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The helium abundance in the ejecta of U Scorpii

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ABSTRACT

U Scorpii (U Sco) is a recurrent nova which has been observed in outburst on 10 occasions, most recently in 2010. We present near-infrared (near-IR) and optical spectroscopy of the 2010 outburst of U Sco. The reddening of U Sco is found to be $E(B - V) = 0.14 \pm 0.12$, consistent with previous determinations, from simultaneous optical and near-IR observations. The spectra show the evolution of the linewidths and profiles to be consistent with previous outbursts. Velocities are found to be up to 14 000 km s^{-1} in broad components and up to 1800 km s^{-1} in narrow-line components, which become visible around day 8 due to changes in the optical depth. From the spectra we derive a helium abundance of $N(\mathrm{He})/N(\mathrm{H}) = 0.073 \pm 0.031$ from the most reliable lines available; this is lower than most other estimates and indicates that the secondary is not helium-rich, as previous studies have suggested.

Key words: stars: individual: U Sco – novae, cataclysmic variables – infrared: stars.

1 INTRODUCTION

U Scorpii (U Sco) is a recurrent nova which has undergone recorded outbursts in 1863, 1906, 1917, 1936, 1945, 1969, 1979, 1987 and 1999 (Schaefer 2010) before a further outburst peaked on 2010 January 28.19 ± 0.17 UT (Schaefer et al. 2010). The mean recurrence time is 10.3 years (Schaefer 2010). U Sco is an eclipsing binary with an orbital inclination of ∼82° (Thoroughgood et al. 2001) and is semi-detached with an orbital period of ≃1.23 days (Schaefer & Ringwald 1995). U Sco consists of a white dwarf (WD) primary and a probable subgiant secondary with a spectral type in the range from K2 (Anupama & Dewangan 2000) to G0 (Hanes 1985), with the WD having a mass close to the Chandrasekhar limit (≃1.37 $M_{\odot}$) (Thoroughgood et al. 2001). The system is at a distance of 12 ± 2 kpc and is far out of the Galactic plane at a height of ∼4.5 kpc (Schaefer 2010).

Starrfield (2008) interprets the outbursts as being due to a thermonuclear runaway (TNR) on the surface of the WD. The TNR occurs when the temperature and density at the base of the layer accreted from the secondary reach critical values of $\simeq 10^8$ K and $\simeq 10^{19}$ N m^{-2}, respectively (Starrfield 2008). The recurrence timescale is consistent with the nova outburst models of Yaron et al. (2005). The energy released from the hydrogen burning is sufficient to allow heavier elements to undergo nuclear fusion. This continues until the energy generation is limited by the long, temperature independent half-lives of some isotopes involved in the CNO cycle such as ^{14}O and ^{13}N.

The 2010 outburst was anticipated by Schaefer (2004) who planned a multiwavelength observing programme ahead of time; this resulted in the 2010 outburst of U Sco having the best temporal coverage of any nova event so far. This led to the discovery of new phenomena such as aperiodic dips in the light curve and flares (Pagnotta et al. 2011; Schaefer 2011). The apparent onset of optical flickering on day 8 of the outburst (Worters et al. 2010) has been identified as an example of such a flare. The spectral evolution between outbursts is consistent, as is the photometric evolution. Banerjee et al. (2010) present near-infrared (near-IR) spectra of the outburst which show broad H I, He I, He II and O I emission lines. The H I lines give an upper limit on the ejected mass of 9.71 ± 9.29 × 10^{-5} $M_{\odot}$ (Banerjee et al. 2010). The helium abundance, $N(\mathrm{He})/N(\mathrm{H})$, of U Sco is highly uncertain (Diaz et al. 2010) with estimates ranging from 0.16 (Iijima 2002) to 4.5 (Evans et al. 2001). An accurate determination of the helium abundance in U Sco is necessary as some studies have suggested that, unlike classical novae, the WD is accreting helium-rich material from the secondary star. As a result, the physics of the TNR has been modified by Starrfield et al. (1988) for the case of U Sco. To explain the presence in the

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system of a helium-rich donor star, Hachisu et al. (1999) proposed an evolutionary sequence in which a helium-rich primary filled its Roche lobe and transferred material to the secondary in the post-common envelope phase. However, Truran et al. (1988) showed that a bright nova outburst is only possible on a 1.38 solar mass WD if H/He $\leq$ 1. This agrees with evolutionary calculations by Sarna, Ergma & Gerskevits (2006), who concluded that any helium enrichment is from the WD.

