A&A 369, 117–131 (2001)
DOI: 10.1051/0004-6361:20010077

Astronomy & Astrophysics

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

II. Outburst mechanisms

I. Negueruela[1,2,3], A. T. Okazaki[4,5], J. Fabregat[6], M. J. Coe[7], U. Munari[8,9], and T. Tomov[8,9]

[1] Observatoire de Strasbourg, 11 rue de l'Université, 67000 Strasbourg, France
[2] SAX SDC, ASI, c/o Nuova Telespazio, via Corcolle 19, 00131 Rome, Italy
[3] Astrophysics Research Institute, Liverpool John Moores University, Byrom St., Liverpool L3 3AF, UK
[4] Faculty of Engineering, Hokkai-Gakuen University, Toyohira-ku, Sapporo 062-8605, Japan
[5] Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, UK
[6] Departamento de Astronomía y Astrofísica, Universidad de Valencia, 46100 Burjassot, Valencia, Spain
[7] Physics and Astronomy Dpt., University of Southampton, Southampton SO17 BJ1, UK
[8] Osservatori Astronomici di Padova e Asiago, via dell'Osservatorio 8, 36012 Asiago (Vicenza), Italy
[9] Centro Interdipartimentale di Studi ed Attività Spaziali (C.I.S.A.S.) "G. Colombo", Università di Padova, Italy

Received 29 May 2000 / Accepted 10 January 2001

Abstract. We present multi-wavelength long-term monitoring observations of V635 Cas, the optical counterpart to the transient X-ray pulsar 4U 0115+63. The evolution of emission lines and photometric magnitudes indicates that the Be star undergoes relatively fast ($\sim$3 − 5 yr) quasi-cyclic activity, losing and reforming its circumstellar disc. We show that the general optical, infrared and X-ray behaviour can be explained by the dynamical evolution of the viscous circumstellar disc around the Be star. After each disc-loss episode, the disc starts reforming and grows until it reaches the radius at which the resonant interaction of the neutron star truncates it. At some point, the disc becomes unstable to (presumably radiative) warping and then tilts and starts precessing. The tilting is very large and disc precession leads to a succession of single-peaked and shell profiles in the emission lines. Type II X-ray outbursts take place after the disc has been strongly disturbed and we speculate that the distortion of the disc leads to interaction with the orbiting neutron star. We discuss the implications of these correlated optical/X-ray variations for the different models proposed to explain the occurrence of X-ray outbursts in Be/X-ray binaries. We show that the hypothesis of mass ejection events as the cause of the spectacular variability and the X-ray outbursts is unlikely to be meaningful for any Be/X-ray binary.

Key words. stars: circumstellar matter – stars: emission-line, Be – stars: individual: 4U 0115+63 – binaries: close – stars: 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). This is the second in a series of papers dedicated to understanding its behaviour and investigating what it can tell us about the general class of Be/X-ray transients. An introduction to the source has been presented in Paper I (Negueruela & Okazaki 2001), where it was shown that V635 Cas is a B0.2Ve star at a distance of $\sim$7 kpc. The primary is seen under a moderate inclination ($40^\circ < i < 60^\circ$), and the high $v \sin i \sim 300\,\mathrm{km\,s^{-1}}$ indicates that it rotates close to its break-up velocity. A model for the system in which the neutron star orbits an $18\,M_\odot$ primary was adopted after showing that the actual mass of the primary would have little impact on the orbital parameters derived. Under those conditions, the 24.3-d eccentric ($e = 0.34$) orbit results in periastron and apastron distances of $a_{\rm per} = 8\,R_*$ and $a_{\rm ap} = 16\,R_*$ respectively.

The disc around the Be star was modelled as a viscous decretion disc, i.e., a quasi-Keplerian disc held by the transport of angular momentum via viscous interactions. The outflow (radial) velocity in such a disc is expected to be strongly subsonic, in agreement with all the observations of Be stars in general and V635 Cas in particular. It was shown that such a disc cannot reach a steady state due to tidal and resonant interaction with the neutron star, and it is truncated at a radial distance which depends on the value of the viscosity, but which for most reasonable values was found to correspond to the 4:1 commensurability of disc and binary orbital periods, which is situated at a

Send offprint requests to: I. Negueruela,
e-mail: ignacio@astro.u-strasbg.fr

distance of 0.39 times the semi-major axis. This truncation radius is closer to the Be star than the first Lagrangian point L_1 for all orbital phases. Given that accretion of material from a very slow outflow implies that mass transfer takes place through L_1, no material can reach the neutron star under normal conditions, which explains the usual quiescent state of the source, with complete absence of X-ray emission.

2. Observations

We present optical and infrared photometry and optical spectroscopy of V635 Cas, taken with a large array of telescopes during the last ten years. The observations cover a large variety of very different states of the source.

2.1. Optical spectroscopy

Spectra of V635 Cas in the red region from a number of sources have been collected in this work. Data from 1990–1994 were retrieved from the La Palma Archive (Zuiderwijk et al. 1994) or taken from N97. These observations were obtained with either the 4.2-m William Herschel Telescope (WHT) or the 2.5-m Isaac Newton Telescope (INT), both located at the Observatorio del Roque de los Muchachos, La Palma, Spain. Most spectra were taken with the Intermediate Dispersion Spectrograph (IDS) on the INT, equipped with the 235-mm camera + R1200Y grating which gives a nominal dispersion of ~0.8 Å/pixel with most of the cameras used. Higher resolution spectra were obtained with either IDS equipped with the 500-mm camera and the R1200Y grating or the Intermediate Dispersion Spectroscopic and Imaging System (ISIS) on the WHT, equipped with the R1200R grating.

During 1995–1998, spectroscopy was regularly obtained with the INT equipped with the 235-mm camera + R1200Y grating and either the Tek 3 CCD (giving a nominal dispersion of ~0.8 Å/pixel) or the EEV #12 CCD (giving a nominal dispersion of ~0.4 Å/pixel). Spectral resolutions (as estimated from the $FWHM$ of arc lines) varied according to slit width (generally matched to seeing) from ~1.2 Å to ~2 Å. All these data were 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).

Some low-resolution spectra were secured with the Boller & Chivens spectrograph attached to the 1.82-m telescope operated by the Osservatorio Astronomico di Padova atop of Mount Ekar, Asiago (Italy). The detector was a Thompson TH7882 UV-coated CCD, 580 × 388 pixels of 23 μm size. We used a 150 ln/mm grating giving a dispersion of 7.8 Å/pixel. The slit was set to 1.5 arcsec, for a PSF on the spectrograph focal plane of ~2.5 pixels. One spectrum was taken with the 1.5-m telescope at Palomar Mountain Observatory (PAL) and one spectrum was taken with the 1-m Jakobus Kapteyn Telescope (JKT) at La Palma.

A complete log of Hα spectroscopy is presented in Table 1. Low-resolution spectra of the region $\lambda\lambda$6800−9500 Å were taken on October 22, 1994 (Asiago) and August 12, 1998 (WHT). In both cases, no obvious stellar features are visible, though the 1998 spectrum could show Pa13 and Pa12 in emission. A higher resolution spectrum taken on September 10, 1998 with the INT shows that the upper Paschen lines have weak emission components that fill in the photospheric absorption features, resulting in the featureless continuum seen at lower resolutions.

2.2. Optical photometry

Several sets of $UBVRI$ photometry have been obtained using the Jacobus Kapteyn Telescope (JKT), located at the Observatorio del Roque de los Muchachos, La Palma, Spain. The telescope was equipped with the Tek4 CCD and the Harris filter set. Instrumental magnitudes were extracted through synthetic aperture routines contained in the IRAF package. Transformation to the Johnson/Cousins system was made by means of a system of secondary standard stars on the same CCD frame[1], calibrated through observations of photometric standards from Landolt (1992) in an earlier photometric run (N97), except for the October 11th 1997 observation, which was part of a larger observing programme and was transformed through calibrations derived from observations of a number of Landolt (1992) standard stars taken on the same night. The photometric errors are the estimated uncertainties in the transformation equations. The data are listed together with the observations from N97 in Table 2.

Photographic photometry has been obtained from 1987–1997 with the 67/92-cm Schmidt telescope operated by Osservatorio Astronomico di Padova atop Mt. Ekar, Asiago (Italy). The telescope has a 205-cm focal length and UBK7 corrective plate. For the B band the standard emulsion/filter combination 103a-O + GG13 was adopted. The brightness of V635 Cas was estimated at the microscope against the same comparison sequence used for CCD photometry. The results of photographic photometry are reported in Table 3.

2.3. Infrared photometry

The source has been monitored in the infrared since 1991 using the Continuously Variable Filter (CVF) on the 1.5-m Carlos Sanchez Telescope (TCS) at the Teide Observatory, Tenerife, Spain. Many of the observations have already been reported in N97 and Negueruela et al. (1998, henceforth N98). However, we have reprocessed the complete dataset using the procedure described by Manfroid (1993) and all instrumental values have been

[1] Finding charts containing the local photometric sequence can be found at the following World Wide Web address: http://www.soton.astro.ac.uk/~ind/v635cas.html

Table 1. Observational details of the red spectroscopy and Hα line parameters. Errors in the measurements of EW are typically 10%, due to the subjective continuum determination. See Sect. 3.3 for the interpretation of the line parameters for different line shapes. When the date is followed by a number, it indicates that the spectrum is shown in Fig. 2

