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ASTRONOMY AND ASTROPHYSICS

The Be/X-ray transient 4U 0115+63/V635 Cas

I. A consistent model

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Abstract. We present photometry and high SNR spectroscopy in the classification region of V635 Cas, the optical counterpart to the transient X-ray pulsator 4U 0115+63, taken at a time when the circumstellar envelope had disappeared. V635 Cas is classified as a B0.2Ve star at a distance of $7-8$ kpc. We use the physical parameters derived from these observations and the orbit derived from X-ray observations to elaborate a model of the system based on the theory of decretion discs around Be stars. We show that the disc surrounding the Be star must be truncated by the tidal/resonant interaction with the neutron star and cannot be in a steady state. This explains many of the observed properties of 4U 0115+63. In particular, because of this effect, under normal circumstances, the neutron star cannot accrete from the disc, which explains the lack of regular Type I outbursts from the source.

Key words: stars: circumstellar matter – emission-line, Be – individual: 4U 0115+63, – binaries:close – neutron – X-ray: stars

1. Introduction

The hard X-ray transient 4U 0115+63 (X 0115+634) is one of the best studied Be/X-ray binary systems (see Campana 1996; Negueruela et al. 1997, henceforth N97). More than 50 of these systems, in which a neutron star orbits a Be star in a moderately eccentric orbit, are known (see Negueruela 1998; Bildsten et al. 1997). The Be star is surrounded by a disc of relatively cool material, presumably ejected from the star due to causes unknown, but generally believed to be associated with fast rotation, magnetic fields and/or non-radial pulsations (Slettebak 1988). The presence of the disc gives rise to emission lines in the optical and infrared spectral regions and an excess in the infrared continuum radiation.

The hard X-ray emission is due to the accretion of circumstellar material on to the neutron star companion. Due to their different geometries and the varying physical conditions in the circumstellar disc, Be/X-ray binaries can present very different states of X-ray activity (Stella et al. 1986). In quiescence, they display persistent low-luminosity ($L_{\rm x} \lesssim 10^{36}$ erg s^{-1}) X-ray emission or no detectable emission at all. Occasionally, they show series of periodical (Type I) X-ray outbursts ($L_{\rm x} \approx 10^{36}-10^{37}$ erg s^{-1}), separated by the orbital period of the neutron star. More rarely, they undergo giant (Type II) X-ray outbursts ($L_{\rm x} \gtrsim 10^{37}$ erg s^{-1}), which do not clearly correlate with the orbital motion. Some systems only display persistent emission, but most of them show outbursts and are termed Be/X-ray transients.

The transient 4U 0115+63 was first reported in the *Uhuru* satellite survey (Giacconi et al. 1972; Forman et al. 1978), though a search of the *Vela 5B* data base revealed that the source had already been observed by this satellite since 1969 (Whitlock et al. 1989). Precise positional determinations by the *SAS 3*, *Ariel V* and *HEAO-1* satellites (Cominsky et al. 1978; Johnston et al. 1978) were used to identify the system with a heavily reddened Be star with a visual magnitude $V \approx 15.5$ (Johns et al. 1978; Hutchings & Crampton 1981), which was subsequently named V635 Cas (Khopolov et al. 1981). Rappaport et al. (1978) used *SAS 3* timing observations to derive the orbital parameters of the binary system, which consists of a fast-rotating ($P_{\rm s} = 3.6$ s) neutron star in a relatively close ($P_{\rm orb} = 24.3$ d) and eccentric ($e = 0.34$) orbit around the Be star (see also Tamura et al. 1992).

Due to the fast rotation of the neutron star, centrifugal inhibition of accretion prevents the onset of X-ray emission unless the ram pressure of accreted material reaches a relatively high value (Stella et al. 1986; N97). The system had only be known to display Type II activity until a short series of Type I outbursts was detected by BATSE and *RXTE* in 1996 (Bildsten et al. 1997; Negueruela et

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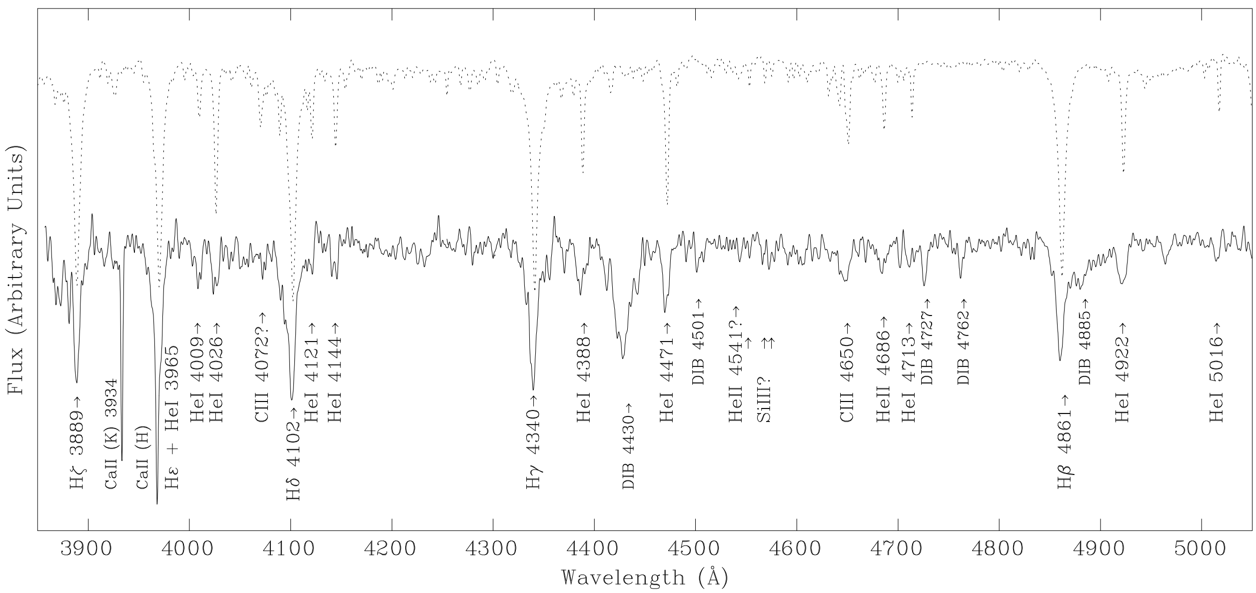