Here we present near-IR and optical spectroscopy of the latest outburst obtained at the New Technology Telescope (NTT), Liverpool Telescope (LT; Steele et al. 2004), Cerro Tololo Inter-American Observatory (CTIO) and South African Astronomical Observatory (SAAO) from which we derive the reddening, helium abundance and broad- and narrow-component linewidths.

2 OBSERVATIONS

We take the observed maximum at 2010 January 28.19 to be day 0 of the outburst and all epochs are relative to this time. Near-IR spectroscopy of U Sco was obtained on days 5.41 and 9.43 at the NTT using the Son Of ISAAC spectrograph. The spectral resolution is ∼1000. For more details see Banerjee et al. (2010). An optical spectrum was also obtained on day 9.43 using the Cassegrain spectrograph on the 1.5-m SMARTS Telescope at CTIO at a resolution of ∼1500. Optical spectra were obtained from 1.93 to 11.93 days after outburst using the Cassegrain spectrograph on the SAAO 1.9-m telescope with a spectral resolution of ∼1000. Optical spectra were also obtained from 6.81 to 12.81 days after outburst using the FRODOSpec (Morales-Rueda et al. 2004) spectrograph at LT at a resolution of ∼5400. An observing log is given in Table 1.

Table 1. Observing log.

Day	Wavelength range (Å)	Facility
1.93	3500–7250	SAAO
4.93	3500–7250	SAAO
5.41	9950–24000	NTT
5.93	3500–7250	SAAO
6.81	3900–5200, 5700–7900	LT
7.81	3900–5200, 5700–7900	LT
7.93	3500–7250	SAAO
8.81	3900–5200, 5700–7900	LT
8.93	3500–7250	SAAO
9.43	4000–4800, 9950–24 000	CTIO, NTT
9.93	3500–7250	SAAO
10.93	3500–7250	SAAO
11.81	3900–5200, 5700–7900	LT
11.93	3500–7250	SAAO
12.81	3900–5200, 5700–7900	LT

3 RESULTS

Figs 1 and 2 show the dereddened optical spectra of U Sco covering most of the first 13 days of the outburst. The strong emission lines are due to H I, He I, N III and, at later times, He II. The He I lines fade