Date	Telescope	Nominal Dispersion (Å/pix)	Shape	Total Hα EW (Å)	$\Delta v_{\rm peak}$ (km s^{-1})	$FWHM$ (km s^{-1})	TBW (Å)
Feb. 14, 1990 (1)	WHT	∼0.8	SPV	−7.0	–	580	23
Dec. 27, 1990 (2)	INT	∼0.4	SHS	−4.6	370	620	40
Jan. 27, 1991 (3)	INT	∼0.8	SPS	−10.0	–	440	18
Aug. 28, 1991 (4)	INT	∼0.4	SHV	−4.3	420	635	52
Dec. 14, 1991 (5)	INT	∼0.4	DPV	−5.4	480	–	22
Aug. 05, 1992 (6)	INT	∼0.8	DPR	−4.1	425	705	47
Jan. 01, 1993	WHT	∼0.4	DPV	−7.0	390	730	42
Sep. 23, 1993	PAL	∼0.8	DPR	−4.9	410	–	44
Dec. 18, 1993	WHT	∼0.4	DPS	−5.5	405	680	48
Dec. 19, 1993 (7)	WHT	∼0.4	DPS	−5.3	390	670	44
Jan. 09, 1995 (8)	INT	∼0.8	SPV	−8.8	–	455	25
Jul. 03, 1995	INT	∼0.8	SHV	−3.6	390	635	55
Sep. 12, 1995 (9)	INT	∼0.4	SHV	−5.0	420	600	55
Oct. 15, 1995	Asiago	∼7.8	SP?	−10.2	–	–	–
Nov. 29, 1995	JKT	∼1.2	SPR	−10.5	–	–	–
Jan. 12, 1996	INT	∼0.8	DPR	−11.3	210	425	50
Jan. 31, 1996	INT	∼1.5	DPR	−8.0	280	560	47
Jun. 20, 1996 (10)	INT	∼0.8	DPR	−7.4	340	590	54
Jul. 09, 1996	INT	∼0.8	DPR	−6.5	390	–	53
Aug. 26, 1996	INT	∼0.8	SPR	−8.4	–	550	24
Feb. 01, 1997 (11)	INT	∼0.8	DPR	−3.6	480	–	27
Jul. 17, 1997 (12)	WHT	∼0.4	ABS	+1.3	–	460	–
Jul. 25, 1997	INT	∼0.8	ABS	+1.2	–	430	–
Aug. 23, 1997	INT	∼0.8	ABS	+1.1	–	430	–
Sep. 05, 1997	INT	∼0.8	ABS	+1.1	–	350	–
Sep. 25, 1997	INT	∼0.8	ABS	+1.0	–	480	–
Oct. 01, 1997	INT	∼0.8	ABS	+1.1	–	330	–
Oct. 13, 1997	INT	∼0.8	DPR	+0.2	700	–	23
Nov. 14, 1997 (13)	WHT	∼0.4	DPS	−0.4	610	–	24
Aug. 02, 1998 (14)	INT	∼0.4	DPS	−6.5	305	700	50
Aug. 07, 1998	INT	∼0.4	DPV	−6.5	325	660	50
Sep. 10, 1998	INT	∼0.8	DPV	−7.4	310	690	51
Sep. 25, 1998 (15)	INT	∼0.4	DPV	−7.5	280	610	46
Dec. 28, 1998 (16)	INT	∼0.8	SPR	−8.7	–	550	26

Table 2. Observational details of the optical photometry. All the observations are from the JKT. The first three datasets are taken from N97

Date	U	B	V	R	I	$B-V$
Dec. 03, 1993		16.90	15.46	14.50	13.29	1.44
Aug. 18, 1994		16.30	14.92	13.95	12.75	1.38
Jan. 19, 1995		16.40	14.79	13.68	12.46	1.61
Oct. 11, 1997	17.07 ± 0.10	16.86 ± 0.03	15.41 ± 0.02	14.52 ± 0.03	13.17 ± 0.08	1.45
Jan. 07, 1998	17.05 ± 0.10	16.92 ± 0.07	15.53 ± 0.04	14.55 ± 0.03	13.49 ± 0.03	1.39
Sep. 05, 1998	17.04 ± 0.08	16.93 ± 0.06	15.37 ± 0.02	14.32 ± 0.02	13.19 ± 0.02	1.56

transformed to the TCS standard system (Alonso et al. 1998) in order to generate a more coherent dataset.

Since the new values do not differ significantly from those published when compared to the range of variability of the source, in Table 4 we only report the data for the period 1996–1998. Measurements for 1991–1995, which are also shown in Fig. 1, can be found in N97 and N98.

3. Results

4U 0115+63 is the most active Be/X-ray transient. Since 1969, it has been observed to undergo thirteen type II outbursts (6 before the discovery of the optical counterpart) and several smaller flares (see Campana 1996). During the period covered by our observations, five outbursts have taken place: in February 1990 (Tamura et al. 1992), March and April 1991 (double-peaked outburst

Table 3. Estimates of the B magnitude of V635 Cas based on plates taken with the 67/92-cm Schmidt telescope of Asiago Observatory. The last column is an estimate of the quality of the plate ranging from A (very good) to D (poor)

plate #	date	lim.mag	B	quality
13792	29-04-87	19.0	16.3	D
13834	01-07-87	<19.2	16.6	B
13850	21-07-87	<19.2	16.8	B
13938	21-11-87	19.4	16.8	A/B
13972	19-12-87	<19.2	16.3	C
14002	11-02-88	17.4	16.4	B
14642	07-10-89	17.4	16.6	B
14702	26-11-89	17.4	16.6	C/B
14924	13-11-90	17.7	17.1	B
14979	18-01-91	17.4	16.3	B
15002	14-02-91	17.1	16.3	A
15353	26-12-92	<19.2	16.6	B/C
15387	17-01-93	>19.2	16.7	B
15395	18-01-93	>19.2	16.6	C
15405	19-01-93	>19.2	16.5	B
15411	21-01-93	19.3	16.5	B/C
15416	22-01-93	19.3	16.4	B
15423	24-01-93	19.3	16.5	B
15427	25-01-93	19.2	16.7	C
15434	27-01-93	>19.2	16.5	C
15438	13-02-93	>19.2	16.6	D
15448	14-02-93	<19.2	16.7	B
15656	15-10-93	<19.2	16.8	B/A
15706	16-12-93	19.4	16.9	B
15721	15-01-94	<19.2	16.8	B/C
15804	10-10-94	>19.2	16.7	B
16223	12-01-97	<19.2	16.8	B

according to Cominsky et al. 1994), May 1994 (N97), November 1995 (Finger et al. 1995) and March 1999 (Heindl et al. 1999). Smaller flares took place in January 1995 and January 1996 (Scott et al. 1996) and a series of four Type I outbursts occurred between August and November 1996 (Bildsten et al. 1997; N98)

Between 1990 and early 1995, our optical observations are relatively sparse. The gaps in our spectroscopic sampling are typically larger than the time-scale for large changes in the shape of the lines and therefore we cannot derive any firm conclusions regarding the correlation between the spectroscopic behaviour and the X-ray activity. However, it is noteworthy that we did obtain spectroscopy of the source on or close to three of the occasions when it was active in the X-ray (February 1990, January 1991 and January 1995) and observed the emission line to be single-peaked, while all observations during quiescence showed double-peaked (sometimes shell-like) weaker lines.

From the summer of 1995 our spectroscopic coverage has been much more complete – though still presenting some large gaps. This has allowed us to study in detail the changes in the emission lines that have taken place during 1995–1997, which are presented in the following subsections.

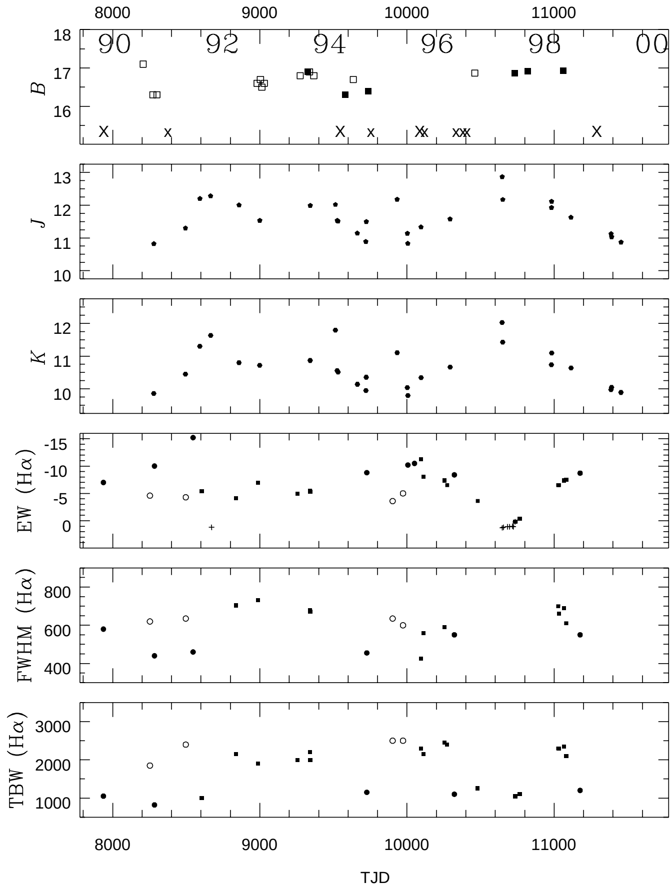

Fig. 1. A general view of the evolution of the infrared and optical lightcurves and Hα line parameters for V635 Cas during 1990–1998. In the top panel, B magnitudes are represented by squares (open when they are plate estimates and filled when they are the result of CCD photometry). Times of X-ray activity are marked. Capital "X" indicates a type II outbursts, while "x" marks a type I outburst or flare. In the three bottom panels, which display the Hα line parameters, absorption lines are represented by crosses, single-peaked lines are shown as filled circles, shell profiles are open circles and double-peaked lines are filled squares (the $FWHM$ and TBW of absorption lines is not plotted, since it has a completely different physical meaning; $FWHM$ is not plotted either for some profiles so asymmetric that it loses any meaning). The two cycles of disc loss and reformation seen in the emission lines are clearly mirrored in the evolution of the J and K magnitudes, but do not appear clearly reflected in the B lightcurve or in the evolution of the $(J-K)$ colours. Error bars have been removed for clarity (see Tables for details)

3.1. Disc loss and reformation

Among the many different kinds of variability that Be stars display, the most obvious is the transition between Be phases and normal B phases. These changes have been observed in a large number of Be stars, with and without companions, and constitute one of the defining characteristics of the Be phenomenon. The absorption spectrum seen is typical of a normal B star and the transitions are interpreted as due to the loss of the circumstellar disc.