Fig. 1. The spectrum of V635 Cas in the classification region. Two exposures taken on November 14, 1997, with ISIS on the WHT equipped with the R1200B grating and the EEV10 camera have been combined for this figure. The comparison spectrum is that of the B0.2V standard τ Sco. Both spectra have been divided by a spline fit to the continuum for normalisation and smoothed with a $\sigma = 0.8$Å Gaussian function for display.

al. 1998). The giant outbursts are associated with large amplitude brightenings of the optical and infrared magnitudes of the counterpart (N97).

This is the first of two papers dedicated to providing a coherent picture of this system and understanding the implications of its unusual behaviour for the general class of Be/X-ray transients. Here we derive the astrophysical parameters of 4U 0115+63 and build a model for circumstellar disc around the Be star that allows us to understand the usual quiescent state of the system. In the second paper (Negueruela et al. 2000; henceforth Paper II), we will analyse the temporal evolution of this disc and investigate how its behaviour is connected with the X-ray activity of the source.

2. Observations

We present optical photometry and optical spectroscopy of V635 Cas, obtained, for the first time, when the emission component was almost completely absent.

2.1. Optical spectroscopy

Observations of the source were taken on November 14, 1997, using the Intermediate Dispersion Spectroscopic and Imaging System (ISIS) on the 4.2-m William Herschel Telescope (WHT), located at the Observatorio del Roque de los Muchachos, La Palma, Spain. The blue arm was equipped with the R1200B grating and the EEV10 CCD, which gives a nominal dispersion of ~ 0.22 Å/pixel over ~ 900 Å. The resolution at $\sim \lambda 4600$Å, estimated from the FWHM of arc lines, is ~ 0.7 Å. Two exposures were taken, centred on $\lambda 4250$Å and $\lambda 4650$Å. A combined spectrum is shown in Fig. 1.

The red arm was equipped with the R1200R grating and the Tek5 CCD, which gives a nominal dispersion of ~ 0.4 Å/pixel at Hα (the resolution is ~ 0.8Å at Hα). A similar observation has been attempted on July 19, 1997, but due to bad weather conditions, the blue spectrum is too noisy to be of any use. An Hα spectrum, though, was obtained using the same setting as in the November observations. The observations are displayed in Fig. 2. All the data have been reduced using the *Starlink* software packages CCDPACK (Draper 1998) and FIGARO (Shortridge et al. 1997) and analysed using FIGARO and DIPSO (Howarth et al. 1997).

2.2. Optical photometry

From the observations listed in Paper II, we have taken the dataset showing the faintest and bluest magnitudes, which corresponds to 1998 January 7. The values measured are $U = 17.05 \pm 0.10$, $B = 16.92 \pm 0.07$, $V = 15.53 \pm 0.04$, $R = 14.55 \pm 0.03$ and $I = 13.49 \pm 0.03$. As discussed in Paper II, these observations coincided with a disc-less phase of V635 Cas and should represent values close to the intrinsic magnitudes of the star. We note that the value for I is compatible with the faintest point measured by

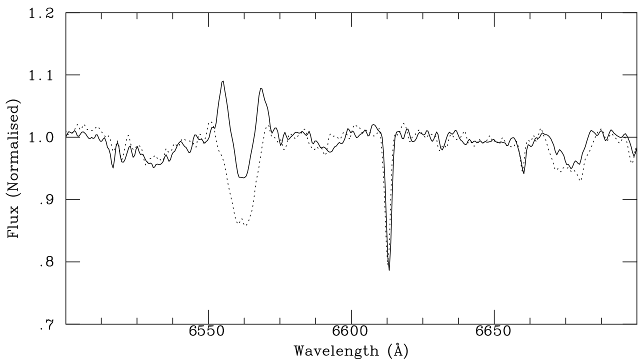

Fig. 2. High resolution spectra of V635 Cas showing the almost completely disc-less state observed in 1997. In the spectrum from July 19 (dashed line) only some residual emission is visible in the He I λ6678 Å line. In the November 14 spectrum, taken simultaneously with the blue spectroscopy, the disc is beginning to reform and some emission is present now in Hα. The peak separation corresponds to $\Delta v_{\rm peak} \approx 600\,{\rm km\,s^{-1}}$, well above what would be seen in the case of angular momentum conservation. The strong narrow features are interstellar diffuse bands. The spectra have been divided by a spline fit to the continuum for normalisation.

Mendelson & Mazeh (1991) in the five years that their photometry covers.

3. Results

3.1. Spectral classification

Unger et al. (1998) have presented intermediate resolution spectroscopy of V635 Cas and classified the source as O9.5V. However, their spectrum had a very low signal to noise ratio and showed several spurious features. The spectrum shown in Fig. 1 has a much higher SNR and better resolution. At the time it was taken, Hα was starting to develop emission peaks after several months during which it had been observed in absorption (see Paper II). All the other Balmer lines are still in absorption, but they all present a similar asymmetric shape, which must be due to new emission components starting to develop. Surprisingly, many He I lines show emission components ($\lambda\lambda$ 4009, 4026, 4144 and 4713 Å), as can be easily seen by comparing the spectrum with that of the B0.2V standard τ Sco (Fig. 1).

The broad shallow lines are typical of a main-sequence early star. He II λ4686 Å can be clearly seen, though it is weak, indicating a spectrum earlier than B0.7. The weakness of the Si III $\lambda\lambda$ 4552, 4568, 4575 Å triplet (if it is at all present) supports the early spectral type and indicates a main sequence star. No obvious O II lines are present, though the C III $\lambda\lambda$ 4072, 4650 Å lines could be blends. If the weak feature at λ4541Å is real, then V635 Cas could be as early as B0V, but not earlier – the Si IV lines, which must be hidden on the very broad wings of Hδ, should be clearly visible for an earlier (or higher luminosity) star. Therefore the star is constrained to belong to the B0-B0.5 range. For simplicity, we will adopt the intermediate B0.2Ve spectral type.