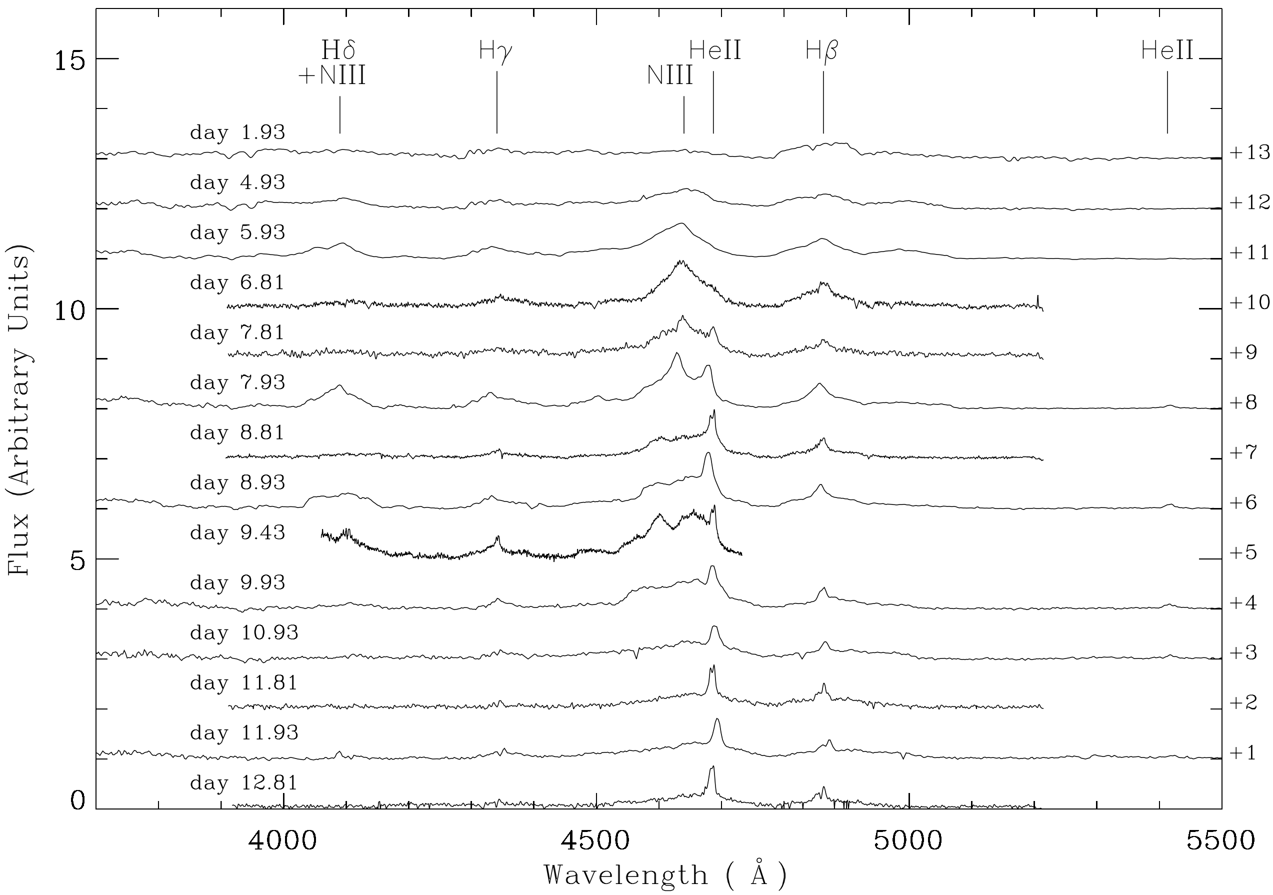

Figure 1. Spectra of U Sco taken from day 1.93 to 12.81 at LT (days ending .81), CTIO (day 9.43) and SAAO (days ending 0.93). The spectra are offset as indicated and the flux is in arbitrary units. LT spectra are smoothed with a Gaussian profile.

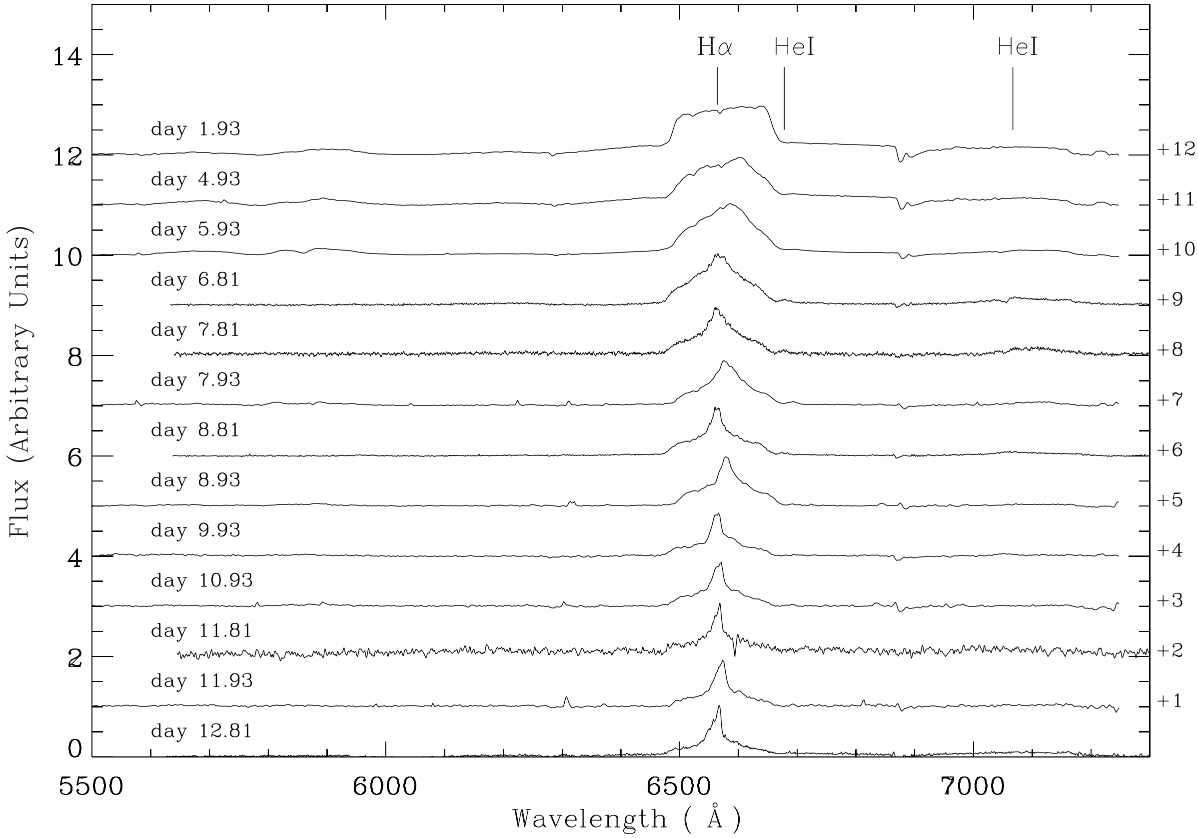

Figure 2. Spectra of U Sco taken from day 1.93 to 12.81 at LT (days ending 0.81) and SAAO (days ending 0.93). The spectra are offset as indicated and the flux is in arbitrary units. LT spectra are smoothed with a Gaussian profile.