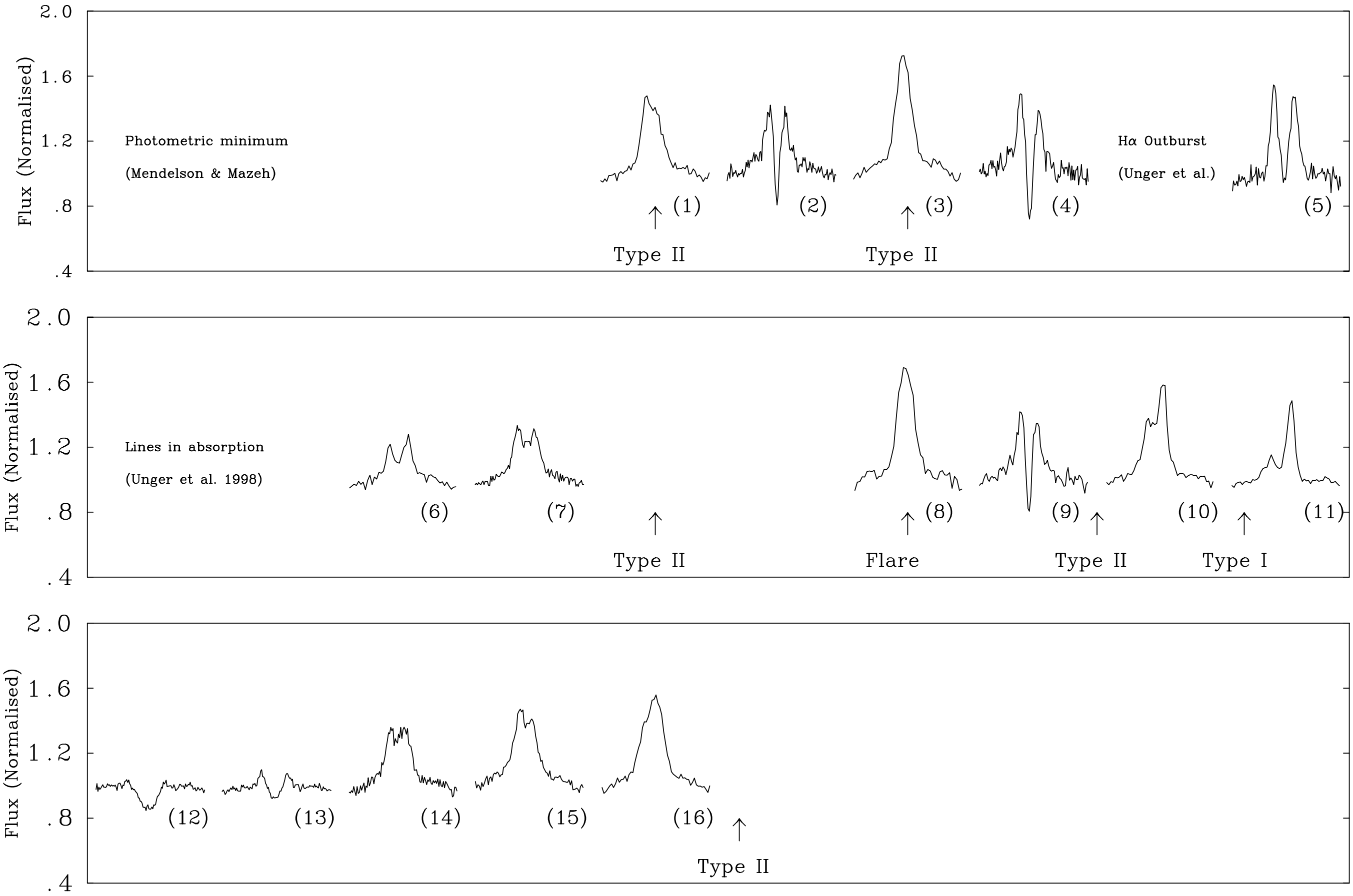

Fig. 2. The three panels show representative Hα lines from the last three cycles. Unfortunately the coverage is not complete. Each cycle starts with a disc-less state and ends in the dissipation of the disc, which leads to the next disc-less state. The disc reappears with some asymmetry already present (density wave?). As the strength of the line increases, the two peaks converge and the line width diminishes (disc growth). This is followed by a number of fast transitions between single-peaked and shell profiles (precession). Finally, the strength of the line decreases and the disc disappears (dissipation). Note that all spectra have been divided by a polynomial fit to the continuum and normalised to the same scale. The numbers refer to Table 1. The times at which X-ray outbursts occurred are marked, but note that the horizontal (temporal) scale is not linear

Table 4. Observational details of the infrared photometry. All the observations are from the TCS

Date	TJD	J mag	H mag	K mag
Jul. 27, 1996	10292.7	11.58 ± 0.04	11.10 ± 0.01	10.67 ± 0.02
Jul. 28, 1996	10293.7	11.68 ± 0.04	11.08 ± 0.01	10.72 ± 0.03
Jul. 29, 1996	10294.6	11.55 ± 0.05	11.10 ± 0.03	10.72 ± 0.02
Jul. 17, 1997	10646.7	12.87 ± 0.16	12.15 ± 0.13	12.03 ± 0.14
Jul. 18, 1997	10648.7	12.67 ± 0.09	12.06 ± 0.05	11.75 ± 0.04
Jul. 19, 1997	10649.7	12.45 ± 0.05	11.93 ± 0.04	11.77 ± 0.03
Jul. 20, 1997	10650.7	12.17 ± 0.05	11.67 ± 0.04	11.43 ± 0.04
Jul. 21, 1997	10651.7	12.46 ± 0.05	11.89 ± 0.04	11.72 ± 0.06
Jun. 16, 1998	10981.7	11.93 ± 0.04	11.26 ± 0.03	10.73 ± 0.05
Jun. 17, 1998	10982.7	12.11 ± 0.06	11.56 ± 0.02	11.10 ± 0.02
Oct. 27, 1998	11114.4	11.63 ± 0.07	11.17 ± 0.04	10.64 ± 0.06

Our observations (see Fig. 3) reveal that during 1996 the strength of the emission lines in V635 Cas gradually declined and sometime between February and July 1997 (unfortunately the period during which the source is too low to be observed from La Palma), the absorption lines typical of the photosphere of an early-type star became visible. Similar disc-less states have been reported in the Be/X-ray binaries X Persei (Roche et al. 1997) and V725 Tau/A 0535+26 (Haigh et al. 1999). The absorption spectrum seen is typical of a normal B star and the transitions are interpreted as due to the loss of the circumstellar disc.

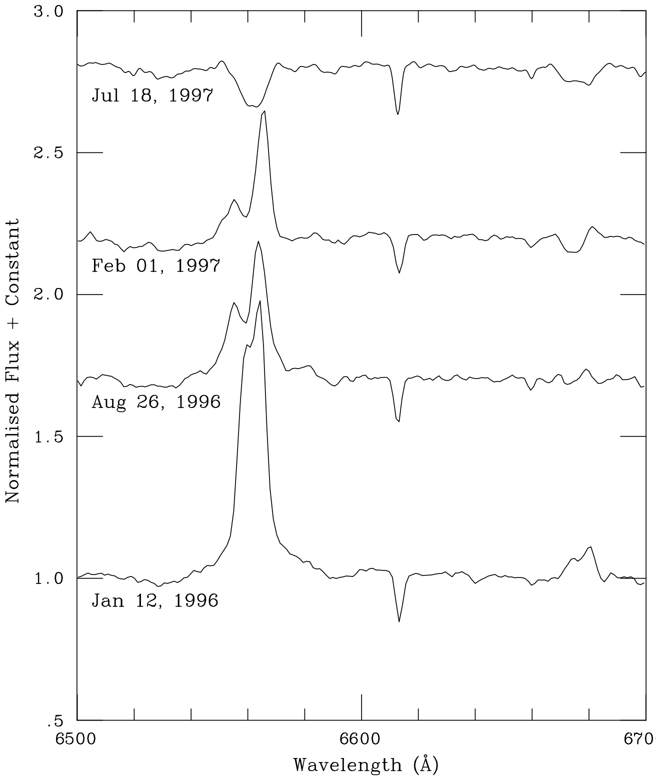

Fig. 3. Series of red spectra of V635 Cas showing the gradual weakening and final disappearance of the emission lines during 1996 and early 1997. Note the increase in the asymmetry as the line strength decreases. All spectra have been divided by a spline fit to the continuum for normalisation and arbitrarily offset for clarity. See Table 1 for observational details of the spectra

Several spectra taken during the summer and autumn of 1997, following the dispersion of the envelope (see examples in Fig. 2 of Paper I) show the profile of Hα basically reflecting the photospheric absorption feature, though some residual emission seems to be present in all the spectra (the effect is much stronger in the He I $\lambda\lambda$ 6678, 7065 Å lines). In the case of the disc-less phase of the Be/X-ray binary X Persei, Telting et al. (1998) conclude that even though the low photometric state lasted many months, the photospheric lines were seen without any contamination for only $\sim$4 weeks. After this, weak emission was observed in the line wings. Therefore it is likely that in the case of V635 Cas there was a short time-span during which the lines were purely photospheric, but this must have taken place as soon as the lines reverted to absorption, i.e., during the gap in our observations. Stronger highly-variable emission wings are seen in the spectra from October and November 1997, as is typical of Be stars showing low-level activity during an extended disc-less state (see Hanuschik et al. 1993; Rivinius et al. 1998 for examples).

The presence of absorption lines coincides with a photometric low state, as can be readily seen by comparing the infrared magnitudes during July 1997 to those of July 1996 and June 1998. This is expected, since free-free emission from the circumstellar disc contributes significantly to the photometric magnitudes (N97). However, the very large variability observed in the infrared magnitudes during one week in July 1997 shows that even when the disc is almost totally absent, low-level activity still results in the presence of some circumstellar material that contributes significantly to the total brightness. Because of this, it is unlikely that any single photometric dataset can be thought to characterise a "state" of the source. It is significant that the $BVRI$ measurements from October 1997 are very similar to those taken at other epochs when the disc was present, while those from January 1998 show a decrease in I by 0.32 mag with respect to the October 1997 values. Since the January 1998 observation presents the faintest and bluest magnitudes in our dataset and the I-band magnitude (which is more likely to suffer from circumstellar contamination than bluer magnitudes) measured on that date is as faint as the faintest point measured by Mendelson & Mazeh (1991, henceforth MM91) in the five years spanned by their photometric monitoring of the source, we expect these magnitudes to be close to the actual apparent magnitudes of the star without any contribution from a disc.