3.2. Distance

As discussed in Paper II, during the second half of 1997 the source showed Hα and all other lines in the red in absorption. On January 7th, 1998, we measured the faintest and bluest magnitudes in our dataset. Here we investigate the possibility that these photometric magnitudes are close to the actual apparent magnitudes of the star without any contribution from a disc, implying that the measured reddening is (almost) purely interstellar.

The intrinsic colour of a B0V star is $(B-V)_0 = -0.26$ (Wegner 1994) and therefore the measured $(B-V) = 1.39$ implies a reddening $E(B-V) = 1.65 \pm 0.08$. Using the relationship $E(U-B) = E(B-V)[0.69+0.04\times E(B-V)]$ from Fitzpatrick (1999), we find $E(U-B) = 1.25$. The measured $(U-B) = 0.13$ implies $(U-B)_0 = -1.12 \pm 0.12$, perfectly compatible with the expected $(U-B)_0 = -1.08$. Further assuming the standard extinction curve for $R = 3.1$ after Fitzpatrick (1999), we find values for $(V-R)_0 = -0.31$ and $(V-I)_0 = -0.60$. These values are, within the errors, close to the intrinsic colours of a B0V star, though slightly too blue. Wegner (1994) gives $(V-R)_0 = -0.14$ and $(V-I)_0 = -0.37$. Such an effect is surprising, since any residual emission is expected to contribute more strongly at longer wavelengths.

We have considered the possibility that the extinction law to V635 Cas is different from the standard, since the line of sight to V635 Cas could intersect the outer regions of the OB association Cas OB7. This association is about 3° in extension, centred at $\sim (l = 123,\ b = +1)$ and the de-reddened $DM = 11.3$ implies a distance of 1.8 kpc (Garmany & Stencel 1992). We have dereddened the photometry using the extinction curves of Fitzpatrick (1999) for different values of R. We find that values of R different from the standard value by more than ~ 0.2 provide dereddened energy distributions that are farther away from the theoretical values than that dereddened with $R = 3.1$. On the other hand, the derived colours become very close to those expected when a value of $E(B-V)$ close to the lower limit allowed by the errors is considered.

We have also measured the EW of the interstellar diffuse band at λ6613Å in several Hα spectra of V635 Cas (N97; Paper II). We have obtained an average value EW = 480±100 mÅ. According to the relation by Herbig (1975), the implied colour excess is $E(B-V) = 1.9 \pm 0.4$, consistent with the photometric value. Likewise, the EW of the interstellar diffuse band at λ4430Å is 4.4 ± 0.4, which results (Herbig 1975) in $E(B-V) = 2.0 \pm 0.2$. We note that the Na I H and K lines cannot be used for distance

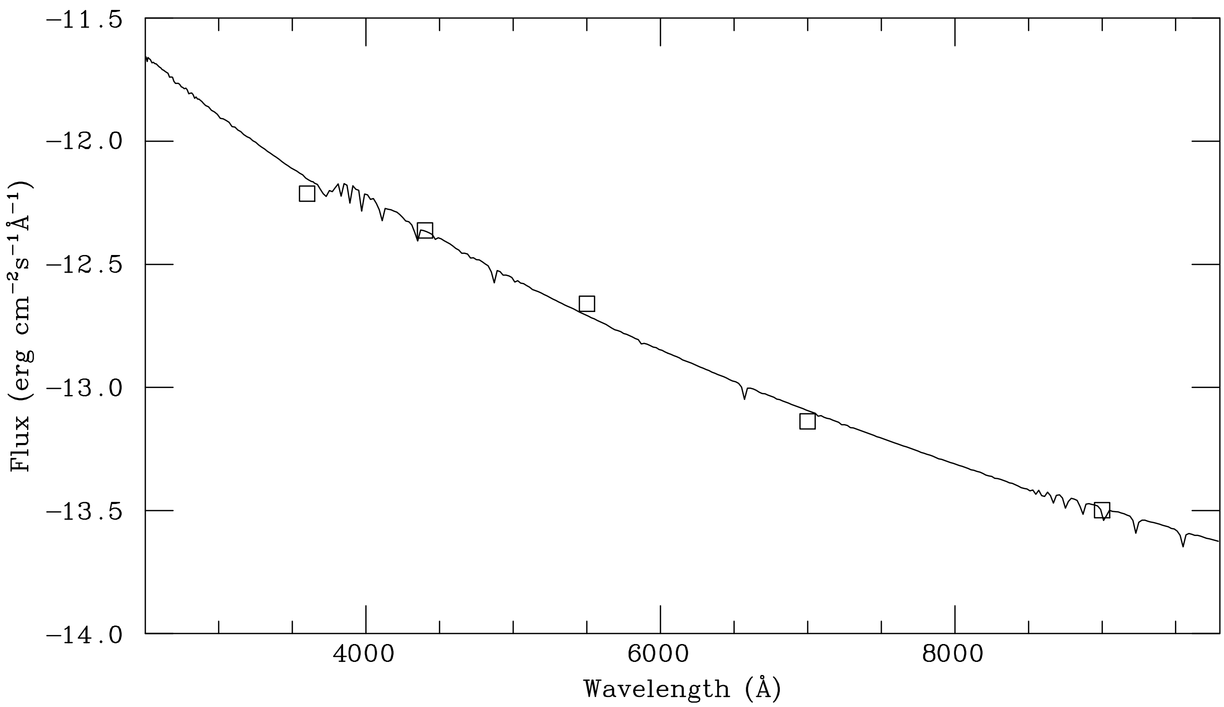

Fig. 3. A Kurucz model for $T_{\rm eff} = 26000$K and $\log g = 4.0$ (the adopted parameters for V635 Cas) has been normalised to the B-band magnitude and is compared to the measured energy distribution (points have been set at the effective wavelengths of the different bands) dereddened with $R = 3.1$ and $E(B-V) = 1.60$ (a value close to the lower limit allowed by the error bars in our photometry).

calibration, since the values measured are well above the saturation value for the relationship with reddening (Munari & Zwitter 1997).

