Modelling the recurrent nova U Scorpii in quiescence

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Abstract. VLT and SALT spectroscopy of U Sco were obtained ~18 and ~30 months after the 2010 outburst. From these spectra the accretion disc is shown to take at least 18 months to become fully reformed. The spectral class of the companion is constrained to be F8+5 IV-V at the 95% confidence level when the irradiated face of the companion is visible.

1. Introduction

The recurrent nova U Scorpii was observed to go into outburst in January 2010. The peak and decline to the pre-outburst V band magnitude were very well observed (Schaefer et al. 2011), however there are very few observations of the system at the quiescent magnitude level (see Johnston & Kulkarni 1992 for an example). U Sco is a semi-detached binary with a high mass white dwarf primary (Thoroughgood et al. 2001) and an orbital period of 1.23 days (Schaefer & Ringwald 1995). The companion is a sub-giant with a mass of 0.88 M⊙ and radius 2.1 R⊙ (Thoroughgood et al. 2001).

2. Observations

Following the 2010 outburst of U Sco and the subsequent return to the pre-outburst magnitude, VLT and SALT spectra were obtained ~18 and ~30 months after outburst respectively, as detailed in Table 1. The VLT spectra, R ~5000, can be seen in Figure 1 with the optical region shown in Figure 2. SALT spectra, R ~1000, are displayed in Figure 3. The VLT spectra show several emission lines, the strongest of which is He ii 4686Å. H Balmer lines are present and have profiles consistent with those expected from an optically thick accretion disc (Warner 2003).

The VLT spectra, taken ~18 months after outburst, are clearly different from those taken 2-3 years after outburst by Johnston & Kulkarni (1992), however they show many of the same features observed by Thoroughgood et al. (2001) ~50 days after the 1999 outburst. The SALT spectra, taken ~30 months after outburst, appear much more similar to the spectra of Johnston & Kulkarni (1992). Clearly there is significant spectroscopic evolution for several months after the system has returned to the pre-outburst magnitude.
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| Orbital phase | Days after outburst | Facility | Wavelength range (µm) |
|---------------|--------------------|----------|----------------------|
| 0.25          | 445                | VLT      | 0.3 - 2.5            |
| 0.40          | 460                | VLT      | 0.3 - 2.5            |
| 0.43          | 460                | VLT      | 0.3 - 2.5            |
| 0.46          | 460                | VLT      | 0.3 - 2.5            |
| 0.55          | 848                | SALT     | 0.4 - 0.63           |
| 0.62          | 459                | VLT      | 0.3 - 2.5            |
| 0.77          | 909                | SALT     | 0.4 - 0.63           |

Table 1. Observing Log.

Figure 1. VLT spectra. Orbital phase and number of days after outburst are shown on the y axis.
3. The accretion disc

The nature of the accretion disc in U Sco was constrained by fitting a model to the VLT spectra. There are two components to the model, one representing the accretion disc and the other the companion star, which is represented by a single model stellar atmosphere. The accretion disc model consists of several annuli, each represented by a model stellar atmosphere produced using the ATLAS code by Kurucz (1992). The effective temperature of each annulus was determined using

$$T_{\text{eff}} = T_\ast \left(\frac{R_{\text{acc}}}{r}\right)^{3/4} \left(1 - \left(\frac{R_{\text{acc}}}{r}\right)^{1/2}\right)^{1/4},$$

where $R_{\text{acc}}$ is radius of the white dwarf, $r$ is the distance from the white dwarf to the disc annulus, and $T_\ast$ is found using

$$T_\ast = 4.10 \times 10^4 R_9^{-3/4} M_1^{1/4} M_{16}^{1/4},$$

where $R_9$ is the white dwarf radius in units of $10^9\text{cm}$, $M_1$ is the white dwarf mass in solar masses, and $M_{16}$ is the mass accretion rate in units of $10^{16}\text{g s}^{-1}$. These equations assume that the disc is in the steady state. The best fits to the mass accretion rate are shown in Table 2. These mass accretion rates are too low to allow U Sco to gain mass given ejected mass estimates of $10^{-6}$-$10^{-7} M_\odot$ (Diaz et al. 2010; Takei et al. 2013) and a recurrence period of $\sim$10 years.
Figure 3. SALT spectra taken at phase 0.55, day 848 (lower spectrum) and phase 0.77, day 909 (upper spectrum).
An alternative measure of the mass accretion rate is the strength of the He\textsc{ii} 4686Å line. Patterson & Raymond (1985) show that the strength of this line is empirically related to the mass accretion rate in compact CVs; the mass accretion rates derived via this method are shown in Table 3. These mass accretion rates are \( \sim \) 100 times higher than those derived from fitting the VLT spectra and are high enough that U Sco could be gaining mass over each outburst cycle. These mass accretion rates also show that the He\textsc{ii} 4686Å line strength is consistent with a high mass white dwarf accreting at a high rate without requiring an over-abundance of helium, contrary to the suggestion of Hachisu et al. (1999) that the companion is helium-rich, and consistent with the solar helium abundance found in the ejecta of the 2010 outburst (Maxwell et al. 2012).

