Optical Spectroscopy of V635 Cassiopeiae/4U 0115+63

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Abstract. V635 Cas is the optical counterpart of the X-ray binary system 4U 0115+63. It was previously tentatively identified as a Be star based on its optical colours and the presence of Hα emission. Our observations indicate that it is an O9e star. This is the first direct determination of this star’s optical spectral type. The presence of a hotter companion star may in part explain the large temporal variation observed in this system.

Extreme variability was observed in 1992 February when both the Hα and a series of Paschen lines changed from emission to absorption. This was interpreted as a disk-loss event and it is the first time that it has been observed in this system. We use far red spectra of V635 Cas to probe the circumstellar disk, discussing the various line formation regions. The lines observed are consistent with a late type Oe star.

The flux standard Hiltner 102 was also observed. Although it is classified as a B0 III star, we re-classify it as a O9.7 II star with a slight nitrogen enhancement.

Key words: stars:circumstellar matter – stars:emission line, Be – stars:binary:neutron stars

1. Introduction

The system V635 Cas/4U 0115+63 is a Be X-ray binary star system (BeXRB) with a 3.61s spin period and a 24.3 day orbital period (Cominsky et al. 1978; Rappaport et al. 1978). The optical counterpart, V635 Cas, was tentatively classified as a early type Be star based on its optical colours and the presence of variable Hα and occasional Hβ emission (Johns et al. 1978; Kriss et al. 1983; Hutchings & Crampton 1981). The temporal evolution of V635 Cas is very different from that of other BeXRBs. The X-ray outbursts from the neutron star are varied in strength but typically last for a month. The associated optical and infrared activity is far more prolonged, lasting typically ~6 months. Unlike many BeXRBs the peak in the X-ray flux is not centred on periastron passage. This suggests that it is the episodic equatorial mass loss from the companion star which is the trigger for each outburst. Mendelson & Mazeh (1991) concluded that X-ray outbursts occur when the optical outburst is relatively long (~200 days) and strong (~1 mag). X-ray emission during weaker optical outbursts is not seen due to centrifugal inhibition of matter and the propeller effect (Kriss et al. 1983; Mendelson & Mazeh 1991).

Negueruela et al. (1997, Paper I) discuss the May-June 1994 X-ray outburst in the context of long term observations of V635 Cas. We conclude that the large variations in optical luminosity originate in the Be circumstellar envelope and not an accretion disk around the neutron star. The orbit of the neutron star is relatively close to the companion and its gravitational pull may play an important role in the evolution of the circumstellar disk.

In this paper we present two data sets that can be used to constrain the physical and geometric models for the circumstellar disk. The companion’s spectral type is a critical parameter for modelling the disk. However this is hard to derive as many of the companion stars in the BeXRBs are faint and the photospheric lines are often filled in with disk emission. Many of the systems have a spectral classification based on optical colours. In Sect. 3.1 we present the first blue spectra of V635 Cas with sufficient signal to noise to derive a spectral class.

The disks in Oe/Be stars are highly variable. We need a database of high quality data in order to model the evolution of the disk size, temperature and density. In Sect. 3.2 we present the first far red optical spectra obtained for this system.

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2. Observations

2.1. Blue Spectra

The spectra were obtained in service mode with the William Herschel Telescope, La Palma using ISIS with the TEK CCD camera and the R600B (0.79 Å pixel\(^{-1}\) dispersion, range \(\lambda\lambda 6350-6750\) Å) and R1200R (0.41 Å pixel\(^{-1}\) dispersion, 0.8 Å pixel\(^{-1}\) resolution, range \(\lambda\lambda 3900-4700\) Å) gratings (Carter et al. 1993). The simultaneous observations of H\(_\alpha\) allowed us to assess any emission component that may be present in the bluer Balmer lines. H\(_\alpha\) was in emission at this time, see Paper I.