Even though the interstellar diffuse bands seem to support a value for $E(B-V)$ close to the upper limit allowed by the error bars, the photometric evidence supports a value close to the lower limit, as can be seen in Fig. 3. The choice of a lower $E(B-V)$ results in a higher distance for V635 Cas.

Assuming an absolute magnitude $M_V = -4.1$ after Vacca et al. (1996), and taking $E(B-V) = 1.65 \pm 0.08$, we derive a distance to V635 Cas of 8 ± 1kpc. This could be an overestimate if some residual emission was still contributing to the intrinsic luminosity of V635 Cas. Moreover, the calibration of Vacca et al. (1996) indicates that early-B stars are hotter than previously thought and therefore the intrinsic $(B-V)_0$ used is probably too low. We note that distances ~ 7 kpc are obtained for the Be/X-ray transient V0332+53 (Negueruela et al. 1999) and for the standard High Mass X-ray Binary 2S 0114+65 (Reig et al. 1996), which is very close in the sky to 4U 0115+63. We consider very likely that the distance to 4U 0115+63 is also ≈ 7 kpc and that all these objects belong to an outer arm of the Galaxy, situated beyond the Perseus arm at a distance $\gtrsim 4$ kpc (Kimeswenger & Weinberger 1989). At this distance, the maximum luminosity of the source, measured by *Vela 5B* during a Type II outburst in 1974 (Whitlock et al. 1989) is close to $\gtrsim 10^{38}$ erg s^{-1}, i.e., close to the Eddington luminosity for a neutron star.

4. A model for 4U 0115+63

4.1. Stellar and orbital parameters

Given the B0.2Ve spectral type of the optical component, we expect it to have a mass $M_* \simeq 19\,M_\odot$ (Vacca et al. 1996). In this case, the mass function $f(M) = 5.0\,M_\odot$ implies an inclination angle $i = 42°$ for a standard neutron star mass $M_{\rm x} = 1.4\,M_\odot$. It is noteworthy that making the companion star moderately undermassive will not change strongly the inclination angle. For example, if $M_* = 12M_\odot$, the inclination angle is $i = 54°$. For any reasonable value of M_*, $40° \lesssim i \lesssim 60°$ or $0.7 \lesssim \sin i \lesssim 0.8$. The dependence on $M_{\rm x}$ is still smaller. Therefore, in what follows we will adopt as a model $M_* = 18\,M_\odot$ and $M_{\rm x} = 1.4\,M_\odot$, implying $i = 43°$. In this case, the measured $a_{\rm x} \sin i$ implies a binary separation $a = 6.6 \times 10^{10}$ m $= 95\,R_\odot$. Assuming $R_* = 8\,R_\odot$ (Vacca et al. 1996), this results in periastron and apastron distances $a_{\rm per} = 8\,R_*$ and $a_{\rm ap} = 16\,R_*$.

We have tried to estimate the inclination of the equatorial plane of V635 Cas by using Buscombe's (1969) approximation and the fits to the FWHM of He I $\lambda\lambda$ 4388, 4471 Å of Steele et al. (1999). This is only a coarse approximation, since weak emission components are present on the wings of the lines and, given the relatively low SNR of the blue spectrum and the broadness of the Balmer lines, several weak lines could be contaminating the line shapes. In spite of this, all the measurements obtained fall in the range $v \sin i \approx 240 - 340$ km s^{-1} with most of them concentrated around $v \sin i = 290$ km s^{-1} and the Balmer lines consistently giving higher values than the He I lines (except Hα).

Therefore, allowing for the effect of emission contamination, we will adopt as an estimate $v \sin i \approx 300$ km s^{-1}, taking into account that the value is not likely to be much smaller, but could be larger. We note that, if we assume coplanarity between the equatorial and orbital plane, this value implies a rotational velocity $v = 440$ km s^{-1}, which is compatible with the assumption that Be stars rotate at $\lesssim 80\%$ of their break-up velocity. Moreover, the double-peaked emission lines which are seen soon after the circumstellar disc starts reforming are typical of a moderate inclination ($i \approx 40° - 60°$), confirming that the value of $\sin i$ cannot be very distant.

Therefore, we find no compelling reason to argue for an inclination between the orbital and equatorial plane. As discussed in Paper II, this does not imply that the circumstellar disc must always remain coplanar.

4.2. Viscous disc around V635 Cas

To date, discs around seven Be stars have been spatially resolved with optical interferometers (Quirrenbach et al. 1997). The size of the Hα-emitting region $R_{\mathrm{H}\alpha}$ of these stars ranges from 3 to 12 stellar radii. The separation of the two peaks of Hα, Δv_{peak}, is significantly wider than $2 v \sin i \, (R_{\mathrm{H}\alpha}/R_*)^{-1}$ expected in an angular-momentum conserving disc, but is consistent with a disc structure in which the rotation velocity is near Keplerian.

Although there is no widely-accepted model to form near-Keplerian discs around Be stars, a viscous decretion disc model proposed by Lee et al. (1991) seems promising (Porter 1999; see also Okazaki 2000a). In this model, the matter supplied from the equatorial surface of the star drifts outward because of the viscous effect and forms the disc. Basic equations for viscous decretion discs are the same as those for viscous accretion discs, except that the sign of $\dot{M}$ (mass decretion/accretion rate) is opposite. The viscous decretion disc model thus predicts a geometrically thin and near-Keplerian disc around a Be star. The outflow in the viscous decretion disc is highly subsonic near the star (Okazaki 1997, 2000b), which is consistent with the observed upper limit on the radial velocity ($3\,\mathrm{km\,s^{-1}}$) in discs around Be stars (Hanuschik 2000).

