments and suggestions on the paper. Critical comments by the referee are gratefully acknowledged.

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