This is consistent with the fact that, even though all visual and infrared magnitudes of V635 Cas fluctuate continuously, the V magnitude has a tendency to take a value of $V \approx 15.5$ when the source is faint. The B-band lightcurve presents smaller fluctuations than the V band and, again, the value during faint states seems to be consistently $B = 16.9$. In Paper I, we showed that the colours derived from the January 1998 observations are consistent with the intrinsic colours of a B0V star with the measured interstellar reddening and consequently used this photometric dataset to determine the distance to the source. Therefore we conclude that, in spite of the observed activity during October and November 1997, the source was basically disc-less in January 1998.

After the disc-less state, disc reformation was very quick. As can be seen in Table 1 and Fig. 4, typical emission lines were present by August 1998, only $\sim$6 months after the photometric minimum. We note that the lines had been observed to be in absorption in February 1992 (Unger et al. 1998). Our observations show that emission was again present in August 1992. Also in this case, the time for disc reformation is constrained to be $\lesssim$6 months.

In both cases, the line profile after the disc-less phase was double-peaked and relatively broad, corresponding to a Be star seen under a moderately large inclination (Hummel 1994; Hanuschik et al. 1996). In Paper I, a moderate inclination of $40^\circ < i < 60^\circ$ was derived. Therefore, this particular line profile must be interpreted as the "quiescence" shape for V635 Cas, in the sense that it reflects the inclination of the system and corresponds to an unperturbed quasi-Keplerian disc (in the sense defined by Hanuschik 1996), while other line profiles correspond to perturbed states of the disc.

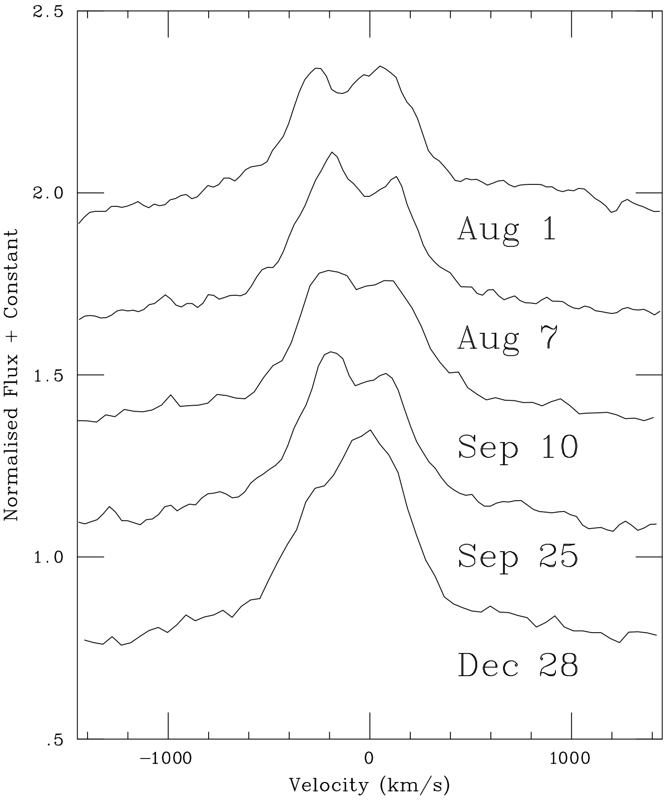

Fig. 4. Evolution of the Hα line during 1998. Compare this series with that shown in Fig. 7 (for the 1992–1993 period). As the line strength grows, both the peak separation and $FWHM$ decrease, indicating a growing disc. All spectra have been divided by a spline fit to the continuum for normalisation and arbitrarily offset for display. See Table 1 for observational details of the spectra

3.2. Timescales

Whitlock et al. (1989) were the first to notice that the X-ray activity of 4U 0115+63 seemed to occur with a quasi-periodicity of ~3 yr during 1974–1989. This quasi-periodicity was broken when the February 1990 outburst was followed by another outburst in March 1991. However, the gap between this outburst and the following one, in May 1994, was slightly over three years. During the 1992–1997 cycle, there were two major outbursts and several type I outbursts and flares, but the gap between the November-December 1995 type II outburst and the next type II outburst in March 1999 was again ~3 years.

Our observations reveal that during the last two 3-year gaps the circumstellar disc dispersed and reformed. If the previous photometric low state in 1989 (MM91) was also due to a disc loss episode, this would mean that the typical gap of ~3 years between X-ray outbursts and the ~3-year cycles of disc loss and reformation occur in phase. Given that the X-ray source is powered by accretion of material from the circumstellar disc, we conclude that the X-ray quasi-periodicity is induced by the typical time-scales for disc loss and reformation.

Since all the variability in the line profiles, infrared magnitudes and X-ray activity seems to be correlated and driven by this disc growth/dispersion cycle (see Fig. 1 where the cyclic nature is apparent in the infrared magnitudes), in what follows we will divide the time covered by these observations into:

- **Cycle A:** Starting with the low photometric state in 1989 (which we interpret as a disc-loss event) and ending at the disc-less episode in early 1992. Two X-ray outbursts were observed in February 1990 and March/April 1991;
- **Cycle B:** Starting with the disc-less state in 1992 and lasting until the disc-less state in 1997. Two type II outbursts took place in May 1994 and November 1995, as well as some smaller flares;
- **Cycle C:** Starting with the disc-less state in 1997 and still continuing. A type II X-ray outburst took place in March 1999.

A second time-scale observed is that of line changes. We find that the typical time-scale for large changes is ~1 month (the shell to single-peaked transitions observed in January 1991 and October 1995) while a particular line shape seems to exist for several months. In the following sections, we will discuss these line changes in detail and conclude that they likely arise from the precession of the warped disc of V635 Cas.

A third, less obvious time-scale could characterise the X-ray activity during each of the cycles. During cycle B, X-ray coverage of the source was continuous. The source was active on four occasions. There were two large outbursts in May 1994 and November 1995, a small flare in January 1995 and a series of small (type I) outbursts after August 1996. We note that the time interval between these four periods of activity (May 1994 – Jan. 1995 – Nov. 1995 – Aug. 1996) was always ~8 – 9 months. Such a separation is comparable to the gap between the two outbursts seen in cycle A (though coverage was not complete around this time and smaller flares could have gone undetected) and the ~6 month quasi-period observed between four weak outbursts that took place during 1969 – 1970 (Whitlock et al. 1989). This third time-scale is also probably associated with the dynamics of the circumstellar disc, as discussed in the next sections.

3.3. Disc warping

As can be seen in Fig. 2, the Hα emission line is extremely variable. The changes affect not only its shape but also the Full Width at Half Maximum ($FWHM$) and the Total Base Width (TBW). Other emission lines, like He I λ6678 Å, undergo a parallel evolution (see Fig. 3 and also N98). In Table 1, the shape of Hα in every spectrum has been indicated according to the following convention: when the line is fundamentally photospheric absorption it is labelled ABS; emission lines have been marked as single-peaked (SP), double-peaked (DP) or shell (SH), followed by a letter that describes the symmetry of the profiles, i.e., red dominated (R), blue dominated (V) or symmetric (S) when the two peaks have a similar strength or the single peak looks symmetric. Thus, SPR means a single peaked profile with the peak on the red side of the line profile.

The different shapes of emission lines seen in different Be stars are in principle attributed to the different inclinations with respect to the line of sight of an equatorial circumstellar disc (see Hanuschik et al. 1995; Hummel 1994). For low inclination angles, single-peaked profiles are seen (generally showing flank inflections due to non-coherent scattering, producing the wine-bottle profile). For intermediate inclinations, double-peaked profiles are seen due to Doppler broadening. For large inclinations, the outer cooler regions of the disc intercept the line of sight and give rise to shell profiles, characterised by deep narrow absorption cores that go below the continuum level, at least in optically thin lines.

Hanuschik (1996) proposed that, for a restricted interval of inclinations around $i \simeq 70°$, changes in the disc radius or thickness can cause the line shapes to change between double-peaked and shell, but this cannot be the reason for the shell episodes of V635 Cas, since it also displays single-peaked profiles. As a matter of fact, shell profiles were only observed as part of fast shell/single-peak transitions that took place during the last phases of cycles A and B, leading in both cases to the dispersion of the disc. Similar phenomenology (generally referred to as spectacular variations) in the isolated Be stars γ Cas and 59 Cyg was explained by Hummel (1998) in terms of variations in the angle under which we are seeing the circumstellar disc due to its precession after it has tilted off the equatorial plane.

In this picture, the circumstellar disc evolves from an intermediate line-of-sight inclination (corresponding to the equatorial plane of the Be star) to a much lower inclination angle. When the disc is seen face-on, we see single-peaked lines and the associated brightening because we observe emission from the whole disc surface. As the disc precesses we come to see it under a large inclination angle and its external regions intercept the light from the inner disc, resulting in the observation of shell lines and a faint state due to self-absorption of disc and stellar emission.

Our dataset is far from having the time resolution of the γ Cas observations that were used to derive this interpretation, and provides only a few snapshots of the evolution of line shapes. We are not able to precisely identify the occurrence of full single-peaked or shell episodes and therefore when considering a spectrum we cannot in general decide to which phase of a shell/single-peak transition it corresponds. However, we note the following similarities:

(I). As γ Cas, V635 Cas is seen under a moderate inclination angle and, when an unperturbed disc is present, it displays double-peaked symmetrical profiles;

(II). As in the case of γ Cas, the shell/single-peak transition events end up in the dispersion of the circumstellar disc. This happens in both cycle A and B;

(III). As in the case of γ Cas, V/R variability occurs during the transitions in both cycle A and B. In cycle B, we know that it started before the onset of single-peak/shell transitions (as in γ Cas). In cycle A, we have no observations previous to the onset of the transitions;

(IV). For the single-peak phase that occurred around October 1996 (last single peak of cycle B), which is the only phase that we can time with some accuracy, we see that the symmetry was $V > R$ before the single peak and $R > V$ after the single peak, as in γ Cas;

(V). In cycle B, the single peaked phase close to January 1995 was accompanied by very bright infrared and optical magnitudes ($J = 10.9$ on Jan. 3). The shell phase during the summer was accompanied by much fainter magnitudes ($J = 12.1$ in late July). The infrared magnitudes reached a maximum close to the next single-peak episode ($J = 10.8$ on Oct. 15) and then faded as the disc dispersed. Similarly, during cycle A the transition between a shell phase and a single peak that took place close to Jan. 1991 was accompanied by a brightening in the I band by more than 1 mag (N97). In contrast, the large increase in Hα EW that immediately preceded the 1992 disc loss was not accompanied by a brightening of the source (Unger et al. 1998; N97).