as the He II lines develop and are no longer detectable by day 11.81. N III and Hγ also fade and are very weak or undetectable by this time. Hδ and He II 4686 Å are both blended with N III. Figs 3 and 4 show near-IR spectra of U Sco; they show the Paschen series of hydrogen in emission along with O I, He I and He II emission lines. Paschen γ and Paschen δ are blended with He I and He II, respectively. Fig. 3 also shows a spectrum from the outburst in 1999 taken at a similar time after maximum to the first of our NTT spectra; the spectra are very similar with the same emission features present and similar relative line strengths.

3.1 Linewidths and flux ratios

Here we measure the FWZI of each line present in our spectra. Some lines also show narrow components; in these cases we also measure the full width at half-maximum (FWHM) of that component. The contribution of instrumental resolution was not found to be significant. Velocities and the associated errors were measured by fitting Gaussian profiles and visual inspection of where the emission meets the continuum. The Hα velocity is consistent with previous outbursts at similar times (Iijima 2002) at 8000–9000 km s^{-1}. The width of each line can be seen in Tables 2–4 and can be seen to be changing with time; however, the profile of the lines is changing rapidly as can be seen in Figs 1 and 2. Tables 3 and 4 show the evolution of the narrow components of Hα and Hβ. Such high-velocity outflows ($\simeq$10 000 km s^{-1}) were also seen in early ($\leq$5 days) spectra of the 2010 outburst of U Sco (Banerjee et al. 2010).

Line fluxes were measured by fitting Gaussian profiles to the lines with a least-squares fit and can be seen in Table 5. Multiple profiles were used in some cases; an example fit can be seen in Fig. 5. These fluxes were then ratioed and compared to theoretical values from Hummer & Storey (1987). From these ratios the abundance of species A to species B can be found using the following equation:

$$\frac{F_A}{F_B} = \frac{\lambda_A}{\lambda_B} \times \frac{N_A}{N_B} \times \frac{\alpha_B}{\alpha_A}, \quad (1)$$

where F is the measured dereddened flux, N is the abundance by number and α is the recombination coefficient from Hummer & Storey (1987) for species A and B, respectively. We assume that the sources of H I, He I and He II emission are co-extensive.

This process was repeated for each available He I (for He$^+$) and He II (for He^{++}) to hydrogen line ratio. Since our spectra show both ionized states of helium in emission, the total abundance can be directly measured instead of using the Saha equation to predict the abundance of one species from the other.

3.2 Reddening

Several studies (Barlow et al. 1981; Burstein & Heiles 1982; Amôres & Lépine 2005) as well as the dust maps of Schlegel, Finkbeiner & Davis (1998) have shown the reddening of U Sco to be in the range $E(B - V) = 0.09$–0.36. The ratios of line fluxes were estimated and compared to the theoretical values derived from Hummer & Storey (1987). We use the optical spectra taken on day 8.81 at LT and day 9.43 at CTIO (Figs 1 and 2), and the IR spectrum taken on day 9.43 at NTT (Fig. 4) to estimate the reddening, as by this time the flux ratios are converging on case B values. We use the extinction law and assumption of $R = 3.1$ of Howarth (1983). Using the ratios Hβ/Paϵ, Hβ/Paβ, Hγ/Paϵ and Hγ/Paβ, the reddening was found