The discrepancy between the two sets of mass accretion rates, and the differences between the VLT and SALT spectra, is consistent with an increase in luminosity of the disc in the time between the two sets of observations. Schaefer et al. (2011) find that the disc has become fully re-established by 67 days after outburst since by this time the system has returned to the pre-outburst magnitude level, however here we find from the spectroscopic evolution until \( \sim \) 30 months after outburst and the low mass accretion rates derived from fits to the VLT spectra, which indicates that the disc is not in the steady state at this time, that it takes at least \( \sim \) 18 months to fully reform.

### Table 2. Best fits for mass accretion rates and companion temperature. Errors are the 95% confidence interval.

| Phase | \( M(M_\odot/\text{yr}) \) | \( T_{\text{companion}} \) |
|-------|-----------------|------------------|
| 0.25  | \( 7.31^{+0.48}_{-0.48} \times 10^{-9} \) | 5000^{+750}_{-250} |
| 0.40  | \( 6.52^{+0.48}_{-0.48} \times 10^{-9} \) | 6500^{+250}_{-250} |
| 0.43  | \( 7.31^{+0.48}_{-0.48} \times 10^{-9} \) | 7000^{+250}_{-250} |
| 0.46  | \( 7.31^{+0.48}_{-0.48} \times 10^{-9} \) | 6500^{+250}_{-250} |
| 0.62  | \( 4.45^{+0.16}_{-0.32} \times 10^{-9} \) | 6000^{+250}_{-250} |

### Table 3. Mass accretion rates derived from He\textsc{ii} 4686Å flux.

| Phase | \( L(\text{ergs s}^{-1}) \) | \( M(M_\odot/\text{yr}) \) |
|-------|-----------------|-----------------|
| 0.25  | \( 4.47\pm0.12 \times 10^{31} \) | 2.81\pm0.03 \times 10^{-7} |
| 0.40  | \( 11.1\pm0.14 \times 10^{31} \) | 9.09\pm0.01 \times 10^{-7} |
| 0.43  | \( 9.34\pm0.14 \times 10^{31} \) | 7.22\pm0.01 \times 10^{-7} |
| 0.46  | \( 9.43\pm0.14 \times 10^{31} \) | 7.39\pm0.01 \times 10^{-7} |
| 0.55  | \( 2.56\pm0.10 \times 10^{31} \) | 1.38\pm0.04 \times 10^{-7} |
| 0.62  | \( 8.42\pm0.10 \times 10^{31} \) | 6.29\pm0.01 \times 10^{-7} |
| 0.77  | \( 4.12\pm0.28 \times 10^{31} \) | 2.56\pm0.07 \times 10^{-7} |

### 4. The companion star

The effective temperature of the companion star was constrained via fitting the VLT spectra as described above. The effective temperatures of the best fit models, and the derived luminosity, radius, and spectral class, are shown in Table 4. The derived luminosities and radii suggest that the companion is a sub-giant star, in agreement with...
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Thoroughgood et al. (2001), and that it fills its Roche lobe. At orbital phases 0.40-0.62 the spectral class is determined to be F2-G3 at the 95% confidence level. The effect of irradiation from the hot component, causing the inwards facing hemisphere of the companion to be heated, appears to be present here. At phase 0.25 there is significant contribution from the outer, cooler hemisphere of the companion resulting in a cooler effective temperature.

| Phase | $T_{\text{companion}}$ (K) | $L/L_\odot$ | $R/R_\odot$ | Spectral class | Spectral class at 95% |
|-------|-----------------|-------------|-------------|----------------|---------------------|
| 0.25  | $5000^{+750}_{-250}$ | 1.41$^{+1.06}_{-0.74}$ | 1.60$^{+0.17}_{-0.18}$ | K0              | G3 - K2             |
| 0.40  | $6500^{+750}_{-250}$ | 3.76$^{+0.67}_{-0.51}$ | 1.54$^{+0.16}_{-0.16}$ | F7              | F5 - F9             |
| 0.43  | $7000^{+750}_{-250}$ | 4.32$^{+1.56}_{-0.40}$ | 1.43$^{+0.19}_{-0.16}$ | F3              | F2 - F9             |
| 0.46  | $6500^{+750}_{-250}$ | 3.41$^{+0.60}_{-0.49}$ | 1.47$^{+0.17}_{-0.45}$ | F7              | F5 - F9             |
| 0.62  | $6000^{+750}_{-250}$ | 4.19$^{+0.49}_{-0.62}$ | 1.91$^{+0.15}_{-0.31}$ | G0              | F9 - G3             |

Table 4. Spectral type from fits to VLT data.

5. Conclusion

From VLT and SALT spectra of U Sco taken $\sim$18 and $\sim$30 months after outburst the accretion disc has been shown to take at least 18 months to become fully reformed. The spectral type of the companion has been constrained to be F8$^{+5}_{-6}$ when the inwards facing hemisphere of the companion is observed.

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