In summary, insofar as the observations constrain the model, they favour a close parallel with the spectacular variations of γ Cas. The only point in which the parallel is not obvious are the large changes in TBW that accompanied the transitions in γ Cas. As a matter of fact, it is very difficult to estimate the TBW of the emission lines in V635 Cas because 1) the continuum is difficult to determine (as discussed in Paper I) and 2) even when the overall profile is a narrow single peak, there is a broad base component, (as illustrated in Fig. 5, but see also the 12th Jan. 1996 profile in Fig. 3) on top of which it sits.

Furthermore, in order to test the validity of the explanation, we calculated synthetic line profiles for the disc model with the parameters listed in Table 1 of Paper I and a viscosity parameter $\alpha = 0.1$ (i.e., the disc whose structure is shown in Fig. 5 of Paper I) and allowed the inclination angle i to vary. Since disc truncation will lead to higher densities in the disc than in isolated Be stars, the line optical depth when the disc is seen pole-on was taken to be $\tau = 10^4$. The profiles were computed using the same method as described in Okazaki (1996), but now the stellar continuum and the deviation from the LTE state of the second energy level of hydrogen have been included. We assumed that the stellar source function is equal to the Planck function at $T_{\rm eff}$ and that the deviation factor, b_2, is given by $b_2 = 1/W$, where W is the dilution factor defined by $W = \frac{1}{2}\{1 - \left[1 - (R_*/r)^2\right]^{1/2}\}$ (e.g., Hirata & Kogure 1984).

As can be seen in Fig. 6, the theoretical profiles match very well the observed profiles for moderate and high inclinations (the small difference between the observed and calculated shell profile being attributable to the $V > R$

asymmetry in the former, which was not considered in the latter), but fail completely to describe the single-peaked profiles. Our interpretation for this is that the disc is not tilted as a solid body but warped (see Fig. 6) and therefore the central parts of the disc are still seen under a moderate inclination and contribute high velocity components to the emission lines that create the observed broad base (which, as expected, has a TBW similar to that of double-peaked profiles).

We conclude then that the alignment with the line of sight of very different geometrical configurations of a precessing warped disc is the cause of the shell/single-peaked transitions in V635 Cas. We can then divide each of the disc formation and dispersal cycles into a number of phases:

(1). A disc-less phase, where low level emission can be occasionally seen on the line wings;
(2). A growing-disc phase, where the EW of Hα is observed to grow, while its $FWHM$ decreases (as seen at the start of cycles B and C). During this phase, there can be fast (days) V/R variability (cf. Fig. 4), but also large-scale V/R variations with longer (many months) quasi-periods, as during the growing phase of cycle B (cf. Fig. 7);
(3). A warping of the disc, followed by its precession. It is during this time that the shell/single-peak transitions are seen;
(4). The dispersal of the disc.

4. Global disc oscillations

As mentioned, the emission lines in V635 Cas do generally display V/R variability. This can be small in scale and rather fast (cf. Fig. 4), and probably associated with episodic slightly enhanced mass loss from the star (a phenomenon seen in many other Be stars with small discs or during disc reformation; cf. Rivinius et al. 1998), but also on a much larger scale (as in Fig. 7). This second variability is similar to the long-term variability observed in many Be stars and Be/X-ray binaries and can be attributed to the presence of an $m = 1$ mode in the disc, where m is the azimuthal wave number (Kato 1983; Okazaki 1991; Papaloizou et al. 1992; Hanuschik et al. 1995; Hummel & Hanuschik 1997).

Hitherto, the characteristics of the $m = 1$ modes in Be discs have been studied only for non-viscous cases, in which the $m = 1$ modes are neutral, i.e., their frequencies have no imaginary part. We have studied the applicability of the $m = 1$ modes to the disc model developed for V635 Cas in Paper I. In what follows, we show that the $m = 1$ modes are overstable in viscous decretion discs. For this purpose, we first consider the stability of the local perturbations which vary as $\exp[i(\omega t - k_{\rm r} r - m\phi)]$. After Kato et al. (1988) who studied the stability of viscous accretion discs to pulsational (i.e., axisymmetric) modes, we can write the local dispersion relation to non-axisymmetric perturbations as

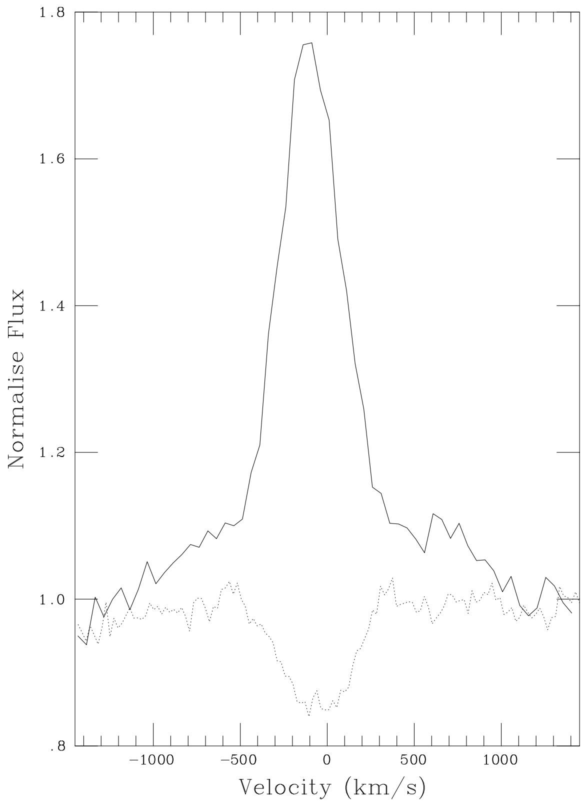

Fig. 5. The complex shape of the Hα emission line. The spectrum from 27th Jan. 1991 is compared to the absorption spectrum observed in July 1997. Note the broad emission component forming a base to the main feature. In Table 1, the TBW of the single-peaked profiles represents the width of the main feature and does not include this broad feature. The two spectra have been divided by 2nd degree polynomial fits to the local continuum

$$(\omega - m\Omega - k_{\rm r}V_{\rm r})\left[(\omega - m\Omega - k_{\rm r}V_{\rm r})^2 - \kappa^2 - c_{\rm s}^2k_{\rm r}^2\right] = -2i\alpha\Omega c_{\rm s}^2 k_{\rm r}^2, \tag{1}$$

where α is the Shakura-Sunyaev viscosity parameter, $c_{\rm s}$ is the sound speed, $V_{\rm r}$ is the radial component of the unperturbed velocity field, and Ω and κ are the frequency of the disc rotation and the epicyclic frequency, respectively.

As pointed out by Kato et al. (1988), among three solutions of Eq. (1), it is the inertial-acoustic mode that is unstable. When the disc is non-viscous, the inertial-acoustic mode is neutral and has the frequency given by

$$\omega - m\Omega - k_{\rm r}V_{\rm r} = \pm(c_{\rm s}^2k_{\rm r}^2 + \kappa^2)^{1/2}. \tag{2}$$

However, when the viscous effect is taken into account as a perturbation, we have

$$\omega - m\Omega - k_{\rm r}V_{\rm r} = \pm(c_{\rm s}^2k_{\rm r}^2 + \kappa^2)^{1/2} - i\alpha\Omega\frac{c_{\rm s}^2k_{\rm r}^2}{c_{\rm s}^2k_{\rm r}^2 + \kappa^2}. \tag{3}$$

Hence, the inertial-acoustic mode becomes overstable when the viscosity is included. The growth rate is given by

$$|{\rm Im}\{\omega\}| = \alpha\Omega\frac{c_{\rm s}^2k_{\rm r}^2}{c_{\rm s}^2k_{\rm r}^2 + \kappa^2} = \alpha\Omega(k_{\rm r}H)^2, \tag{4}$$

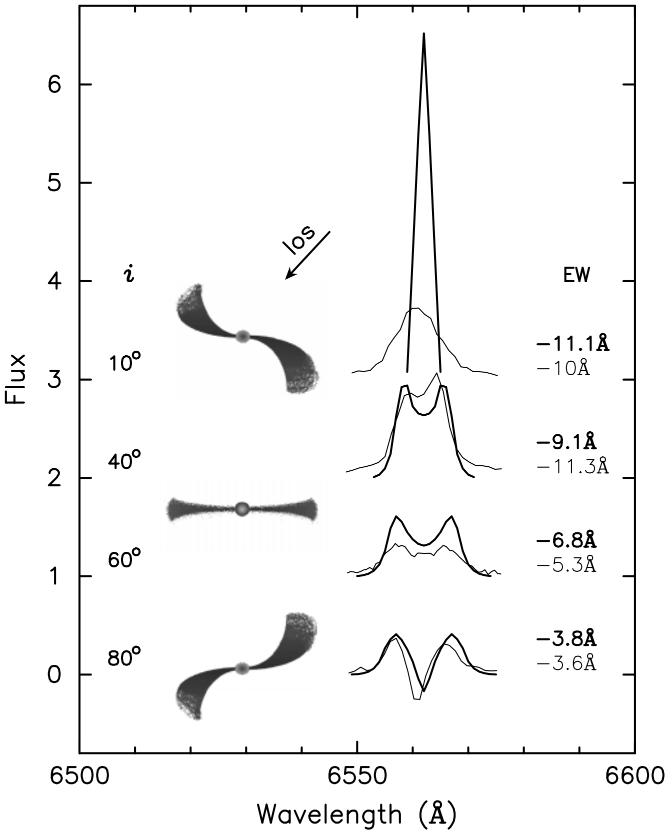

Fig. 6. Synthetic line profiles computed using a disc model with the parameters for V635 Cas derived in Paper I (thick lines) are compared to observed profiles (thin lines). The inclination angle i has been allowed to vary in order to reproduce the tilt caused by disc warping. Annotated on the right hand side of each profile is the model EW for the line (thick print) and the corresponding measured EW on the observed profile (thin print). The profiles chosen for comparison are those that most closely match the theoretical lines, but the actual inclination angle of the disc under which they were produced (which is, of course, unknown) may well be different from the inclination chosen for the model. A schematic model of the disc configurations that would produce the profiles is included. The line of sight is supposed to have an inclination with respect to the equatorial plane of $\sim$50°. The top configuration will produce profiles as those observed (i.e., with a narrow peak coming out of a broad base), rather than the simple single-peak theoretical profile, which corresponds to a purely tilted disc. Due to the disc warp, the central regions of the disc, which are still seen under a moderate inclination angle, contribute high-velocity components, which result in the observed broad base (see Fig. 5)