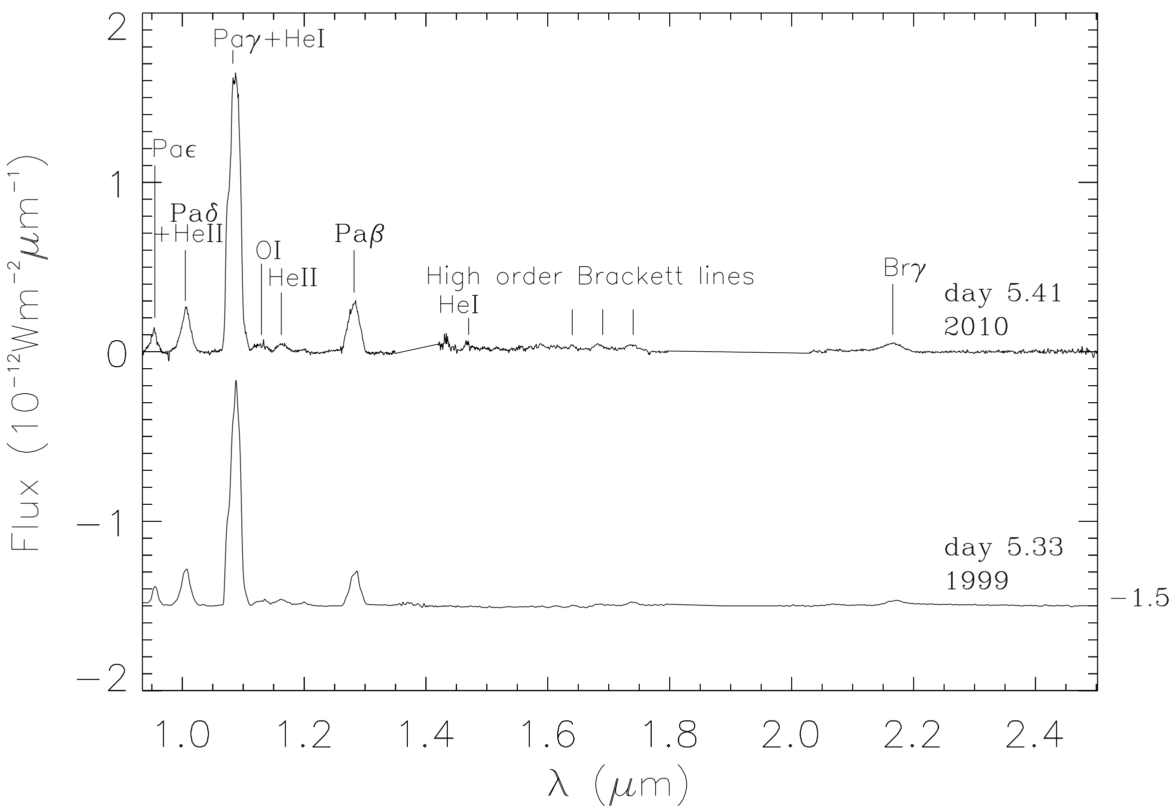

Figure 3. Top: IR spectrum of U Sco taken at the NTT on day 5.41 of 2010 outburst. Bottom: IR spectrum of U Sco taken at the NTT 5.33 days after the maximum of the 1999 outburst from Evans et al. (2001), offset as indicated on the right-hand side.

