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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: neutron – stars: individual: V635 Cas – stars: individual: Hiltner 102

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 (~1mag). 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.

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, 1.6 Å pixel^{-1} resolution, 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 obser-

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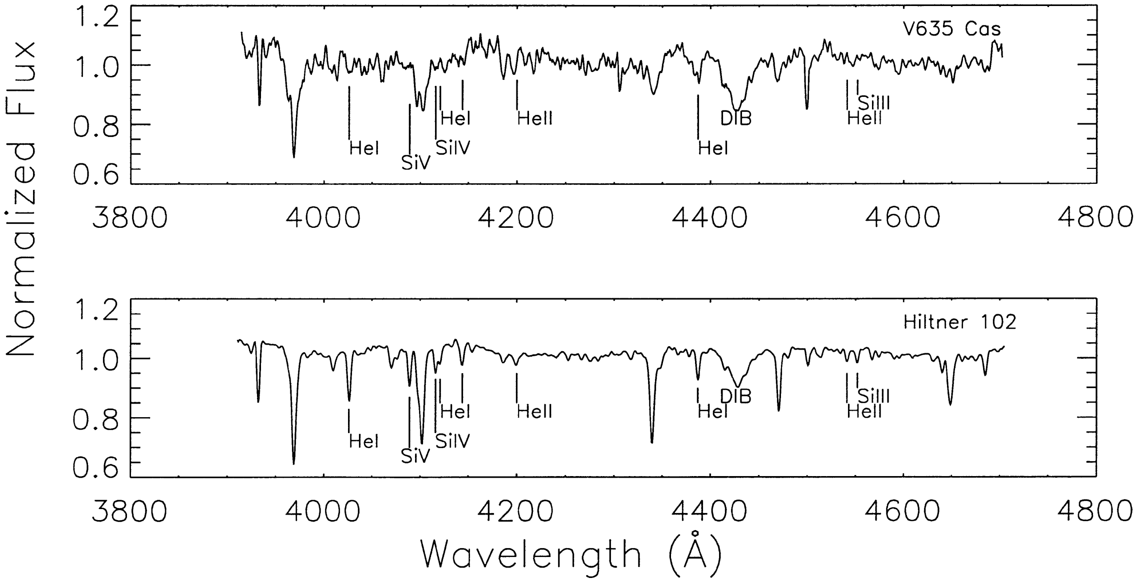

Fig. 1. $\lambda\lambda$ 3900 Å–4700 Å Spectra: V635 Cas (upper) and Hiltner 102 (lower)

vations of Hα allowed us to assess any emission component that may be present in the bluer Balmer lines. Hα was in emission at this time, see Paper I.

V635 Cas was observed over two nights (900 s and 2×1500 s on 1993 December 18 and 2×1000 s 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).

Fig. 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 (σ = 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 19445 (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 II λ 4541 Å/ He I λ 4387 Å and the He II λ4200 Å/ He I λ 4144 Å ratios. For an O 9.7 star the strength of the He II λ 4541 Å $\sim$ Si III λ4552 Å. The luminosity class was

Table 1. The observed lines in the far red CCD spectra

Element	λ_{lab} Å	λ_{obs} Å	Notes
FeII	6473.9	6481	
FeII	6506.3	6506	
Hα	6562.8	6562	
HeI	6678.15	6678	
HeI	7065.19	7064	
CII	7231	7235	
	7236		
HeI	7281.35	7280	
KI	7664.90	7662	
KI	7698.96	7698	
OI	7771.96	7769	
	7774.18		
	7775.40		
P19	8413.32	8411	
OI	8426.16		blended with P18
P18	8437.96	8436	
P17	8467.26	8464	
CaII	8498.02		blended with P16
P16	8502.49	8499	
CaII	8542.09		blended with P15
P15	8545.39	8542	
P14	8598.39	8596	
CaII	8662.14		blended with P13
P13	8665.02	8662	
NI	8629.2		lines blended
	8680–6		
	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 OI 8446 Å and CaII triplet can only be inferred by an increase in the relative strengths of the Paschen lines. The NI and KI are only suspected to be present, see text.