Since the mass of the neutron star is much smaller than that of the Be star, its presence will hardly affect the mass loss process from the Be star and will have a minor effect on the formation and structure of the Be disc except in the region near the critical Roche potential. We note that the overall characteristics of the discs in Be/X-ray binaries, as derived from the observation of emission lines and their evolution are not fundamentally different from those of isolated Be stars (see Negueruela et al. 1998, where a discussion of the similarities and main differences is presented; and see also Section 5).

Table 1. Model parameters for V635 Cas/4U 0115+63.

Parameter	Notation	Value
Binary orbit		
Period	P_{orb}	24.3 d
Inclination	i	43°
Semi-major axis	a	$95\,R_\odot (= 12\,R_*)$
Eccentricity	e	0.34
Neutron star		
Mass	M_{x}	$1.4\,M_\odot$
Be star		
Mass	M_*	$18.0\,M_\odot$
Radius	R_*	$8.0\,R_\odot$
Effective temperature	T_{eff}	26,000 K
Be disc		
Temperature	T_{d}	20,800 K
Scale-height at $r = R_*$	$H(R_*)/R_*$	$2.6 \cdot 10^{-2}$

Therefore, as a first approximation, we will assume in this paper that the viscous decretion disc model, which has been developed as a disc model for isolated Be stars, is applicable to Be discs in Be/X-ray binaries. That is, we will assume that the disc surrounding V635 Cas is near-Keplerian when unperturbed. For simplicity, we also assume that the disc is isothermal with a temperature of $0.8 T_{\mathrm{eff}}$, where the effective temperature of the star is $T_{\mathrm{eff}} = 26000\,\mathrm{K}$. Table 1 summarizes the model parameters adopted for 4U 0115+63.

4.3. Tidal truncation of the viscous disc

Artymowicz & Lubow (1994) investigated the tidal/resonant truncation of the accretion discs in eccentric binary systems and found that the disc size becomes smaller in a system with larger eccentricity. Following their formulation of the companion-disc interaction, we study below the tidal truncation of the Be-star disc in 4U 0115+63.

In order to evaluate the tidal/resonant torque exerted by the neutron star on the Be-star disc, we consider the binary potential in a coordinate system (r, θ, z) in which the origin is attached to the Be star primary:

$$\Phi(r,\theta,z) = -\frac{GM_*}{r} - \frac{GM_{\mathrm{x}}}{[r^2 + r_2^2 - 2 r r_2 \cos(\theta - f)]^{1/2}} + \frac{GM_{\mathrm{x}} r}{r_2^2} \cos(\theta - f), \quad (1)$$

where M_* and M_{x} are masses of the Be and neutron stars, respectively, r_2 is the distance of the neutron star from the primary, and f is the true anomaly of the neutron star. The third term in the right hand side of Eq.(1) is the indirect potential arising from the fact that the coordinate origin is at the primary.

We expand the potential by a double series as

$$\Phi(r,\theta,z) = \sum_{m,l} \phi_{ml} \exp[i(m\theta - l\Omega_B t)], \quad (2)$$

where m and l are the azimuthal and time-harmonic numbers, respectively, and $\Omega_B = [G(M_* + M_{\rm x})/a^3]^{1/2}$ is the mean motion of the binary with semimajor axis a. The pattern speed of each potential component is given by $\Omega_p = (l/m)\Omega_B$.

Inverting Eq.(2) and denoting the angle $\theta - f$ as φ, we have

$$\begin{aligned} \phi_{ml} \;=\; & -\frac{GM_{\rm x}}{a}\left\{\frac{2}{\pi^2}\int_0^\pi d(\Omega_B t)\frac{a}{r_2}\cos(mf - l\Omega_B t)\right. \\ & \times \int_0^\pi d\varphi \frac{\cos m\varphi}{(1+\beta^2 - 2\beta\cos\varphi)^{1/2}} \\ & \left. -\frac{\delta_{m1}}{\pi}\int_0^\pi d(\Omega_B t)\frac{a}{r_2}\beta\cos(mf - l\Omega_B t)\right\}, \end{aligned} \quad (3)$$

where $\beta = r/r_2$ and δ_{m1} is the Kronecker delta function.

For each potential component ϕ_{ml}, there can be outer and inner Lindblad resonances at radii where $\Omega_p = \Omega \pm \kappa/m$ and a corotation resonance at the radius where $\Omega_p = \Omega$. Here, κ is the epicyclic frequency, and here and hereafter the upper and lower signs correspond to the outer Lindblad resonance (OLR) and inner Lindblad resonance (ILR), respectively. The radii of these resonances are given by

$$r_{\rm LR} = \left(\frac{m \pm 1}{l}\right)^{2/3} (1+q)^{-1/3} a \quad (4)$$

and

$$r_{\rm CR} = \left(\frac{m}{l}\right)^{2/3} (1+q)^{-1/3} a, \quad (5)$$

where $q = M_{\rm x}/M_*$.

For near-Keplerian discs, where $\Omega \sim \kappa \sim (GM_*/r^3)^{1/2}$, Goldreich & Tremaine's (1979; 1980) standard formula for torques T_{ml} at the outer Lindblad resonance (OLR) and inner Lindblad resonance (ILR) is reduced to

$$T_{ml} = \pm \frac{m(m\pm1)\pi^2\sigma(\lambda \mp 2m)^2\phi_{ml}^2}{3l^2\Omega_B^2}, \quad (6)$$

where σ is the surface density of the disc at the resonance radius and $\lambda = (d\ln\phi_{ml}/d\ln r)_{\rm LR}$. Similarly, the torque at the corotation resonance (CR) is written as

$$T_{ml} = \frac{2m^3\pi^2\sigma\phi_{ml}^2}{3l^2\Omega_B^2}. \quad (7)$$

Note that angular momentum is removed from the disc at the ILRs, whereas it is added to the disc at the OLRs and CRs.