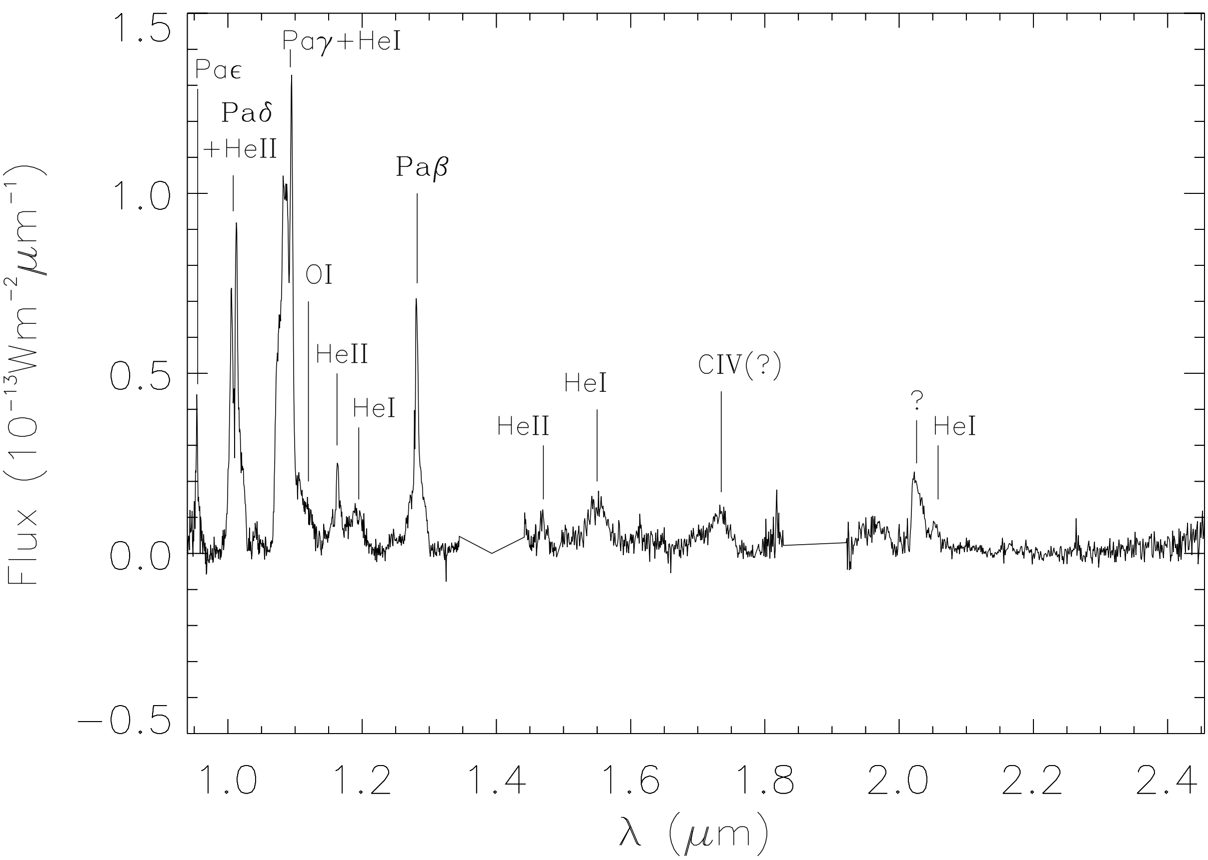

Figure 4. IR spectrum of U Sco taken at the NTT on day 9.43 of 2010 outburst.

Table 2. Broad-component linewidths (FWZI, km s^{-1}) from LT (days ending 0.81) and SAAO (days ending 0.93).

	Hγ	N III 4616 Å	He II 4686 Å	Hβ	Hα	He I 6678 Å	He I 7065 Å
1.93	–	–	–	8000 ± 2000	10 000 ± 1000	–	–
4.93	–	–	–	9000 ± 2000	9000 ± 1000	–	–
5.93	12 000 ± 2000	–	–	12 000 ± 2000	9000 ± 1000	–	–
6.81	9000 ± 3000	8000 ± 2000	6000 ± 2000	9000 ± 2000	8000 ± 1000	2000 ± 500	13 000 ± 3000
7.81	–	8000 ± 1000	6000 ± 2000	9000 ± 2000	8000 ± 1000	1000 ± 500	10 000 ± 2000
7.93	10 000 ± 2000	–	6000 ± 3000	9000 ± 2000	9000 ± 1000	–	–
8.81	8000 ± 2000	12 000 ± 2000	4000 ± 2000	8000 ± 2000	8000 ± 500	1500 ± 250	12 000 ± 2000
8.93	9000 ± 2000	–	6000 ± 2000	9000 ± 1000	9000 ± 1000	–	–
9.93	4000 ± 1000	–	4000 ± 1000	3000 ± 1000	9000 ± 2000	–	–
10.93	4000 ± 1000	–	2000 ± 500	3000 ± 1000	9000 ± 1000	–	–
11.81	–	–	1500 ± 500	2000 ± 1000	8000 ± 2000	–	–
11.93	4000 ± 1000	–	2000 ± 500	2000 ± 500	9000 ± 1000	–	–
12.81	–	–	1200 ± 250	1500 ± 500	8000 ± 1000	–	–

Table 3. Narrow-component linewidths (FWHM, km s^{-1}) from LT data.

Day	6.81	7.81	8.81	11.81	12.81
Hβ	1001.95 ± 72.36	836.21 ± 131.3	953.53 ± 41.62	882.85 ± 61.97	1234.63 ± 85.49
Hα	1071.35 ± 50.0	1146.4 ± 46.77	849.94 ± 23.94	753.96 ± 57.1	1380.0 ± 41.95

Table 4. Narrow-component linewidths (FWHM, km s^{-1}) from SAAO data.

Day	1.93	4.93	5.93	7.93	8.93	9.93	10.93	11.93
Hβ	–	–	–	1782.15 ± 106.9	1318.17 ± 108.8	975.48 ± 71.76	764.72 ± 53.5	1192.30 ± 80.41
Hα	–	–	–	1413.54 ± 68.99	876.78 ± 40.20	778.07 ± 32.47	841.79 ± 30.53	882.26 ± 36.28

Table 5. Dereddened line fluxes. Fluxes and errors are relative to Hβ on that date for optical data and Paβ for near-IR data.

