VARIABILITY OF THE ACCRETION DISK OF V926 Sco INFERRED FROM TOMOGRAPHIC ANALYSIS

S. D. Connolly1, C. S. Peris2,3, and S. D. Vrtilek3

1 University of Southampton, Highfield, Southampton, SO17 1BJ, UK; sdc1g08@soton.ac.uk
2 Department of Physics, Northeastern University, Boston, MA 02115, USA; peris.e@husky.neu.edu, cperis@cfa.harvard.edu
3 Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA; svrtilek@cfa.harvard.edu

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ABSTRACT

We present phase-resolved spectroscopic observations of the low-mass X-ray binary V926 Sco (4U 1735-44), covering the orbital period of 0.23 days, obtained with the Walter Baade 6.5 m Magellan Telescope at the Las Campanas Observatory in 2010 June and 2011 June. We use Hα radial velocities to derive a systemic velocity of $-109 \pm 4$ km s$^{-1}$. The FWHM of the lines observed in common with previous authors are significantly lower during our observations suggesting much reduced velocities in the system. The equivalent width of the Bowen fluorescence lines with respect to He II $\lambda4686$ are factors of two or more lower during our observations in comparison to those previously reported for the system, suggesting reduced irradiation of the secondary. Doppler and modulation tomography of Hα and He II $\lambda4686$ show asymmetric emission that can be attributed to a bulge in the accretion disk, as inferred from He II observations by previous authors. The X-ray fluxes from the source at times concurrent with the optical observations are significantly lower during our observations than during optical observations taken in 2003. We suggest that the system is in a lower accretion state compared to earlier observations; this explains both the lower velocities observed from the disk and the reduction of emission due to Bowen fluorescence detected from the secondary.

Key words: accretion, accretion disks – stars: individual (V926 Sco) – stars: neutron

Online-only material: color figures

1. INTRODUCTION

V926 Sco (4U 1735-44) is a low-mass X-ray binary that is persistent in X-rays. The shape of its X-ray color–color diagram caused Hasinger & van der Klis (1989) to classify it as an atoll persistent in X-rays. The shape of its X-ray color–color diagram through optical photometry (Corbet et al. 1986; Pederson et al. 1981), which showed a shallow sinusoidal variation in the light curve, interpreted as due to the varying aspect of the X-ray heated secondary object (e.g., van Paradijs et al. 1988). Although sinusoidal variation can also be produced by asymmetries in the disk, for example through the varying visibility of an irradiated inner disk bulge (Hellier & Mason 1989) or by superhumps (Haswell et al. 2001), the variation was attributed to the donor by Casares et al. (2006).

A periodic variation in the Hα line observed by Smale et al. (1984) was confirmed by Smale & Corbet (1991) and attributed to varying emission originating from a bulge or splash region at or near the point on the disk at which the gas stream impacts the outer rim. Augusteijn et al. (1998) found similar variation in He II $\lambda4686$ and the blend of N III and C III emission lines ($\lambda\lambda4634$–$4651$) produced by Bowen fluorescence, and attributed both to a disk bulge.

Doppler tomography (Horne & Marsh 1986) was carried out on V926 Sco by Casares et al. (2006), using data taken in 2003 June with the FORS2 Spectrograph on the 8.2 m Yepun Telescope at the Observatorio Monte Paranal. Tomography of Hα $\lambda4686$ showed an extended area of bright emission on one side of the disk, suggesting that the variation in this emission does arise from a bulge in the accretion disk, consistent with Smale & Corbet (1991). However, Casares et al. (2006) found that N III $\lambda4640$ emission was coincident with the estimated velocity of the donor star, as opposed to a disk bulge. They attributed this to fluorescence of the donor, irradiated by UV photons from the hot inner disk, as originally suggested for Sco X-1, along with several other X-ray binaries, by McClintock et al. (1975).

Our spectra cover nearly twice the bandwidth of Casares et al. (2006) including in particular the Hα line for which no previous tomographic study has been done and which is particularly useful for studying emission from the disk. In addition to Doppler tomography we also undertake modulation tomography (Steeghs 2003) which allows us to take into consideration variations in the brightness of the components of the system which are harmonic with the orbital period. As Doppler tomography is limited by the assumption that the brightness of the components of a system do not vary, its combination with modulation tomography allows more accurate interpretation of the velocity maps of a system.

In Section 2 we describe the optical observations obtained and used for this study. In Section 3 we present our analysis of the spectral features. In Section 4 we present Doppler and modulation tomography of the lines and end with a summary and conclusions in Section 5.