V635 Cas was observed over two nights (900s and 2\times 1500s on 1993 December 18 and 2\times 1000s on 1993 December 19). The flux standard Hiltner 102 was also observed (300s on 1993 December 18). The seeing was poor on 1993 December 18. The data were reduced using the FIGARO and DIPSO packages (Shortridge & Meyerdicks 1996; Howarth 1996).

Figure 1 is a plot of V635 Cas (upper) and Hiltner 102 (lower) obtained on 1993 December 19 and 18, respectively. The data have been smoothed with a Gaussian (\(\sigma = 2\), width = 5 pixels, 1 pixel = 0.8 Å). To normalise the spectra we fitted a third order polynomial to the continuum and then divided the spectra by this fit.

2.2. Red Spectra

The far red spectra (\(\lambda\lambda 6400-8900\) Å, 5 Å pixel\(^{-1}\) dispersion, 11 Å resolution) were obtained using the all-transmission Mark IIIa spectrograph on the 1.3m McGraw-Hill telescope at Michigan-Dartmouth-MIT Observatory, Kitt Peak, Arizona. The detector was a TI-4849 CCD, inside the BRICC camera (Luppino 1989), except on 1991 October 27, when a Thomson chip was used. All spectra were taken through a 2.2′′ slit, with exposure times of 1800 s. There was cirrus on 1991 October 20.

Spectra of hot stars were taken to map the telluric atmospheric bands in this part of the spectrum, which were removed using the methods of Wade & Horne (1988). There is a wrinkle in the spectra at 7600 Å due to the removal of the A-band which is the strongest atmospheric feature. There is also an atmospheric absorption band in the region P11 to P7. Each time a spectrum of V635 Cas was taken, one spectrum each of two flux standards were also taken. These were G191B2B (Oke 1974) and HD 194445 (Oke & Gunn 1983). Comparing the individual spectra of these standards, taken at different epochs, we found the relative fluxes in the spectra to be consistent to within a few percent. Errors in relative fluxes due to losses from an unrotated slit were therefore not serious, unsurprising since these spectra are all so red (Filippenko 1982).

Absolute fluxes were another matter: we estimate from the same spectra that the absolute flux levels should not be trusted to within 30%. Although this will effect flux measurements of the lines, it will not affect equivalent width or velocity measurements. The instrumental uncertainties do not account for the upturn in the spectrum on 1991 October 27 and we believe this to be real.

The \(\lambda\lambda 6400 – 7500\) Å and \(\lambda\lambda 7600 – 8900\) Å spectra are given in Fig. 2. The 1991 October 20 spectrum has been normalised to the continuum value at 7264 Å as the night was not photometric.

Tables 2 and 3 list the dereddened line fluxes. The spectra were dereddened assuming a standard Galactic extinction law (Rieke & Lebofsky 1985; Howarth 1983) and \(E(B – V) = 1.5\) (Hutchings & Crampton 1981).

3. Discussion

3.1. Spectral Classification

The spectral class of V635 Cas was determined by comparison with Hiltner 102 and the standards published by Walborn & Fitzpatrick (1990). The Walborn (1971) scheme hinges on the ratios of neutral and singly-ionised helium and the first three ions of silicon.

The comparison with the standard star Hiltner 102 which is identified as a B0 III in the Simbad database led us to reclassify Hiltner 102 as a O9.7 II star. The spectral classification was based on the He\(_\Pi\) \(\lambda 4541\) Å/He\(_i\) \(\lambda 4387\) Å and the He\(_\Pi\) \(\lambda 4200\) Å/He\(_i\) \(\lambda 4144\) Å ratios. For an O9.7 star the strength of the He\(_\Pi\) \(\lambda 4541\) Å \~ Si\(_\III\) \(\lambda 4552\) Å. The luminosity class was determined from the Si\(_\IV\) \(\lambda 4089\) Å/He\(_i\) \(\lambda\lambda 4026, 4121, 4144\) Å and the Si\(_\IV\) \(\lambda 4116\) Å/He\(_i\) \(\lambda 4121\) Å ratios. Hiltner 102 may have a slight nitrogen enhancement.