	Hβ	Hγ	Paβ	Paϵ	He I 6678 Å	He II 4686 Å	He II 5411 Å	HeII 1.163 μm
8.81	1 ± 0.01	1.02 ± 0.03	–	–	0.007 ± 0.001	–	–	–
9.43	–	–	1 ± 0.04	0.45 ± 0.02	–	–	–	0.18 ± 0.01
9.93	1 ± 0.04	0.29 ± 0.02	–	–	–	0.34 ± 0.02	0.074 ± 0.010	–
10.93	1 ± 0.02	0.12 ± 0.01	–	–	–	0.19 ± 0.01	0.022 ± 0.002	–
11.93	1 ± 0.03	0.25 ± 0.04	–	–	–	0.28 ± 0.03	0.036 ± 0.006	–

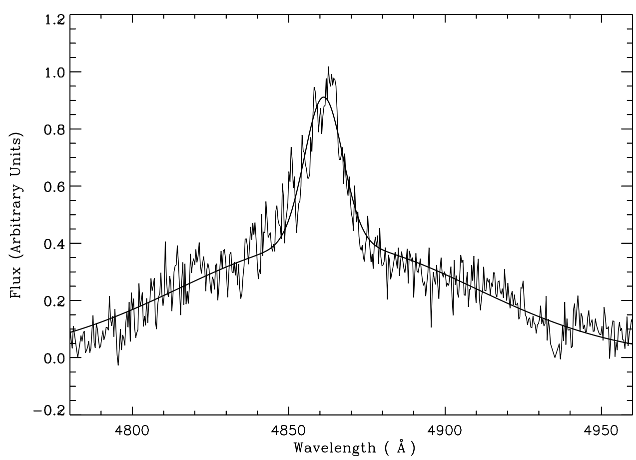

Figure 5. Fit of Hβ using a pair of Gaussian profiles.

to be in the range $E(B - V) = 0.0$–0.29 with a mean of $E(B - V) = 0.14 \pm 0.12$, consistent with the previous studies. Although U Sco is at a distance of 12 kpc, low reddening is consistent with both the line of sight leaving the plane of the galaxy and the system being at a height of $z = 4.5$ kpc above the galactic plane (Schaefer 2010). For the spectra used in this work we adopt $E(B - V) = 0.2$ as a good compromise between our own value and previous estimates.

3.3 Helium abundance

The helium abundance of U Sco was calculated using H I, He I and He II recombination lines. We use the line fluxes on days 8.81 (LT), 9.93–11.93 (SAAO) and 9.43 (NTT) to estimate the helium abundance, as by this time the line ratios are converging on case B values. The large Hα/Hβ ratio throughout the time coverage we have available shows that Hα should not be used in our abundance analysis due to optical depth effects.

Abundance analyses of helium are complicated by the metastability of the lowest triplet level of He I, 2^3S, which can cause some lines to become optically thick. Furthermore, collisional excitations from this level enhance triplet lines. The collisional contributions are 56 per cent for 5876 Å, 78 per cent for 7065 Å and 72 per cent for 1.083μm using relations from Kingdon & Ferland (1995) and Peimbert & Torres-Peimbert (1987) at a temperature of 2×10^4 K at the high density limit. The contribution is lower in the singlet lines,

Table 6. Helium abundances.

Helium line	Derived abundance
He I 6678 Å	0.012 ± 0.015
He II 4686 Å	0.047 ± 0.011
He II 5411 Å	0.076 ± 0.023
He II 1.163 μm	0.061 ± 0.010

although collisions from the 2^1S level must be taken into account. The ratio of 7065/4471 is an optical depth indicator (Osterbrock & Ferland 2006) and this ratio (1.31) is inconsistent with the case B value (∼0.5), further evidence that the 7065 Å line is unsuitable for this analysis. In our abundance analysis we consider the singlet He I line at 6678 Å for which the collisional contribution is 27 per cent using equation 12 of Kingdon & Ferland (1995) at a temperature of 2×10^4 K. At temperatures of 10^4 and 3×10^4 the collisional contributions for this line are 7 per cent and 36 per cent, respectively. We also use He II lines at 4687 Å (LT and SAAO), 5411 Å (SAAO) and 1.163 μm (NTT).