2. OBSERVATIONS

Observations of V926 Sco were carried out on the nights of 2010 June 5, 7 and 2011 June 22, 26, using the IMACS spectograph on the Walter Baade 6.5 m Magellan telescope at the Las Campanas Observatory. A long-slit diffraction grating with 600 lines mm$^{-1}$ at a tilt angle of 11°23 was used, giving a wavelength range of approximately 4449–7581 Å (excluding small gaps due to CCD chip edges), with 37 km s$^{-1}$ (FWHM) resolution. A slit width of 0.9 arcsec was used on 2011 June 22 and of 0.7 arcsec on 2011 June 26 and 2010 June 5.7. Sixty useful spectra were obtained, with exposures of 420–600 s, covering a total of approximately 1.5 orbital periods (Table 1).
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Figure 1. Smoothed average continuum-subtracted spectra of V926 Sco for the nights of 2010 June 5, 2011 June 22, and 2011 June 26 show Hα, Hβ, He II λ4686 & λ5412, C IV λ5807, He I λ4922 & λ6678, and the blend of N III and C III emission (λλ4634–4651) comprising the Bowen complex. Interstellar lines are marked as IS.

Table 1
Observation Log

| Date       | UTC (Start) | UTC (End) | MJD (Start) | MJD (End) | Phase Coverage | No. of Spectra | Exposure(s) |
|------------|-------------|-----------|-------------|-----------|----------------|----------------|-------------|
| 2010 Jun 5 | 00:39:20    | 04:18:51  | 55353.0273  | 55353.1798 | 0.22–1.01      | 15             | 420–600     |
| 2010 Jun 7 | 01:00:45    | 01:42:32  | 55355.0422  | 55355.0712 | 0.99–1.14      | 4              | 600         |
| 2011 Jun 22| 05:54:58    | 09:02:57  | 55735.2465  | 55735.3770 | 0.76–0.44      | 15             | 600         |
| 2011 Jun 26| 01:59:24    | 07:08:33  | 55739.0829  | 55739.2976 | 0.18–1.29      | 26             | 600         |

Figure 2 shows the evolution of the main spectral features over the orbital period. We use the spectroscopic ephemeris of Casares et al. (2006) to determine orbital phases:

\[ T_o(\text{HJD}) = 2452813.495(3) + 0.19383351(32)E \]

where \( T_o \) is defined as the compact object superior conjunction. Hα and He II λ4686 display the classic double peak variation, with the peak shifting from red to blue over the orbital period as expected for emission from an accretion disk. The Bowen complex varies in strength over the orbit but does not show the double peak behavior. In order to determine the relative contribution of the spectral features, we fit the average nightly profiles with Gaussians. For the Bowen blend we used Gaussians representing the N III transitions (λλ4634, 4641, 4642) and C III transitions (λλ4647, 4651, 4652). For Hα, He II λ4686, and He I λ6678 we used two Gaussians each to represent the blue and red shifted emission from the disk. For all lines we used single Gaussians (for Bowen this was at λ4641) to determine the instrumental EW. The fits are plotted in Figure 3 and values for the fitted parameters are listed in Table 2. For the 2011 data, where we had full phase coverage, we also calculated EWs as a function of orbital phase (Figure 4). The EWs increase every three exposures. The images were corrected for bias and flat-fielded, then the spectra were extracted using IRAF optimal extraction for a weak spectrum, as described by Massey et al. (1992), to give the best possible signal to noise ratio. Anomalies due to cosmic rays and CCD errors were removed. The spectra were wavelength-calibrated using the time-nearest HeNeAr comparison arcs, with a separate second order polynomial fit of each of the four CCD chips across which the spectra were spread. In each case, the rms scatter was < 0.01 Å. The flux standard Feige 110 was observed on the night of 2011 June 22. However, since none of our nights were photometric, we plot only relative intensities and give equivalent widths (EWs) in instrument counts.

3. SPECTRAL FEATURES AND PROFILES

The spectra of V926 Sco averaged over the nights of 2010 June 5 and June 22 and 2011 June 26 are presented in Figure 1. Each contains relatively strong Hα emission in addition to weaker lines of Hβ, He II λ4686 & λ5412, He I λ4922, and a blend of N III and C III emission lines (λλ4641–4651) attributed to Bowen fluorescence, C IV λ5807, and He I λ6678. These emission features are consistent with those found by previous spectroscopic studies (Casares et al. 2006; Cowley et al. 2003; Augusteijn et al. 1998; Smale & Corbet 1991). Several absorption features attributed to interstellar and atmospheric absorption are also present.
Figure 2. Left (a): Hα spectra from 2010 in 10 phase bins, showing the evolution of the lines over the orbital period. The dashed line marks the laboratory wavelength of $\lambda 6562.8$. Center (b): as in (a) for 2011 June 26. Left (c): 2011 data of and HeⅡ and the Bowen blend in 10 phase bins, showing the evolution of the lines over the orbital period. The dashed lines represent $\lambda 4640$ and $\lambda 4686$.