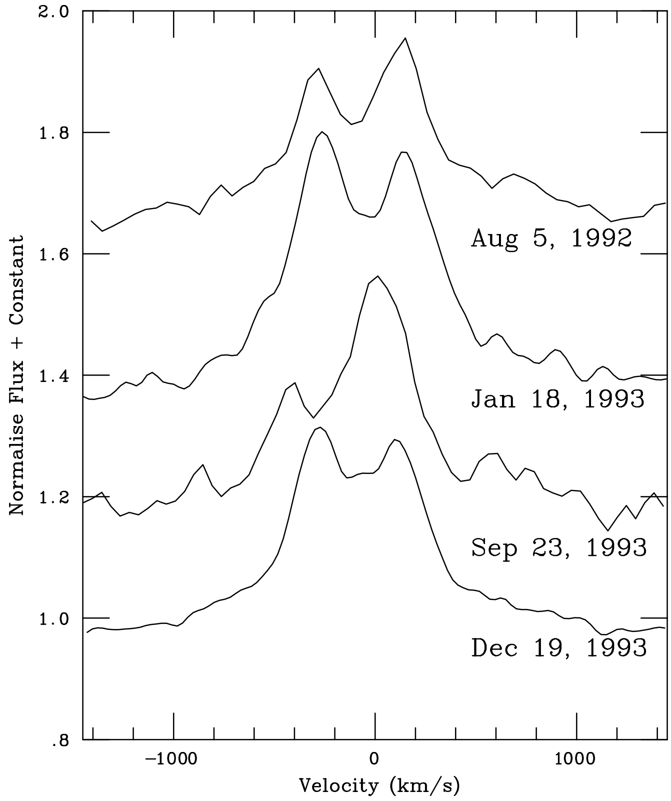

Fig. 7. Evolution of the Hα line during 1992–1993, showing evidence of a global mode propagating in the circumstellar disc. All spectra have been divided by a spline fit to the continuum for normalisation and arbitrarily offset for display. See Table 1 for observational details of the spectra

where the second equality holds for geometrically-thin, near Keplerian discs, in which $c_{\rm s} \sim \Omega H$ and $\kappa \sim \Omega$.

Next, we study the stability of global $m = 1$ perturbations. For simplicity, we consider isothermal perturbations. It can be shown that linearized equations for $m = 1$ isothermal perturbations superposed on the unperturbed axisymmetric disc discussed in Paper I are written as

$$\left[i(\omega - \Omega) + V_{\rm r}\frac{\rm d}{{\rm d}r}\right]\frac{\sigma_1}{\sigma_0} + \frac{1}{r\sigma_0}\frac{\rm d}{{\rm d}r}(r\sigma_0 v_{\rm r}) - \frac{iv_\phi}{r} = 0, \quad (5)$$

$$c_{\rm s}^2\frac{\rm d}{{\rm d}r}\left(\frac{\sigma_1}{\sigma_0}\right) + \left[i(\omega - \Omega) + \frac{{\rm d}V_{\rm r}}{{\rm d}r} + V_{\rm r}\frac{\rm d}{{\rm d}r}\right]v_{\rm r} - 2\Omega v_\phi = 0, \quad (6)$$

$$c_{\rm s}^2\left(-\frac{i}{r} + \alpha\frac{\rm d}{{\rm d}r}\right)\frac{\sigma_1}{\sigma_0} + \frac{\kappa^2}{2\Omega}v_{\rm r} + \left[i(\omega - \Omega) + \frac{V_{\rm r}}{r} + V_{\rm r}\frac{\rm d}{{\rm d}r}\right]v_\phi = 0, \quad (7)$$

where σ_0 and σ_1 are the unperturbed surface density and the Eulerian surface-density perturbation, respectively, and $(v_{\rm r}, v_\phi)$ is the vertically averaged velocity field associated with the perturbation. As boundary conditions, we impose $(v_{\rm r}, v_\phi) = \mathbf{0}$ at the inner edge of the disc and $\Delta p = 0$ at the outer disc radius, where Δp is the Lagrangian perturbation of pressure. Solving Eqs. (5)–(7) with the unperturbed state shown in Fig. 5 of Paper I and the above boundary conditions, we have the fundamental $m = 1$ mode shown in Fig. 8. The period of the mode is 1 yr and the growth time is 4.6 yr. Note that we have a similar growth time (6 yr) from Eq. (4) based on the local analysis, taking $k_{\rm r} \sim \pi/r_{\rm d}$, where $r_{\rm d}$ is the disc outer radius. Since $r_{\rm d}$ is close to the periastron distance in a rough sense, we expect from Eq. (4) that a system with a larger periastron distance will show a slower growth of the $m = 1$ mode.

The disc perturbed by the $m = 1$ mode becomes eccentric and shows quasi-periodic changes in Balmer line

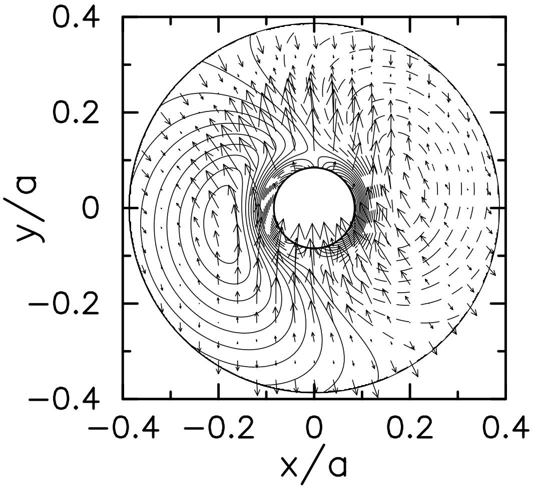

Fig. 8. Linear, isothermal $m = 1$ mode in the viscous disc around V635 Cas. The unperturbed disc structure is given in Fig. 5 of Paper I. The period of the mode is 1 yr and the growth time is 4.6 yr. Both disc and mode rotate counterclockwise. The contours denote the relative density perturbation in linear scale. The solid (dashed) contours are for the region with positive (negative) density enhancement. Arrows superposed on the contours denote the perturbed velocity vectors normalized by the unperturbed angular velocity, $(v_r/V_\phi,\ v_\phi/V_\phi)$

profiles, the so-called long-term V/R variations. The slow growth of the $m = 1$ mode suggests that this phenomenon will be observed only after the disc is fully developed, but before it becomes unstable to warping. During 1992–1993, 4U 0115+63 exhibited the long-term V/R variations, which are similar to those of isolated Be stars, except that the period of variability is much shorter for 4U 0115+63 than for isolated Be stars (see Fig. 7). We note that the characteristics of the $m = 1$ mode shown in Fig. 8 are in agreement with these variations. The model could also explain the V/R variability observed in 1996–97, though it is also possible that these variations were due to the warp in the Be disc or, more likely, a combination of both effects.

5. Discussion

5.1. The shell-ejection hypothesis

Many authors (e.g., Kriss et al. 1983) have attributed the onset of type II outbursts in Be/X-ray binaries to hypothetical events of enhanced mass loss from the Be star. In this picture, a shell of material is ejected from the Be star and, after reaching the orbit of the neutron star, part of it is accreted via an accretion disc. 4U 0115+63 has long been considered the prototypical system in which this behaviour was observed. This hypothesis is difficult to hold in view of the observations presented here, which suggest completely different causes for the observed behaviour. However, since this is a very extended and generally invoked picture, we would like to show its lack of consistency, taking as an example the strong type II X-ray outburst starting on Nov. 18, 1995 (Finger et al. 1995), shortly after the last single peak phase of cycle B and its associated brightening.

Figure 9 shows the change in the emission lines that took place, which must reflect a global and profound change in the mass distribution of the disc, since the change in symmetry persisted for a long time and ultimately led to the dispersal of the circumstellar disc (see Fig. 3 and the discussion in N98). If we try to explain all these changes and the type II X-ray outbursts as a consequence of the ejection of a shell of material, we find that:

- Since the shell ejection resulted in a global change of the physical conditions of the disc, an amount of matter comparable to a substantial fraction of the disc mass must have been ejected;
- The shell ejection resulted in a global change of the mass distribution in the disc, indicating that it was *very* asymmetric. The shell becomes a blob, with $M_{\rm blob} > 10^{-10}\,M_\odot$ (mass accreted in order to produce the observed X-ray luminosity);
- The episode resulted in a global change of the disc structure in less than one month. This means that the blob must have been ejected with a rather high radial velocity ($\gtrsim 5\,{\rm km\,s^{-1}}$);
- The episode resulted in a very luminous X-ray outburst – the blob was able to impact the neutron star about one month later. Such a short timescale suggests that the blob was not circularized and merged into the Be disc because of the action of viscous forces.

We cannot think of any physical mechanisms within the framework of our knowledge of Be stars (or stars in general) that could generate such a scenario. We are therefore forced to drop the shell ejection hypothesis. We note that a modified version of this picture was defended in N97. This was mainly due to the fact that, due to sampling effects, shell lines were the most frequent shape in the sample, leading to the interpretation that they represented the quiescence state of the system and therefore that the system inclination with respect to the line of sight was very large.