V635 Cas is harder to classify due to two factors. It is fainter than Hiltner 102 (\(V = 15.5\) vs. Hiltner 102, \(V = 10.42\)) and the disk emission causes the filling in
Table 1. The Observed Lines in The Far Red CCD Spectra

| Element | λ_{lab} \ Å | λ_{obs} \ Å | Notes |
|---------|-------------|-------------|-------|
| Fe ii   | 6473.9      | 6481        |       |
| Fe ii   | 6506.3      | 6506        |       |
| Hα      | 6562.8      | 6562        |       |
| He i    | 6786.15     | 6787        |       |
| C ii    | 7236        | 7235        |       |
| He i    | 7281.35     | 7280        |       |
| K i     | 7664.90     | 7662        |       |
| O i     | 7771.96     | 7769        |       |
| P19     | 8413.32     | 8411        | blended with P18 |
| O i     | 8426.16     | 8436        | blended with P18 |
| P18     | 8437.96     | 8436        |       |
| P17     | 8467.26     | 8464        |       |
| Ca ii   | 8498.02     | 8499        | blended with P16 |
| P16     | 8502.49     | 8502.49     |       |
| Ca ii   | 8542.09     | 8542        | blended with P15 |
| P15     | 8545.39     | 8545        |       |
| P14     | 8598.39     | 8596        |       |
| Ca ii   | 8662.14     | 8662        | blended with P13 |
| P13     | 8665.02     | 8662        |       |
| N i     | 8629.2      | 8630.65     | lines blended |
| 8680    | 8703        | 8712.9      |       |
| P12     | 8750.5      | 8748        |       |
| P11     | 8862.79     | 8862        |       |

Line identification from Meinel et al. (1975); the line centres can vary due to blending; the presence of O i 8446 Å and Ca ii triplet can only be inferred by an increase in the relative strengths of the Paschen lines. The N i and K i are only suspected to be present, see text.

3.2. Probing The Circumstellar Disk

No far red optical spectra have been previously published for V635 Cas. Dramatic spectral variability occurred. The Hα line changed from emission to absorption on a timescale of four months or less (Unger 1993). This is the first time that a phase change has been seen in this system. The phase change was also reflected in the Paschen and He I lines and by the low in the JHK lightcurve. We interpreted this as a disk loss event which was discussed by Unger (1993) and in Paper I. Here we will interpret the emission line data.

With sufficient resolution many of the emission lines in Be stars are double peaked. Huang (1972) interpreted this in terms of a simple model consisting of a disc rotating about the star. The outer radius of the emission region can be estimated using the ratio of the peak separation to the star’s rotational velocity. The spectral resolution of our observations is not sufficient to show the expected double peak structure of the lines. Previous Hα spectra of higher resolution (0.8 Å dis-
Table 3. Line Parameters P19 λ 8413 Å–P11 λ 8863 Å