Figure 3. Gaussian fits to Hα, HeⅠ $\lambda 6678$, the Bowen complex, HeⅡ $\lambda 4686$, and Hβ for each of the nights listed in Table 1. Values of the fitted parameters are listed in Table 2. Left (a): Hα and HeⅠ $\lambda 6678$ both showed the classic double peak expected from emission from an accretion disk and required two Gaussians for good fits. Right (b): fits using two Gaussians for the Bowen blend: $\lambda 4634$ and $\lambda 4641$. HeⅡ $\lambda 4686$ and Hβ also displayed double peaks and required two Gaussians. (A color version of this figure is available in the online journal.)

between phases 0.5–0.8 consistent with emission from the disk bulge. The source appears to be reduced in intensity from 2010 to 2011; however since we do not have absolute fluxes we cannot determine this. We do find that the EW of the Bowen complex is significantly reduced from 2010 to 2011. Since the 2010 phase coverage is poor, for the Bowen complex we construct tomograms only for the 2011 data. The reduction in flux observed for 2011 June 22 compared to 2011 June 26 is attributed to the larger slit size used due to poor seeing. The increase in slit size also reduced our spectral resolution; hence
Figure 4. Equivalent widths for the 2011 data in 10 phase bins. The phase of peak equivalent width (0.7) is consistent with emission from the disk bulge. The 2010 data do not have sufficient phase coverage to warrant phase resolved values.

Table 2

| Line               | FWHM (km s\(^{-1}\)) | EW (Inst Cts) | Centroid (Å) |
|--------------------|------------------------|---------------|--------------|
| 2010 Jun 5         |                        |               |              |
| Bowen blend        | 956 ± 31               | 23.1 ± 1.5    | 4641.1       |
| He II λ4686        | 420 ± 20               | 23.5 ± 2.0    | 4685.6       |
| Hβ                 | ...                    | ...           | 4860.9       |
| Hα                 | 417 ± 10               | 60.6 ± 2.6    | 6561.2       |
| He I λ6678         | ...                    | ...           | 6678.0       |
| 2010 Jun 7         |                        |               |              |
| Bowen blend        | 710 ± 39               | 23.0 ± 2.4    | 4640.1       |
| He II λ4686        | 425 ± 23               | 41.3 ± 4.3    | 4686.1       |
| Hβ                 | ...                    | ...           | 4860.9       |
| Hα                 | 419 ± 10               | 69.2 ± 5.1    | 6562.3       |
| He I λ6678         | ...                    | ...           | 6678.0       |
| 2011 Jun 22        |                        |               |              |
| Bowen blend        | 770 ± 63               | 6.9 ± 1.0     | 4641.9       |
| He II λ4686        | 380 ± 25               | 11.5 ± 1.4    | 4684.6       |
| Hβ                 | 313 ± 65               | 4.2 ± 1.6     | 4860.3       |
| Hα                 | 394 ± 10               | 37.3 ± 1.8    | 6561.8       |
| He I λ6678         | ...                    | ...           | 6679.9       |
| 2011 Jun 26        |                        |               |              |
| Bowen blend        | 928 ± 33               | 11.3 ± 1.0    | 4641.3       |
| He II λ4686        | 383 ± 11               | 24.3 ± 1.3    | 4684.7       |
| Hβ                 | 283 ± 24               | 8.9 ± 1.5     | 4859.8       |
| Hα                 | 379 ± 9                | 65.1 ± 1.6    | 6581.3       |
| He I λ6678         | 483 ± 28               | 10.7 ± 1.2    | 6676.8       |

Figure 5. Radial velocity curves for Hα and He II λ4686 using the spectroscopic ephemerides of Casares et al. (2006). 1σ errors and the best-fit sinusoid are indicated. The derived systemic velocity using Hα is 109 ± 4 km s\(^{-1}\).

Tomography is an imaging technique allowing two-dimensional velocity-space maps of a system to be reconstructed from spectra taken at multiple orbital phases. Spectra are assumed to be one-dimensional projections of the system in velocity space at a given phase. Under this assumption, if an accurate ephemeris is known an inversion technique can be used for our tomographic analysis of Hα and He II λ4686 we use data from 2010 June 5 and 2011 June 26. The four spectra obtained on 2010 June 7 were used only to complete the radial velocity curve.