Table 2. Line Parameters Hα λ 6563 Å– OI λ 7772 Å

TJD†	Date	Line Å	EW Å	Flux††
8546	91 Oct 16	Hα	–15.2	13.6
8550	91 Oct 20	6563	–17.8	–
8557	91 Oct 27		–17.5	22.8
8672	92 Feb 19		+1.2	1.54
8546	91 Oct 16	HeI	–2.3	1.98
8550	91 Oct 20	6678	–	–
8557	91 Oct 27		–1.6	2.03
8672	92 Feb 19		+0.46	0.57
8546	91 Oct 16	HeI	–2.1	1.60
8550	91 Oct 20	7065	–	–
8557	91 Oct 27		–2.3	2.68
8672	92 Feb 19		+0.47	0.48
8546	91 Oct 16	HeI	–1.5	1.07
8550	91 Oct 20	7281	–1.3	–
8557	91 Oct 27		–0.4	0.46
8672	92 Feb 19		+1.2	1.1
8546	91 Oct 16	KI	+0.5	0.33
8550	91 Oct 20	7665	+1.4	–
8557	91 Oct 27		+0.5	0.50
8672	92 Feb 19		+0.6	0.43
8546	91 Oct 16	KI	+0.9	0.50
8550	91 Oct 20	7699	+0.9	–
8557	91 Oct 27		+1.0	0.89
8672	92 Feb 19		+1.0	0.72
8546	91 Oct 16	OI	–0.5	0.28
8550	91 Oct 20	7772	–1.6	–
8557	91 Oct 27		–	–
8672	92 Feb 19		–	–

† TJD = JD − 2440000;

†† Flux $\times 10^{-13}$ erg s^{-1} cm^{-2} The line fluxes have been dereddened – see text.

determined from the Si V λ4089 Å/ He I $\lambda\lambda$ 4026, 4121, 4144 Å and the Si IV λ 4116 Å/ He I λ 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 c.f. Hiltner 102, V = 10.42) and the disk emission causes the filling in of the bluer singly ionized hydrogen and helium lines. For example the filling in is evident in Hγ λ 4340 Å. In addition the HeII lines appear to be filled in. The strong He II λ 4200 Å absorption indicates that the star is earlier that previously assumed based on its optical colours: it is an 09e star.

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 HeI 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 dispersion, 1.6 Å resolution) indicate that the peak separation remains fairly constant and that it was $\sim$462 km s^{-1} in 1991 August 28 (Unger 1993). The unresolved spectra are consistent with either this or a narrower value.