In near Keplerian discs, the viscous torque formula derived by Lin & Papaloizou (1986) is written as

$$T_{\rm vis} = 3\pi\alpha G M_* \sigma r \left(\frac{H}{r}\right)^2 \quad (8)$$

[see also Artymowicz & Lubow (1994)], where α is the Shakura-Sunyaev viscosity parameter and H is the vertical scale-height of the disc. In our isothermal disc model (the parameters used are listed in Table 1), H is given by

$$\frac{H}{r} = 8.9 \cdot 10^{-2} \left(\frac{r}{a}\right)^{1/2}. \quad (9)$$

The disc is truncated if the viscous torque is smaller than the resonant torque. The criterion for the disc truncation at a given resonance radius is, in general, written as

$$T_{\rm vis} + \sum_{ml}(T_{ml})_{\rm ILR} + \sum_{ml}(T_{ml})_{\rm OLR} + \sum_{ml}(T_{ml})_{\rm CR} \le 0, \quad (10)$$

where the summation is taken over all combination of (m,l) which give the same resonance radius. For example, at the n:1 resonance radius, at which $\Omega = n\Omega_{\rm B}$, the summation is taken over all combinations of (m,l) with $l = n(m-1)$ for ILRs, $l = n(m+1)$ for OLRs, and $l = nm$ for CRs. Actually, criterion (10) is determined only by the viscous torque and the torques from the ILRs of several lowest-order potential components, because the torques from the ILRs dominate those from the OLR and CR in circumstellar discs and high-order potential components contribute little to the total torque, even if the eccentricity of the orbit e is not small (Goldreich & Tremaine 1980; Artymowicz & Lubow 1994).

Criterion (10) at a given resonance is met for α smaller than a critical value, $\alpha_{\rm crit}$. In Fig. 4, we plot $\alpha_{\rm crit}$ at $n:1$ resonance radii. The resonant torques at the $n:1$ radii are stronger than those at radii with other period commensurabilities located nearby. It is important to note that $\alpha_{\rm crit} \gtrsim 1$ at the 2:1 and 3:1 resonance radii. The disc is truncated at the 3:1 radius if $0.17 \lesssim \alpha \lesssim 0.97$ or at the 4:1 radius if $0.037 \lesssim \alpha \lesssim 0.17$. Note also that the Be-star disc in 4U 0115+63 cannot be in a steady state. The gas supplied by the Be star will decrete outward and be accumulated in the outermost part of the disc. This could contribute to make the disc dynamically unstable, as will be discussed in Paper II.

It could be argued that the tidal truncation of the circumstellar disc is an assumption implicit in our choice of a viscous decretion model for the disc, but it holds irrespective of disc model as long as the outflow velocity in the disc is very subsonic, as observed for many Be stars. In order to show this, let us compare the timescale for disc truncation, $\tau_{\rm trunc}$, with the drift timescale $\tau_{\rm drift}$. We can find $\tau_{\rm trunc}$ via the viscous timescale $\tau_{\rm vis}$. Since the ratio of the viscous torque to the resonant torque is $\alpha/\alpha_{\rm crit}$, we have $\tau_{\rm trunc} \sim (\alpha/\alpha_{\rm crit})\tau_{\rm vis} \sim \alpha_{\rm crit}^{-1}(\Delta r/H)^2\Omega^{-1}$. In deriving the second similarity, we have used $\tau_{\rm vis} \sim (\Delta r)^2/\alpha c_s H \sim$

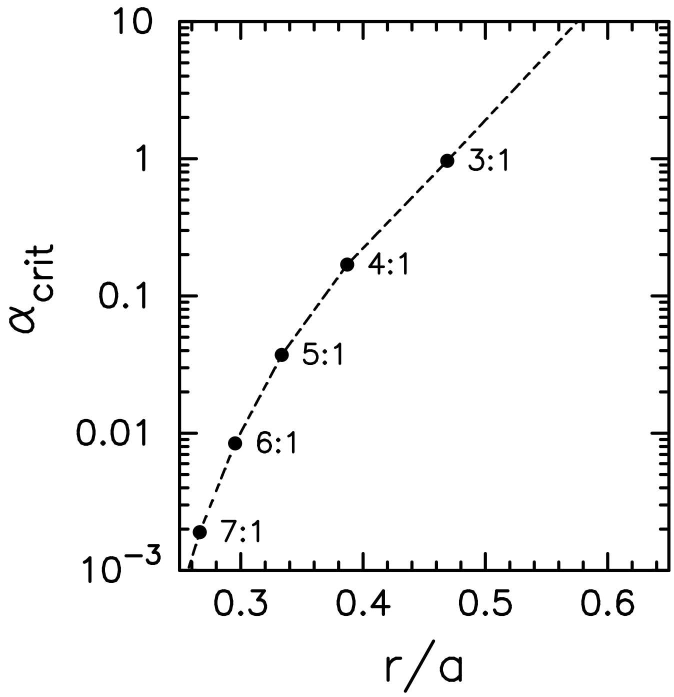

Fig. 4. Critical values of α at $n:1$ resonance radii. Annotated in the figure are the locations of the $n:1$ commensurabilities of disc and binary orbital periods.

$(\Delta r)^2/\alpha H^2\Omega$, where c_s is the sound speed and Δr is a gap size (i.e., an interval between the disc outer radius and the radius at which the neutron star's gravity begins to dominate). On the other hand, the drift timescale is written as $\tau_{\rm drift} \sim \Delta r/v_r \sim \mathcal{M}_r^{-1}(\Delta r/H)\Omega^{-1}$, where v_r and $\mathcal{M}_r$ are the radial velocity and Mach number, respectively. Consequently, we have

$$\frac{\tau_{\rm trunc}}{\tau_{\rm drift}} \sim \frac{\mathcal{M}_r}{\alpha_{\rm crit}}\frac{\Delta r}{H}. \tag{11}$$

As shown in Fig. 4, $\alpha_{\rm crit} \sim 1$ at the 3:1 radius. From Eq.(9) with $r/a \sim 0.5$, we expect $\Delta r/H = \Delta r/r/(H/r) \sim O(1)$ for the disc of V635 Cas. Therefore, we conclude that the disc truncation timescale is much shorter than the drift timescale if the outflow is very subsonic. Note that this conclusion holds for Be/X-ray binaries in general, because all Be/X-ray binaries have similar disc parameters and the orbital parameters of these systems do not range very widely.