| TJD† | Date     | Line | EW | Flux†† |
|------|----------|------|----|-------|
| 8546 | 91 Oct 16| P19  | −0.6| 0.24  |
| 8550 | 91 Oct 20| 8413 | −1.2|       |
| 8557 | 91 Oct 27|      | −   |       |
| 8672 | 92 Feb 19|      | −   |       |
| 8546 | 91 Oct 16| P18* | −1.8| 0.68  |
| 8550 | 91 Oct 20| 8438 | −3.2|       |
| 8557 | 91 Oct 27|      | −1.3| 1.03  |
| 8672 | 92 Feb 19|      | −   |       |
| 8546 | 91 Oct 16| P17  | −2.3| 0.83  |
| 8550 | 91 Oct 20| 8467 | −2.1|       |
| 8557 | 91 Oct 27|      | −1.7| 1.3   |
| 8672 | 92 Feb 19|      | −   |       |
| 8546 | 91 Oct 16| P16* | −3.4| 1.18  |
| 8550 | 91 Oct 20| 8502 | −4.2|       |
| 8557 | 91 Oct 27|      | −3.4| 2.52  |
| 8672 | 92 Feb 19|      | −   |       |
| 8546 | 91 Oct 16| P15* | −4.6| 1.55  |
| 8550 | 91 Oct 20| 8545 | −5.3|       |
| 8557 | 91 Oct 27|      | −3.8| 2.71  |
| 8672 | 92 Feb 19|      | −   |       |
| 8546 | 91 Oct 16| P14  | −6.4| 2.01  |
| 8550 | 91 Oct 20| 8598 | −6.4|       |
| 8557 | 91 Oct 27|      | −5.23| 3.66 |
| 8672 | 92 Feb 19|      | −   |       |
| 8546 | 91 Oct 16| P13* | −6.1| 1.87  |
| 8550 | 91 Oct 20| 8665 | −8.7|       |
| 8557 | 91 Oct 27|      | −4.4| 3.07  |
| 8672 | 92 Feb 19|      | +0.8| 0.43  |
| 8546 | 91 Oct 16| P12  | −5.3| 1.57  |
| 8550 | 91 Oct 20| 8750 | −5.8|       |
| 8557 | 91 Oct 27|      | −6.2| 4.25  |
| 8672 | 92 Feb 19|      | +0.6| 2.83  |
| 8546 | 91 Oct 16| P11  | −4.5| 1.21  |
| 8550 | 91 Oct 20| 8863 | −2.9|       |
| 8557 | 91 Oct 27|      | −3.8| 2.66  |
| 8672 | 92 Feb 19|      | +2.9| 1.44  |

† TJD = JD − 2440000; †† Flux × 10^{-13} erg s^{-1} cm^{-2} The line fluxes have been dereddened - see text. * blended, see Table 1.

3.2.1. He i Lines
The He i emission is clearly seen at λ 6678 Å and λ 7065 Å on 1991 October 16 and 27. Hence the line at λ 7281 Å is probably He i and not an artifact introduced by the removal of the variable telluric H₂O absorption band.

3.2.2. Paschen Lines
Generally, Be stars with earlier spectral type have stronger emission in Paschen lines (Andrillat et al. 1990). We observe P19–P11 in emission on 1991 October 16 and 20, and weaker emission from P18–P11 on 1991 October 27. The emission lines disappear, with P13, P12 and P11 in absorption on 1992 February 19.

We hoped to be able to constrain the electron density in the disk by investigating the relative Paschen line strengths. The line fluxes were dereddened using a standard Galactic law, $R = A(V)/E(B − V) = 3.1$ (Rieke & Lebofsky 1985; Howarth 1983) and assuming $E(B − V) = 1.5$ for V635 Cas (Hutchings & Crampton 1981). It is difficult to fix the continuum level between the various Paschen lines due to the broad emission wings and blending with other lines (see Table 1).

Line ratios were calculated for the unblended lines (i.e. P19, P17, P14, P12, P11). We estimate that the errors in the line fluxes are ~30%. These ratios were compared with case B optically thin recombination line strengths for a $T_e = 10^4$ K, $n_e = 10^8$ cm$^{-3}$ and $T_e = 10^4$ K, $n_e = 10^{10}$ cm$^{-3}$ plasma (Hummer & Storey 1987; Storey & Hummer 1995). The line ratios were also compared with the optically thick line ratios based on the simple assumption that the disk is a $T = 10^4$ K blackbody with the same line widths and emitting areas for all the observed Paschen lines.