Following Evans et al. (2001) we estimate the electron density using Paschen and Brackett series H I lines from our near-IR spectra (Figs 4 and 5) using the equation

$$F(H) = \frac{\epsilon \phi N_e^2}{\alpha} \times \frac{V^3 t^3}{3D^2}, \quad (2)$$

where F is the flux of a hydrogen line, ϵ is the case B emissivity from Hummer & Storey (1987), α is the number of electrons per hydrogen, ϕ is the volume filling factor, N_e is the electron density, V is the velocity, D is the distance and t is the time since maximum in days. We follow Evans et al. (2001) by assuming $\alpha = 1$, $\phi = 0.01$ and $D = 12$ kpc. Our results are consistent with those of Evans et al. (2001) at similar times; therefore, we adopt their values of electron density of 10^{10} cm^{-3} for data taken before day 9.43 and 10^9 cm^{-3} for data taken at later times. The recombination coefficients are relatively insensitive to temperature; we assume $T_e = 20\,000$ K. We derive $N(\mathrm{He}^+)/N(\mathrm{H}^+) = 0.012 \pm 0.015$ and $N(\mathrm{He}^{++})/N(\mathrm{H}^+) = 0.061 \pm 0.010$ from the data obtained at LT, NTT and CTIO using the He I line at 6678 Å and the He II line at 1.163 μm. From the SAAO data we derive $N(\mathrm{He}^{++})/N(\mathrm{H}^+) = 0.047 \pm 0.011$ using the He II line at 4686 Å and $N(\mathrm{He}^{++})/N(\mathrm{H}^+) = 0.076 \pm 0.023$ using the line at 5411 Å. These results are summarized in Table 6.

4 DISCUSSION

The helium abundance in U Sco has been the subject of many studies which have resulted in a wide range of values from 0.16 to 4.5 (Barlow et al. 1981; Anupama & Dewangan 2000; Evans et al. 2001; Iijima 2002). We find the abundance to be $N(\mathrm{He})/N(\mathrm{H}) = 0.073 \pm 0.031$, lower than that found by Iijima (2002), Barlow et al. (1981), Anupama & Dewangan (2000) and Evans et al. (2001). A high helium abundance would suggest that the secondary in U Sco is a highly evolved star; however, the value derived here is close to the solar value N(He)/N(H) = 0.085 (Asplund et al. 2009). Our estimate suggests that assumptions about the helium-rich nature of the secondary are unfounded and that the secondary did not accrete helium-rich material significantly in the post common envelope phase (Hachisu et al. 1999). In the evolutionary calculations of Sarna et al. (2006), U Sco is best represented by their sequence B, with a hydrogen-rich secondary. For our helium abundance analysis we have considered the data (≥day 8) and the lines for which we can be confident that case B recombination applies. Other estimates have been larger than our value, especially those based only on the He II lines. These large abundances result from the use of the Saha equation, which is highly sensitive to the assumed electron temperature. However, we use both He I and He II lines in our analysis, avoiding the use of the equation to derive the total helium abundance. The temperature dependencies in this analysis are in the recombination coefficients, which are relatively insensitive to the value chosen, and in the collisional correction for He I lines. Using a range of lines from days 8.81 and 9.43 and a range of recombination coefficients we determine several $\mathrm{He}^{++}/\mathrm{He}^+$ ratios, each of which suggests electron temperatures of 2.3–2.4 $\times 10^4$ K; therefore, we use recombination coefficients for the closest temperature from Hummer & Storey (1987) of $T_e = 2 \times 10^4$ K.

The hydrogen line profiles have broad and narrow components. The narrow components become prominent around day 8 and arise from slow moving material at speeds of ∼1000 km s^{-1}. The broad components are composed of material travelling at velocities of up to ∼10 000 km s^{-1}. The rise in the strength of the narrow components could be explained by optical depth effects. The ejecta begin to become optically thin around day 8; before this time slower moving material would be concealed by the shell of optically thick fast moving material. As the faster moving material expands and becomes optically thin, the flux from the slow moving material becomes visible. He II lines also begin to dominate the helium emission around day 8; however, this is most likely due to photo-ionization of helium rather than an optical depth effect. The measured linewidths are generally higher for the SAAO data than for near-simultaneous LT data; possible reasons for this are the difference in resolution and signal-to-noise issues. There also appears to be clear structure to the Hβ line in the LT spectra which is not present in the SAAO spectra. A possible source of the narrow components is an inclination effect; since U Sco is a high inclination system most of the velocity is in the plane of the sky; therefore, we may be observing a small radial component. This is consistent with the asymmetric ejecta models of Drake & Orlando (2010). Data over a longer time range and with better orbital phase coverage are required to explore this further.

5 CONCLUSION

We present optical and near-IR observations of the 2010 outburst of U Scorpii. We find the helium abundance of U Scorpii to be $N(\mathrm{He})/N(\mathrm{H}) = 0.073 \pm 0.031$. This estimate is lower than most previous studies and does not support their conclusions which suggest that the secondary in this system is helium-rich. The velocities seen in the 2010 outburst are consistent with those seen in previous outbursts, with some hydrogen and He II lines being seen to have both narrow and broad components in our later spectra. Further observations are planned to investigate the nature and metallicity of the secondary in this system.

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