5.2. The mechanism for type II outbursts

The body of observations presented here suggests a completely different explanation for the optical and X-ray behaviour of 4U 0115+63. The dynamical evolution of the (presumably viscous decretion) disc surrounding the Be star is responsible for the spectacular changes in optical brightness and line shapes, and represents the driving force inducing the X-ray behaviour of the system.

As outlined in Sect. 3.3, the cycles of disc loss and reformation are the main modulator of the X-ray behaviour. In each one of those cycles, after the phase of disc growth, the disc must reach the radius at which it is truncated by the presence of the neutron star (presumably, the 4:1 resonance). As a consequence of truncation, the density of the circumstellar disc must grow for a time, until the disc

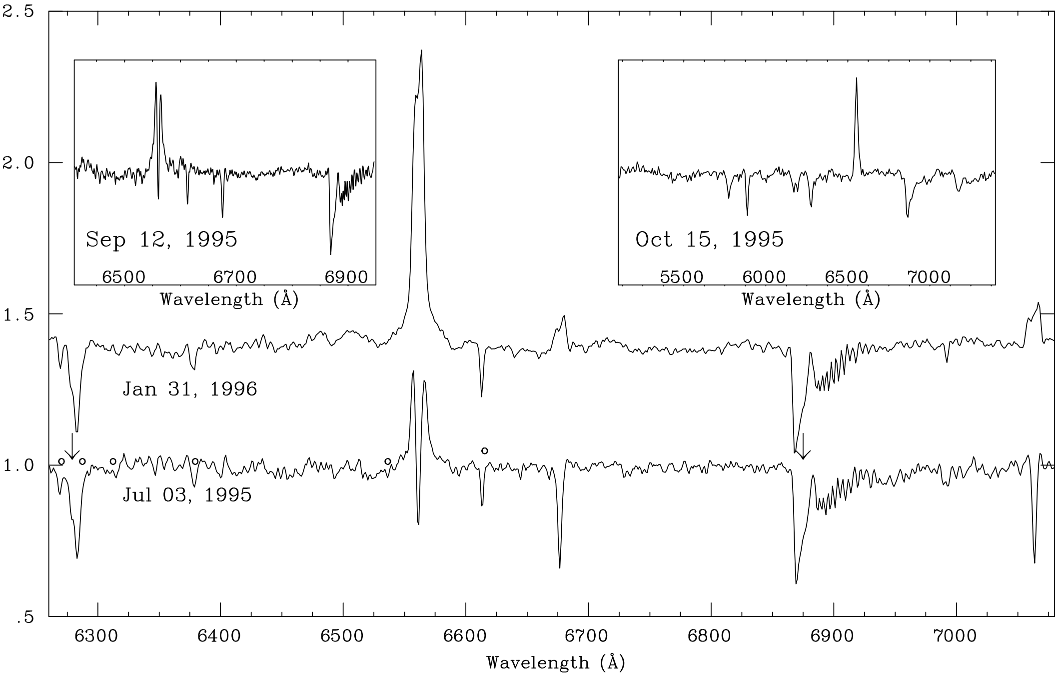

Fig. 9. A large change in the shape of the emission lines took place immediately before the November 1995 type II X-ray outburst. The two spectra in the main panel, taken with the same instrumental setting, allow a direct comparison of the change in Hα and He I $\lambda\lambda$ 6678, 7065 Å lines. The spectra in the two small insets, with very different resolutions and spectral ranges, strongly constrain the time during which the change took place. The duration of the event was less than one month. All spectra have been divided by a spline fit to the continuum for normalisation and arbitrarily offset for clarity. The strongest diffuse interstellar bands are marked with a "○" on the spectrum from July 3rd, while the strongest telluric features are marked by an arrow. See Table 1 for observational details of the spectra

becomes sufficiently optically thick to continuum radiation for radiation-driven warping to become possible (see Porter 1998 for a discussion). As the disc warps, the tilt of the outer regions increases until they come to be close to perpendicular to the line of sight.

The observation of shell lines alternating with single-peaked profiles indicates that the disc must, at some point, start precessing. When the warping is driven by radiation, the time-scale of this precession is given by Porter (1998) as

$$T \approx \left(\frac{R_*}{R_\odot}\right)^{\frac{5}{2}} \left(\frac{M_*}{M_\odot}\right)^{\frac{1}{2}} \left(\frac{L_*}{L_\odot}\right)^{-1} \mathrm{yr} \qquad (8)$$

where we interpret L_* as the stellar luminosity to which the disc becomes optically thick. In the case of V635 Cas, in which several per cent of the total luminosity is expected to contribute to drive the warp, we have $T \approx O(100\,\mathrm{d})$, which is a typical time-scale for the changes in the emission lines.

At present, it is not clear if the tidal warping of the neutron star will contribute to make the disc precess as a rigid body. Early results by Papaloizou & Terquem (1995) and Larwood (1998) seem to indicate that tidal torques when the disc is not coplanar with the binary orbit will lead to a rigid body precession of the disc. However, recent results by Lubow & Ogilvie (2000) indicate that a disc that extends as far as the 4:1 resonance is too big for tidal torques to be effective. For this reason, we will not discuss the role of tidal torque. If the orbit was not coplanar with the equatorial disc, tidal torque would act on it from the beginning, but the overall behaviour would not be very different.

The observations of V635 Cas show that during cycles A and B the X-ray outbursts take place during (or shortly before) the phase of shell/single-peak transitions. Though we cannot rule out the possibility that there is no causal connection between these two phenomena (for example, if the accumulation of a large amount of material is a pre-condition for both disc warping and mass transfer to the neutron star, neither will happen at the start of the cycle), the large perturbation induced on the disc by the combined effects of global modes and radiative warping offers a good candidate for the reason why tidal truncation can be occasionally overcome. We envisage that, since the disc is heavily distorted, its outer regions, in which the density is high due to the resonant truncation, can overflow the critical Roche potential towards the gravitational well of the neutron star. We speculate that if the disc is heavily elongated in the direction towards periastron, as the precession time-scale is long compared to the orbital period, it can shift its dense outer part onto the neutron star for several orbital periods. Once matter has flown onto the neutron star, the onset and duration of the type II outburst will depend on the timescales characteristic of the accretion disc around the neutron star.

We note that this picture is supported by the observed quasi-periodicity of X-ray activity *inside* one cycle and the association of X-ray outbursts with single-peaked lines, which suggests that some particular disc configuration is necessary in order to have X-ray activity, even though this does not imply that such configuration must necessarily result in an X-ray outburst. We must emphasize that, in this picture, the coincidence of single-peaked profiles and X-ray outbursts is due only to the system orientation to the line of sight and that some other phase of the shell/single-peak transition could coincide with mass transfer to the neutron star if the orbit was orientated differently.

5.3. Mass-loss estimates

In order to estimate the amount of material accreted during a type II outburst, we will assume a constant luminosity $L_{\rm x} \approx 3\ 10^{37}\,{\rm erg\,s^{-1}}$ during one month. This is probably an overestimate, but will make up for the assumption of $\eta = 1$ efficiency in the conversion of gravitational energy into X-rays. The derived accretion rate on to the neutron star $\dot{M}_{\rm x} = 1.6\ 10^{17}\ {\rm g\,s^{-1}} = 2.5\ 10^{-9}\ M_{\odot}\,{\rm yr^{-1}}$ means that an amount $\approx 2\ 10^{-10}\ M_{\odot}$ is accreted.

Since the disc does not disappear during a type II outburst, but actually the strength of the lines does not seem to be too much altered, the original mass of the disc must be comparable to the amount of material accreted. Therefore we can assume $M_{\rm disc} \sim 5\ 10^{-10}\ M_{\odot}$ at least – this is, for example, one order of magnitude less than the estimates of disc mass in X Persei by Telting et al. (1998). Since the type II outbursts have been observed to occur between 1 and 2 years after the star is seen in a disc-less state, the mass loss rate from the Be star must be $\dot{M}_{\rm Be} \gtrsim 5\ 10^{-10} M_{\odot}\,{\rm yr^{-1}}$ while the disc is reforming.

Hanuschik et al. (1993) showed that during mass loss events in the Be star μ Cen, the mass loss rate was $\approx 4\ 10^{-9}\ M_{\odot}\,{\rm yr^{-1}}$. This events lasted typically a few days and the amount of material supplied was not enough to build a disc. V635 Cas would only need to be supplying a continuous mass loss rate one order of magnitude smaller than that from μ Cen during outbursts in order to rebuild its disc in the $\sim$6 months determined by our observations. If this material was reaching the neutron star, it would permanently provide enough material for an X-ray luminosity $L_{\rm x} \approx 6\ 10^{36}\,{\rm erg\,s^{-1}}$, which is comparable to that of type I X-ray outbursts.

Since 4U 0115+63 is not displaying persistent X-ray emission at such level (or any detectable level), it is clear that most of the material lost from the Be star is kept in the disc and does not reach the vicinity of the neutron star. Tidal truncation provides an obvious mechanism to prevent material from leaving the disc during the normal state of the system. When dynamical instability leads to the disruption of the disc, material is fed onto the neutron star at a much higher rate than it is leaving the Be star. This means that no "enhanced mass loss phase" from the Be star is necessary in order to explain the occurrence of X-ray outbursts. Moreover, since only a fraction of the disc mass will be fed onto the neutron star during a type II outburst, it is even likely that most of the disc material will fall back onto the Be star during the disc loss process, supporting the idea by Porter (1999) that most of the material in a decretion disc must be reaccreted by the Be star.

5.4. Implications for other Be/X-ray binaries

We have developed a model for the Be/X-ray binary 4U 0115+63 and used it in combination with an empirical approach to explain the phenomenology of this source. The Be/X-ray transient 4U 0115+63 was selected for careful monitoring because its typical timescales seem to be shorter than those of other Be/X-ray binaries, and it is therefore only natural that our model has been first applied to it. However, there is nothing in the derivation of the model or the explanations for the phenomenology of 4U 0115+63 that seems to be exclusive to this system, and we are tempted to attribute the speed of the changes in comparison to similar systems to the closer orbit of the neutron star.