4.4. Disc structure

As mentioned above, the disc around V635 Cas cannot be steady. Nevertheless, it is instructive to study the steady disc structure as a model for the inner disc and/or the disc in the initial formation epoch. In this section, we assume the disc to be axisymmetric and azimuthally average the potential given by Eq. (1).

Okazaki (1997; see also Okazaki 2000b) showed that the equations which determine the velocity field in an isothermal decretion disc can be reduced to

$$\left(V_r - \frac{c_{\rm s}^2}{V_r}\right)\frac{{\rm d}V_r}{{\rm d}r} = -\frac{GM_*}{r^2} + F_{\rm rad} + \frac{\ell^2}{r^3} + \frac{5}{2}\frac{c_{\rm s}^2}{r} \tag{12}$$

and

$$\ell = \ell(R_*) + \alpha c_{\rm s}^2\left[\frac{R_*}{V_r(R_*)} - \frac{r}{V_r}\right], \tag{13}$$

where $\ell = rV_\phi$ is the specific angular momentum, $F_{\rm rad}$ is the vertically averaged radiative force, and V_r and V_ϕ are the radial and azimuthal components of the vertically averaged velocity, respectively. Eqs. (12) and (13) show that the viscous decretion disc is an equatorial wind, in which material is slowly accelerated outward by the pressure force.

Since the radial flow in Be-star discs is considered to be subsonic, the radiative force would arise not from the optically-thick strong lines but from an ensemble of optically-thin weak lines. Hence, for the radiative force, we adopt the parametric form proposed by Chen & Marlborough (1994).

$$F_{\rm rad} \simeq \frac{GM_*}{r^2}\eta\left(\frac{r}{R_*}\right)^{\epsilon}, \tag{14}$$

where η and ϵ are parameters which characterize the force due to the ensemble of optically-thin lines.

Given the radial velocity component at the stellar surface, the flow structure in the disc is obtained by solving Eqs. (12) and (13) numerically. The surface density distribution is then obtained from the equation of mass conservation. In Fig. 5, we show the structure of the isothermal decretion disc around V635 Cas with $\alpha = 0.1$, $V_r(R_*)/c_{\rm s} = 10^{-3}$, and the outer radius at the 4:1 resonance. The parameters characterizing the radiative force, η and ϵ, are chosen so that the fundamental $m = 1$ mode in the disc has the period corresponding to the observed line profile variabilities (see Paper II).

The solution shown in Fig. 5 is not unique. We found that, for $\alpha = 0.1$, there is a smooth solution for $V_r(R_*)/c_{\rm s} < 3\times10^{-3}$. Any flow with $\alpha = 0.1$ and $V_r(R_*)/c_{\rm s} \gtrsim 3\times10^{-3}$, however, has a spiral critical point and does not go smoothly from the stellar surface to the disc outer radius. Thus, the radial flow in a decretion disc must be highly subsonic near the star. Such a flow satisfies the disc truncation condition, $\tau_{\rm trunc}/\tau_{\rm drift} < 1$, discussed in § 4.3.

5. Discussion

The truncation of the disc by the tidal/resonant interaction with the neutron star could explain many of the observed properties of V635 Cas. In N97, it was shown that large changes in the infrared magnitudes were not associated with significant changes in the associated colours.

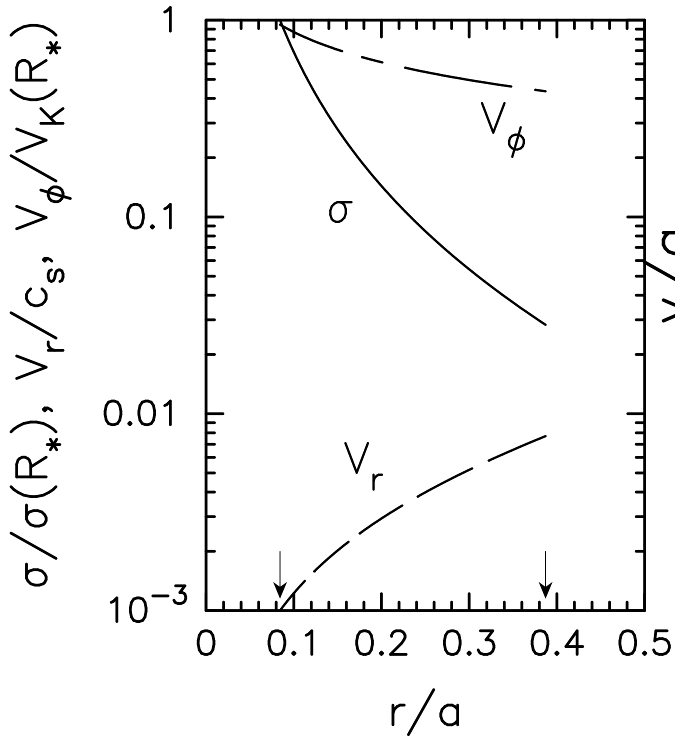

Fig. 5. Structure of the viscous decretion disc around V635 Cas with $\alpha = 0.1$ and $V_r(R_*)/c_\mathrm{s} = 10^{-3}$. The radiative force in the form of $\eta(r/R_*)^\epsilon \times GM_*/r^2$ with $(\eta, \epsilon) = (0.1, 0.1)$ is included. Solid, dashed, and dash-dotted lines denote $\sigma/\sigma(R_*)$, V_r/c_s, and $V_\phi/V_\mathrm{K}(R_*)$, respectively, where $V_\mathrm{K} = (GM_*/r)^{1/2}$ is the Keplerian velocity. Two arrows denote the inner radius at $r = R_*$ and the outer disc radius located at the 4:1 resonance radius.