Figure 5 shows the radial velocities for Hα and He II λ4686 obtained by cross-correlating all 60 individual spectra with Gaussians of FWHM as listed in Table 2. We used the spectroscopic ephemerides of Casares et al. (2006) as listed above. The curves are in antiphase with that expected from the secondary and consistent with emission from the disk. Our best-fit sine-wave to the Hα data give us a systemic velocity of −109 ± 4 km s\(^{-1}\) with a semi-amplitude of 95 ± 5 km s\(^{-1}\). Our systemic velocity is consistent (within 2σ) with the value (121 ± 7 km s\(^{-1}\)) found by Casares et al. (2006) when using the wings of their He II λ4686 profile (which are expected to follow the motion of the compact star) and our errors are a factor of two smaller. Our He II λ4686 is weak compared to Hα but its radial velocity curve peaks at the same phase as Hα.

4. TOMOGRAPHY
to produce possible fits to the data. In this case, a reduced $\chi^2$ test was used to modify an arbitrary starting image (e.g., a uniform or Gaussian distribution) such that the predicted data from this image fit the real data. Due to the large number of possible fits for a given value of $\chi^2$, the “Maximum Entropy Method” is employed to select the image which is most likely to be accurate; the image with the highest entropy is chosen at each iteration, on the assumption that a higher entropy corresponds to a smoother and therefore more physically realistic image of the system (Narayan & Nityananda 1986). For a complete description of imaging accretion disks using Doppler tomography, see Marsh & Horne (1988).

Modulation tomography produces additional velocity maps showing the magnitude of periodic, sinusoidal modulations in the brightness of the structural features of the system, in addition to the velocity maps of the time-averaged brightness seen in Doppler tomography. This allows variations in the brightness of a system to be taken into account when interpreting the time-averaged velocity maps. Although modulation tomography allows more accurate interpretation of velocity data than Doppler mapping alone, which assumes emission to be constant over the orbital period, data with a higher signal to noise ratio is required. For a more detailed description of modulation tomography of emission lines, see Steeghs (2003).

The modulation tomograms we produced are shown in Figures 6(a), (b), and 7(b). In each case, the figure is split into four panels. The upper two panels contain the trail of the original spectra around the chosen emission line on the left and the trail predicted from the final velocity map, for which $\chi^2$ is minimized, on the right. Lighter colors indicate higher intensities in each case. Each figure also contains two-dimensional velocity maps. The lower left panel is the same as those produced by Doppler tomography, showing the brightness of the components of the system averaged over the orbital period. The lower right panel shows the amplitude of modulations in the brightness of the components of the system which are harmonic with the orbital period. In this case, bright areas indicate the regions with the greatest amplitude of modulation.

Each of the tomograms is overlaid with estimated values for the velocities of the neutron star, the donor’s Roche lobe and the center of mass of the system. We used $K_2 = 298 \pm 83 \text{ km s}^{-1}$ as determined by Casares et al. (2006). Since Casares et al. suggested a range (0.05–0.41) of mass ratios for V926 Sco we adopted their middle value of 0.23, giving a $K_1$ of 68 km s$^{-1}$. We tried both our derived value of $-109 \pm 4 \text{ km s}^{-1}$ and the value used by Casares et al. ($-140 \pm 4 \text{ km s}^{-1}$) for the systemic velocity. Tests using a range of values near these velocities favored our derived value for the best fits. The Keplerian velocity of the disk along the accretion stream and the ballistic trajectory of the stream are also plotted, with circles along each line indicating steps of 0.1 Lagrangian radii from the compact object.

Because the time-averaged Hα and He $\Pi \lambda 4686$ showed little change in FWHM and EW between 2010 June 5 and 2011 June 26, we were able to combine the data to improve our modulation tomograms. Doppler tomograms for both years are consistent with the modulation tomograms but show less detail, so we present only the modulation tomograms in this paper. Both lines show significant enhancement of emission in the lower left quadrant of the lower left panel (Figures 6(a) and (b)); the corresponding modulation maps also show strong variation around these regions as would be expected of any non-symmetric feature in the system. The enhanced regions are
Figure 7. Tomograms of the N\textsc{iii} λ4640 component of the Bowen complex from 2011. Left (a): Doppler tomogram. Right (b): modulation tomogram. (A color version of this figure is available in the online journal.)

superposed on crescent shaped emission with the Hα tomogram showing a second crescent in the upper right quadrant of the lower left panel.