General results for Be star systems indicate that Pβ and Pγ line ratios are well away from the case B values (Sellgren & Smith 1992) and that P19 and higher Paschen lines are consistent with optically thin emission (Briot 1981). However, these data have a turnover in the relative line strengths at both P17 and P11. For example on 1991 October 16 the relative line fluxes for P17, P14, P12, P11, normalised to P17 are 1.0:2:4:1:9:1.5. This means that we cannot constrain the disk density. For optically thin emission we would expect that the relative line strengths increase as you descend the Paschen series, the opposite is true for optically thick emission from a blackbody. To constrain these models we require observations of additional lines in the series and at a higher resolution so that the lines are not blended.
3.2.3. O\textsc{i} Lines

The O\textsc{i} λ 8446 Å emission is more frequent in early type stars (Andrillat et al. 1990) and if seen is always present in emission (Andrillat 1986). This line is blended with P18 and we would expect it to be in emission when the O\textsc{i} λ 7772-74-75 Å lines are in emission. The O\textsc{i} λ 8446 Å line has a greater tendency to go into emission than the O\textsc{i} λ 7772-74-75 Å line due to Bowen fluorescence (Bowen 1947). Assuming the lines are optically thin and adopting the P19 equivalent width for P18, which would underestimate the strength of P18, we obtain equivalent widths of -1.2 Å and -2.0 Å for O\textsc{i} λ 8446 Å on 1991 October 16 and 20, respectively. The measured equivalent widths of O\textsc{i} λ 7772-74-75 Å on 1991 October 16 and 20 are -0.5 Å and -1.6 Å, respectively. We may have underestimated the strength of the O\textsc{i} λ 8446 Å line but our values are well below the observed ratio of ~4 which has been reported for these lines in other Be stars (Jaschek et al 1993).

3.2.4. Other Possible Features

There are two absorption lines present in all the spectra at λ 7665 and λ 7699 Å which could be K\textsc{i} lines. These lines have low excitation potentials of 1.6 eV but more importantly the ionization potential of potassium is 4.3 eV, so any emission must be shielded from the strong UV flux, i.e the line is probably formed in the outer regions of the disk. Alternatively the K\textsc{i} lines could be due to interstellar absorption.

There are two possible Fe\textsc{ii} emission lines at ~6480 Å and 6508 Å. The Fe\textsc{ii} has a low excitation potential, ~4–5eV, and we may expect the line to be formed in the outer disk if we assume the excitation potential is correlated with the disk size as in the Balmer series. However, the Fe\textsc{ii} line can be subject to Ly\textsc{α} fluorescence and hence we could also see it in the inner parts of the disk (Sletstebak et al 1992). Higher resolution spectra to determine the positions of all of these lines and the individual peak separations are needed.

The emission line at λ 7235 Å is present in all the 1991 October spectra. Assuming it is not an artefact due to the removal of the telluric H$_2$O absorption band we tentatively identify it as C\textsc{ii} λ 7234 Å. This line is excitable by resonance fluorescence from the UV continuum and we would expect the line to be formed near the star (Williams & Ferguson 1983).

There are possibly some N\textsc{i} λλ 8629, 8680-83-86, 8703-12-19 Å emission lines. If neutral nitrogen is seen it is always in emission and it is more frequent in early type spectral classes (Jaschek et al 1992; Andrillat et al 1990).

Finally there is a possible emission feature at λ 8810 Å on 1991 October 27. Higher resolution spectra are needed to confirm the presence of these lines.
4. Conclusions

V635 Cas is now classified as an O9e star. We have demonstrated that a true spectral classification, although difficult to obtain, is needed to accurately model the BeXRBs. The filling in of critical lines by the disk emission precludes a determination of the luminosity class. We hope that future observations during a disk-loss event will improve on this result.

The far red spectra are an ideal probe of the circumstellar disk. Higher resolution spectra including additional lines in the Paschen series would enable us to confirm various line blends/strengths and measure the peak separation between the wings in the individual lines. This would enable us to model the size, density and velocity distribution in the disk. In particular the line profiles would help us parameterize the tidal effects of the neutron star at periastron.

Clearly this is a complex system as demonstrated by the dramatic spectral and photometric changes that occur on a short timescale of months. A precise determination of the spectral class, luminosity and $v\sin i$ requires frequent high resolution simultaneous multi-wavelength observations in order to catch the system in a disk-less state. In particular infrared observations of the H$\alpha$ lines are needed to further constrain the disk models.

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