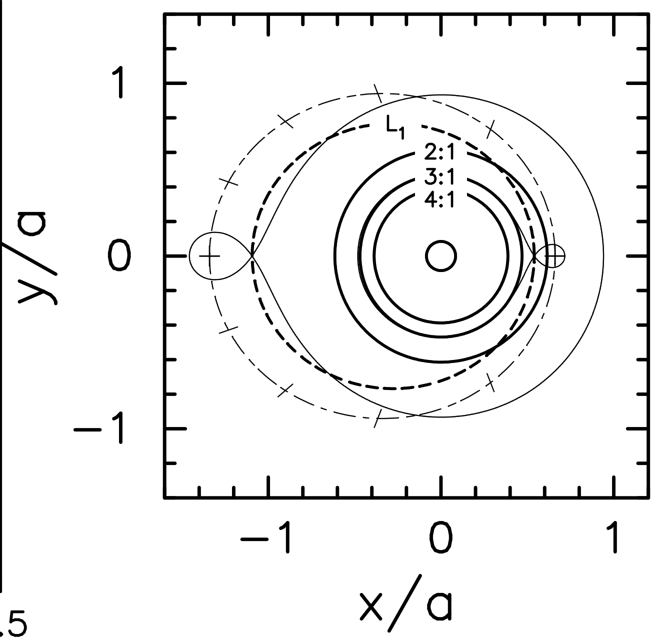

Fig. 6. A description of the orbital model adopted for 4U 0115+63, in the reference system centred on the Be star. The dash-dotted line represents the orbit of the neutron star. The thick dashed line represents the position of the first Lagrangian point (L_1) around the orbit. The solid thin lines are the effective Roche lobes of the two stars at apastron and periastron (the position of the neutron star is marked with a cross). The labelled thick solid lines are the locations of the $n:1$ commensurabilities of disc and binary orbital periods. Note that the radius of the 3:1 commensurability is smaller than the radius of the L_1 point at periastron.

According to the models of Dougherty et al. (1994), this should correspond to a very small disc with a very high density - such that it is optically thick at all wavelengths for continuum radiation. The formation of such a disc is easy to explain if tidal truncation forces outflowing material to fall back on to the inner regions of the disc. It will also explain why the observed correlation between the strength of Hα and the circumstellar reddening observed in Be stars (Fabregat & Reglero 1990) does not seem to hold for Be/X-ray binaries - the disc could become very dense and the circumstellar reddening would not be measuring the size of the disc. Finally it would explain the correlation between the maximum strength of Hα and orbital period in Be/X-ray binaries found by Reig et al. (1997).

The reality of this correlation has been questioned by Apparao (1998), who claims that the EW of Hα does not represent an appropriate measurement of the size of the disc and that the actual luminosity radiated in Hα does not show any correlation with the size of the orbit. We agree that the EW of Hα at a given time does certainly not represent a measurement of the size of the envelope. Many other factors such as the optical properties of the envelope, which seem to be highly variable, or an asymmetric density distribution in the disc (Negueruela et al. 1998; see also Paper II) affect the observed EW. However, the *maximum* EW of Hα ever observed may provide a comparative estimate of the maximum size of an envelope if the source has been consistently monitored for a sufficiently long time – for example in the case of V635 Cas, where the typical timescales of variability are of the order of a few months (Paper II), ten years of monitoring provide a good estimate of the EW of Hα at maximum.

Given that we expect the viscosity in the disc to be of the order of $\alpha \lesssim 0.1$ as in accretion discs (e.g., Blondin 2000; Matsumoto 1999), the disc around V635 Cas is likely to be truncated at the 4:1 resonance. Even if the viscosity is higher and becomes ≈ 1, truncation still occurs at the 3:1 resonance. In Fig. 6, it can be seen that even the 3:1 resonance is significantly smaller than the radius of the first Lagrangian point (even when the neutron star is at periastron). Here, the potential ψ describing the effects of the gravitational and centrifugal forces on the motion of test particles orbiting the Be star is given by

$$\psi(r,\theta,z) = \Phi(r,\theta,z) - \frac{1}{2}\Omega^2(r)r^2, \tag{15}$$

where Φ is the potential defined by Eq. (1). As a consequence, the neutron star will not be able to accrete a significant amount of material from the circumstellar disc. This fact explains the lack of series of Type I outbursts from 4U 0115+63. In order to have Type I outbursts in this system, we will need a large amplitude $m = 1$ mode to make the disc eccentric and cause Roche lobe overflow toward the neutron star.

Accepting that the disc of Be/X-ray binaries is tidally truncated naturally explains why Be/X-ray binaries spend most of their time in quiescence. In general, the neutron star cannot accrete from the dense regions of the disc. The low-luminosity X-ray activity observed in systems such as A 0535+262 (Motch et al. 1991) would then be due to the accretion of some residual low-density outflow. In the case of V635 Cas, this material is not accreted because of the propeller mechanism. If we accept this picture, it is precisely the very existence of X-ray outbursts that needs to be explained. This will be addressed in Paper II.

6. Conclusions

By observing the source during a disc-loss episode, we have been able to determine the stellar parameters of V635 Cas. The object is classified as a B0.2Ve star at a distance of $7 - 8$ kpc. Both the mass function and the estimated $v \sin i$ indicate a moderate inclination for the orbital and equatorial planes. The derived distance implies that the source can radiate close to the Eddington luminosity for a neutron star during bright outbursts.

With the newly determined parameters, we have constructed a model for 4U 0115+63. Based on the viscous decretion disc model for Be stars, we have numerically solved a criterion for tidal truncation and found that the disc surrounding V635 Cas must be truncated at a resonance radius depending on the viscosity parameter and cannot be in a steady state. Although we have adopted a particular disc model, our conclusion is robust as long as the outflow in the disc is subsonic, a hypothesis supported by several observational facts. Under normal conditions, the neutron star cannot accrete enough material to overcome the centrifugal barrier and switch on the X-ray emission.

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