The main conclusions of the application of the viscous decretion model to the Be discs in Be/X-ray binaries hold for other systems, i.e., their discs will be truncated by the resonant interaction of the neutron star. A detailed analysis of the parameter space and the possible behaviours derived is left for a forthcoming paper. However, it looks very likely from the results of this paper that the two types of X-ray outbursts in Be/X-ray transients must be associated with two different mechanisms or phenomena.

The explanations advanced for the behaviour of 4U 0115+63 further support the picture developed in N98 in which type II outbursts are associated with catastrophic perturbations of circumstellar discs. Even though N98 could not decide in which direction a causal connection between the perturbation and the outburst was taking place, the case of 4U 0115+63 strongly suggests that it is the perturbation in the disc which leads to the outburst, and not the other way around. Bildsten et al. (1997) speculated that the type II outbursts of Be/X-ray transients could be caused by a thermal instability in an accretion disc surrounding the neutron star. The results presented here are difficult to reconcile with such a mechanism, since one would expect that, in that case, the onset of type II outbursts would be completely independent of the behaviour of the decretion disc surrounding the Be star, in open contradiction to the observations presented here and in N98.

The large perturbation in the disc of V725 Tau, the optical counterpart to A 0535+26, which occurred at the time of its last type II outbursts (N98) led to the gradual dissipation of the circumstellar envelope (see Haigh et al. 1999; Negueruela et al. 2000). Such behaviour is reminiscent of that observed in V635 Cas and probably indicates some similarly quasi-cyclical activity on a longer time-scale. Since these two sources are the Be/X-ray transients for which more regular optical monitoring has been presented, it is tempting to generalize this result. Both the observations and the estimate of mass loss rates and accretion rates during X-ray outbursts support the idea that type II outbursts in Be/X-ray transients are associated with major dynamical disturbances of the Be star disc rather than "shell ejection" or "enhanced mass loss".

However, we do not imply that large perturbations are a necessity for X-ray outbursts in all Be/X-ray transients. As a matter of fact, a whole cycle of disc growth and dispersal was observed between 1996 and 2000 in LS 992, the optical counterpart to RX J0812.4−311 (Reig et al. 2001). The time-scales for the cycle, for disc loss and disc formation were very similar to those seen in V635 Cas. However, the X-ray behaviour was completely different. As soon as the disc reached a certain size, the source started a series of type I outbursts which lasted while the disc was present (Reig et al. 2001). We speculate that in this system (whose orbital parameters are, except for the presumed 81-d orbital period, unknown) the truncation mechanism is not as efficient as in 4U 0115+63 and the disc can transfer mass to the neutron star at every periastron passage. It is even likely that it is precisely because the efficient truncation of the disc does not allow mass transfer to the neutron star during long periods (preventing type I outbursts) that the disc in V635 Cas experiences large-scale perturbations and type II outbursts occur.

Finally, both observational and theoretical results for 4U 0115+63 confirm the hypothesis advanced for V 0332+53 (Negueruela et al. 1999) that the long periods of quiescence of Be/X-ray transients can be due to the limitation of the disc size by the neutron star. Therefore we can conclude that the mechanism controlling the overall X-ray behaviour of the systems is the dynamical interaction of the Be decretion disc with the neutron star.

6. Conclusions

We have studied the long-term behaviour of the prototypical Be/X-ray transient 4U 0115+63/V635 Cas. Long-term monitoring observations indicate that the disc around V635 Cas undergoes quasi-cyclic formation and dissipation. The time-scale of this quasi-cycle is compatible with viscous processes. A quasi-Keplerian viscous decretion disc model predicts a time-scale in good agreement with our observations.

Our long-term monitoring observations also revealed that V635 Cas exhibited all types (double peaks, single peak, shell, and absorption) of emission line profiles typically seen in Be stars. We interpret the drastic changes in the line shapes as due to warping and/or tilting episodes of the disc. These large changes in the disc are associated with type II X-ray outbursts, a fact difficult to reconcile with models in which the outbursts are caused by physical processes that affect only the vicinity of the neutron star.

We have shown that viscous decretion discs are overstable against global one-armed modes. Modelling the disc around V635 Cas as a viscous decretion disc naturally reproduces the typical time-scales of V/R variability observed in the system.

Due to tidal truncation, the Be disc acts as a natural reservoir of material, storing mass lost from the Be star and then feeding it onto the neutron star at a very high rate after it has become very perturbed. We are led to conclude that it is the dynamical evolution of the circumstellar disc under the influence of the radiation pressure from the central star and the tidal effect of the neutron star companion that controls the X-ray phenomenology.

Acknowledgements. We are very grateful to the PATT and CAT committees for the allocation of time on their telescopes. This work would not be possible without the ING service programme. Special thanks to Don Pollacco for his interest in the monitoring of V635 Cas. The WHT, INT and JKT are operated on the island of La Palma by the Royal Greenwich Observatory in the Spanish Observatorio del Roque de Los Muchachos of the Instituto de Astrofísica de Canarias. This research has made use of the La Palma Data Archive and of the Simbad database, operated at CDS, Strasbourg, France. Special thanks to Dr. Eduard Zuiderwijk for his help with the La Palma data. Thanks are due to all the astronomers that have been involved in this monitoring campaign. James Stevens obtained and reduced the November 1997 optical photometry. We thank the referee Wolfgang Hummel for his many careful and constructive remarks, which certainly contributed to improve the paper. Data reduction was mainly carried out using the Liverpool John Moores University *Starlink* node, which is funded by PPARC. During this work, IN was supported by a PPARC postdoctoral fellowship and later an ESA external fellowship.

References

Alonso, A., Arribas, S., & Martínez-Roger, C. 1998, A&AS, 131, 209
Bildsten, L., Chakrabarty, D., Chiu, J., et al. 1997, ApJS, 113, 367
Campana, S. 1996, ApSS, 239, 113
Cominsky, L., Roberts, M., & Finger, M. H. 1994, in The Second Compton Symposium, ed. C. E. Fichtel, N. Gehrels, & J. P. Norris (AIP Press, New York), 294
Draper, P. W. 1998, Starlink User Note 139.7, R.A.L.
Finger, M. H., Scott, M., Magedon, K., et al. 1995, IAUC, 6266
Haigh, N. J., Coe, M. J., Steele, I. A., & Fabregat, J. 1999, MNRAS, 310, L21
Hanuschik, R. W. 1996, A&A, 308, 170
Hanuschik, R. W., Dachs, J., Baudzus, M., & Thimm, G. 1993, A&A, 274, 356
Hanuschik, R. W., Hummel, W., Dietle, O., & Sutorius, E. 1995, A&A, 300, 163
Hanuschik, R. W., Hummel, W., Sutorius, E., Dietle, O., & Thimm, G. 1996, A&AS, 116, 309
Heindl, W. A., Coburn, W., Gruber, D. E., et al. 1999, ApJ, 512, L49
Hirata, R., & Kogure, T. 1984, Bull. Astr. Soc. India, 12, 109
Howarth, I., Murray, J., Mills, D., & Berry, D. S. 1997, Starlink User Note, 50.20, R.A.L.
Hummel, W. 1994, A&A, 289, 458
Hummel, W. 1998, A&A, 330, 243

Hummel, W., & Hanuschik, R. W. 1997, A&A, 320, 852
Kato, S. 1983, PASJ, 35, 249
Kato, S., Honma, F., & Matsumoto, R. 1988, MNRAS, 231, 37
Kriss, G. A., Cominsky, L. R., Remillard, R. A., Williams, G., & Thorstensen, J. R. 1983, ApJ, 266, 80
Landolt, A. U. 1992, AJ, 104, 340
Larwood, J. D., MNRAS, 299, L32
Lubow, S. H., & Ogilvie, G. I. 2000, ApJ, 538, 326
Manfroid, J. 1993, A&A, 271, 714
Mendelson, H., & Mazeh, T. 1991, MNRAS, 250, 373 (MM91)
Negueruela, I., Grove, E. J., Coe, M. J., et al. 1997, MNRAS, 284, 859 (N97)
Negueruela, I., Reig, P., Coe, M. J., & Fabregat, J. 1998, A&A, 336, 251 (N98)
Negueruela, I., Roche, P., Fabregat, J., & Coe, M. J. 1999, MNRAS, 307, 695
Negueruela, I., Reig, P., Finger, M. H., & Roche, P. 2000, A&A, 356, 1003
Negueruela, I., & Okazaki, A. T. 2001, A&A, 369, 108, Paper I
Okazaki, A. T. 1991, PASJ, 43, 75
Okazaki, A. T. 1996, PASJ, 48, 305
Papaloizou, J. C. B., & Terquem, C. 1995, MNRAS, 274, 987
Papaloizou, J. C. B., Savonije, G. J., & Henrichs, H. F. 1992, A&A, 265, L45
Porter, J. M. 1998, A&A, 336, 966
Porter, J. M. 1999, A&A, 348, 512
Reig, P., Negueruela, I., Buckley, D. A. H., et al. 2001, A&A, 367, 266
Rivinius, Th., Baade, D., Stefl, S., et al. 1998, A&A, 333, 125
Roche, P., Larionov, V., Tarasov, A. E., et al. 1997, A&A, 322, 139
Scott, D. M., Finger, M. H., Wilson, R. B., Prince, T. A., & Vaughan, B. 1996, IAUC, 6450
Shortridge, K., Meyerdicks, H., Currie, M., et al. 1997, Starlink User Note, 86.15, R.A.L
Tamura, K., Tsunemi, H., Kitamoto, S., et al. 1992, ApJ, 389, 676
Telting, J. H., Waters, L. B. F. M., Roche, P., et al. 1998, MNRAS, 296, 785
Unger, S. J., Roche, P. D., Negueruela, I., et al. 1998, A&A, 336, 960
Whitlock, L., Roussel-Dupré, D., & Priedhorsky, W. 1989, ApJ, 338, 381
Zuiderwijk, E. J., Martin, R., Raimond, E., et al. 1994, PASP, 106, 515