3.2.1. HeI lines

The HeI 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

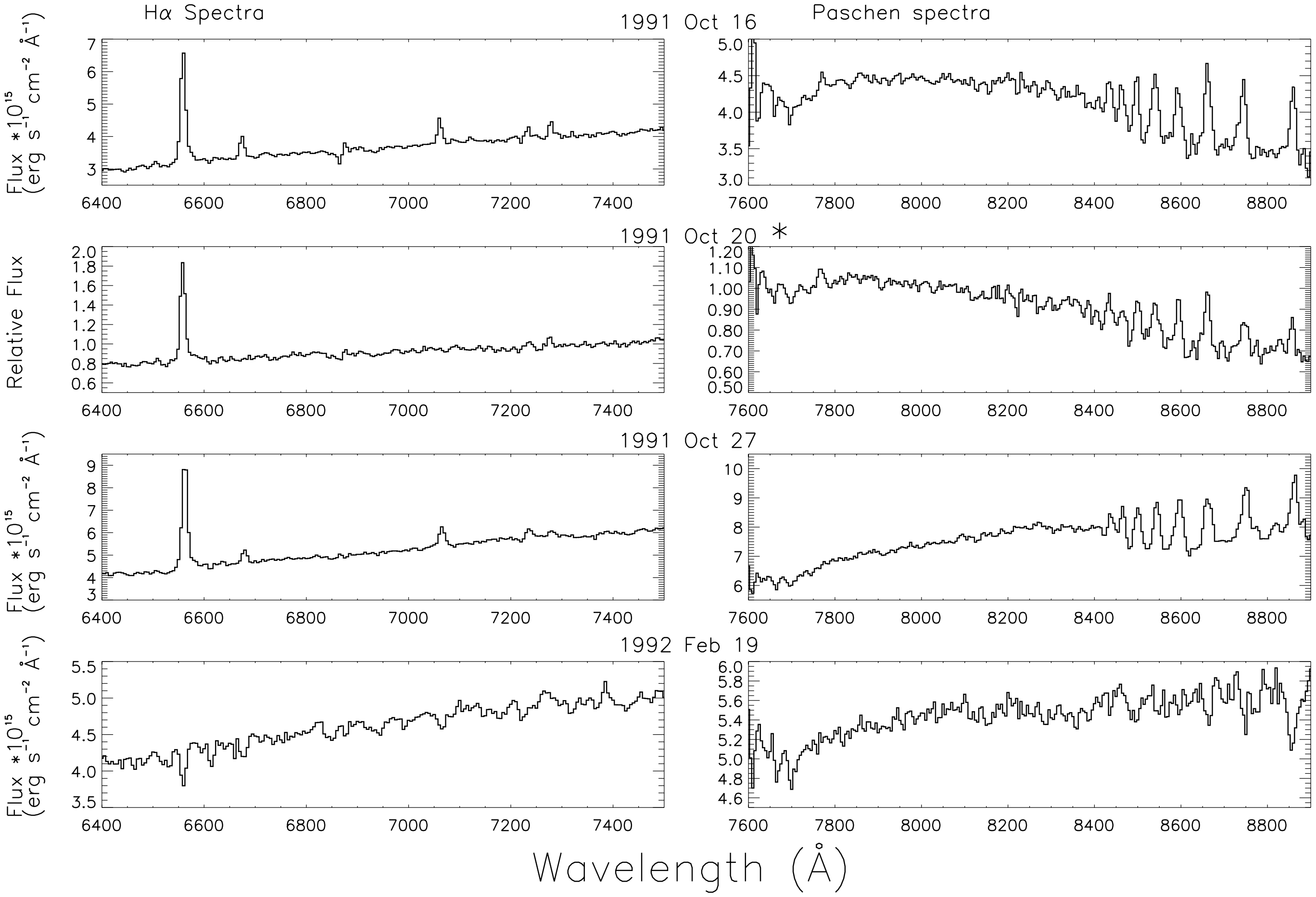

Fig. 2. V635 Cas $\lambda\lambda$ 6400 Å–8900 Å Spectra

HeI and not an artifact introduced by the removal of the variable telluric H_2O 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. OI lines

The OI 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

Table 3. Line Parameters P19 λ 8413 Å–P11 λ 8863 Å

TJD[†]	Date	Line Å	EW Å	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 $\times 10^{-13}$ erg s^{-1} cm^{-2} The line fluxes have been dereddened – see text.
[*] blended, see Table 1.

expect it to be in emission when the O I λ 7772-74-75 Å lines are in emission. The O I λ 8446 Å line has a greater tendency to go into emission than the O 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 under estimate the strength of P18, we obtain equivalent widths of -1.2 Å and -2.0 Å for O I λ 8446 Å on 1991 October 16 and 20, respectively. The measured equivalent widths of of O 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 I λ 8446 Å line but our values are well below the observed ratio of $\sim$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 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 I lines could be due to interstellar absorption.

There are two possible FeII emission lines at $\sim$6480 Å and 6508 Å. The FeII has a low excitation potential, $\sim$4–5 eV, 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 FeII line can be subject to Lyα fluorescence and hence we could also see it in the inner parts of the disk (Slettebak 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_2O absorption band we tentatively identify it as C 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 I $\lambda\lambda$ 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 $\sim$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 I lines are needed to further constrain the disk models.

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