Since the EW of the Bowen complex changed by a factor of two from 2010 to 2011 we made separate tomograms for the two years. Because of the complexity and weakness of the Bowen blend, we first constructed Doppler tomograms. When the complex was stronger (2010) we had 0.9 phase coverage in only 12 bins, which led to poor maps and indeed showed only noise. In 2011, although the complex was weak, we had full phase coverage with over 20 phase bins (Figure 7(a)), and found a hint of emission consistent with the disk bulge but no emission associated with the secondary as reported by Casares et al. (2006). A modulation tomogram of the 2011 data shows the same behavior as the Doppler map for 2011 (Figure 7(b)); however, as the phased spectra in Figure 2(c) demonstrate, there is no variation in amplitude within errors of measurement.

5. DISCUSSION AND CONCLUSIONS

Modulation tomography of the Hα and He\textsc{ii} λ4686 emission lines in the spectra of V926 Sco were found to support the suggestion of earlier authors (Casares et al. 2006; Augusteijn et al. 1998; Smale & Corbet 1991) that the accretion disk around the primary contains a large, extended bright region, attributed to a bulge in the disk.

Our observations show significant changes in the disk and secondary star emission from V926 Sco, both since the 2003 observations of Casares et al. (2006) and between 2010 and 2011 in our own observations. We find that the FWHM of the Bowen complex, He\textsc{ii} λ4686, and Hβ are lower by a factor of about two compared to those reported by Casares et al. (2006). This suggests significantly lower velocities present in the system. While we only have EW in instrumental counts, we find that the EW of the Bowen complex is of the same order or considerably less than the EW of He\textsc{ii} λ4686, whereas Casares et al. found the EW of the Bowen complex to be twice that of He\textsc{ii} in 2003.

A significant reduction in X-ray emission is seen over the same period in the RXTE/ASM light curve of the system; the

Figure 8. RXTE/ASM light curve of V926 Sco. Marked in blue is the time of optical observations taken in 2003 June by Casares et al. (2006), times of our optical observations, made in 2010 and 2011 June are marked in red. The X-ray count rate during the current observations, 11 ± 3 counts s\(^{-1}\) (2011) and 8 ± 3 counts s\(^{-1}\) (2010) represent upper limits since the gain of the RXTE/ASM was higher during its last two years of operation (R. Remillard, private communication) and are significantly lower than during the 2003 observation (18 ± 2 counts s\(^{-1}\)). (A color version of this figure is available in the online journal.)

X-ray flux has decreased from an average of approximately 18 ± 2 counts s\(^{-1}\) in 2003 to approximately 11 ± 3 counts s\(^{-1}\) in 2010 and 8 ± 3 counts s\(^{-1}\) in 2011 (see Figure 8). In particular, since the 2010–2011 data were obtained during the last two years of the operation of RXTE, during which it is known that the ASM was running at a higher gain than that used for calibration, the real count rate is likely to be even lower. This indicates a reduction in the accretion rate of the system. Since Bowen fluorescence of the secondary is attributed to UV heating of
the secondary surface by irradiation, the lower accretion rate is consistent with there being lower flux from the disk and compact object and hence less illumination to produce Bowen from the secondary.

In both Hα and He II λ4686 we see crescent shaped emission as seen by Casares et al. (2006) from He II. This suggests the possibility of an eccentric disk, a phenomenon that occurs at mass ratios below $\sim$0.33 (Haswell et al. 2001). Normally, the comparatively large mass of the compact object, together with conservation of angular momentum, leads to the formation of a circular accretion disk centered on the compact object. Below this mass ratio, however, the 3:1 resonance has been found to cause eccentric instability, leading to a non-axisymmetric, precessing disk (Haswell et al. 2001). In these cases, we would expect so called “superhumps” to be observed in the light curve of the system (Calvelo et al. 2009; Zurita et al. 2002). While superhumps have not been detected in photometric studies of V926 Sco (e.g., Corbet et al. 1986; Pederson et al. 1981) an eccentric disk cannot be ruled out. Higher resolution observations at different epochs are required to either confirm or refute this possibility. The offset crescent shapes seen in the strong Hα tomogram may also suggest that angular momentum in the disk is being transported by density waves in the disk. This behavior has been seen in tomography of certain Cataclysmic Variables (Steeghs et al. 2000) and references therein). Steeghs et al. (2000) showed that two-armed trailing spirals in position coordinates map into two-armed crescent shapes in velocity coordinates.

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**Facilities:** Magellan:Baade, RXTE

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