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Large-scale perturbations in the circumstellar envelopes of Be/X-ray binaries

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Abstract. We investigate the spectroscopic characteristics of the optical components of Be/X-ray binary systems, using data collected during our seven-year monitoring campaign. We find examples of major changes in the emission line profiles associated with Type II X-ray outbursts, later developing into V/R variability cycles. We show that the time-scales for V/R variability in Be/X-ray transients extend from a few weeks to years and interpret all these changes as due to the presence of global disruptions of the axisymmetric density distribution in the extended envelopes of the Be stars in these systems. The association between X-ray outbursts and V/R variability, the occurrence of very fast changes and the very short quasi-periods of variability displayed by Be/X-ray binaries lead us to conclude that the presence of the neutron star is an important factor affecting the dynamics of the disc-like envelopes. The interaction between the compact companion and the disc would explain the correlation between Hα strength and orbital period recently found. The characteristics of the V/R cycles are, however, mainly independent of the binary parameters.

Key words: stars: circumstellar matter – stars: emission line, Be – binaries: close – stars: neutron – X-rays: stars

1. Introduction

Be/X-ray binaries constitute the major subclass of massive X-ray binaries, in which X-ray emission is due to accretion of matter from an early-type mass-losing star by a compact companion (see Apparao 1994, White et al. 1995, for reviews). Be stars are early-type non-supergiant stars, which at some time have shown emission in the Balmer lines. Both the emission lines and the characteristic strong infrared excess when compared to normal stars of the same spectral types are attributed to the presence of a cool circumstellar envelope, presumably in the shape of a disc (see Slettebak 1988). The physical reasons which give rise to the disc are unknown, but it is generally believed that the high rotational velocity of Be stars plays an important role, even though it is accepted that some other mechanism(s) must be at work.

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Most Be/X-ray binaries have relatively eccentric orbits and the compact companion (in general, a neutron star, but in some cases possibly a white dwarf) spends most of its time far away from the disc surrounding the Be star. Three kinds of X-ray activity are observed (Stella et al. 1986, henceforth SWR):

(1). Persistent low-luminosity ($L_{\rm x} \lesssim 10^{36}$ erg s^{-1}) X-ray emission. Some sources (e.g., X Persei) have always been observed in this state.
(2). Periodical (Type I in SWR) X-ray outbursts ($L_{\rm x} \approx 10^{36} - 10^{37}$ erg s^{-1}), coinciding with the periastron passage of the neutron star. Type I outbursts have been observed in numerous sources, such as A 0535+262 (Motch et al. 1991) and EXO 2030+375 (Norton et al. 1994).
(3). Giant (Type II in SWR) X-ray outbursts ($L_{\rm x} \gtrsim 10^{37}$ erg s^{-1}), which do not show any orbital modulation. Type II outbursts are normally seen in those sources that also display Type I activity (see Parmar et al. 1989, Finger et al. 1996a for examples).

Be/X-ray binary systems which display outbursts are collectively termed Be/X-ray transients. Most transients (e.g. A 0535+26) also show low-luminosity X-ray emission when they are not in outburst, but in systems containing fast-rotating neutron stars, centrifugal inhibition of accretion prevents X-ray emission (SWR) except during outbursts (e.g., 4U 0115+634). Type I outbursts occur in series between long periods of X-ray inactivity (or low-luminosity emission), while the onset of Type II outbursts is completely unpredictable.

2. The circumstellar envelopes of Be/X-ray binaries

2.1. Line profiles and circumstellar structure

Loose correlations between the optical/infrared properties of Be/X-ray binaries and their X-ray behaviour have been observed to exist (e. g., Corbet et al. 1986a; Coe et al. 1994). This correlation is to be expected, since the optical/infrared observations provide information about the changing conditions in the circumstellar envelope from which the neutron star is accreting. Simple models of the circumstellar environment have been used to fit the observed lightcurves (see Apparao 1994 and references therein). In the most basic of these models, the size of the disc is supposed to be the main factor. When the disc is so large that it reaches the orbit of the neutron star, Type I X-ray outbursts occur. When the disc is smaller the neutron star cannot accrete. Low-luminosity emission can be due to accretion from the low-density transition regions between the envelope and the interstellar material or the low-density fast wind believed to be emitted from the polar regions of Be stars (Lamers & Waters 1987, Slettebak 1988).

Waters et al. (1988) showed that the infrared photometric magnitudes and the X-ray lightcurves of Be/X-ray binaries indicated that the neutron stars were accreting from a high-density, low-velocity wind . Waters et al. (1989) analysed the influence of the changing conditions in the circumstellar envelope on the X-ray lightcurves making use of a more complicated model, which takes into account the rotation of the envelope. They found that wind velocities in the range 100 — 600 km s^{-1} at the distance of periastron passage of the neutron star can account for the observed X-ray luminosities. In their model, the relative velocity of the wind was the main factor affecting the X-ray luminosity. High luminosities during Type II outbursts imply small relative velocities (~ 100 km s^{-1}), while Type I outbursts imply larger velocities.

However, the existence of this wind outflow at large distances — which would be common to all Be stars — is not reflected in the shapes of the Hα emission lines, which are frequently symmetric and believed to be determined by rotation (Hanuschik et al. 1993). Therefore it seems that a heretofore unknown mechanism (see Chen et al. 1992 for a discussion) accelerates the circumstellar material outwards in the regions beyond the Hα formation zone. The exact size and location of this zone is not known, but most estimates support an outer radius in the range 5 — 20 R_* (see Hummel & Vrancken 1995).

In recent years, a much improved description of the structure of the circumstellar envelopes of Be stars has begun to emerge. The appearance of high-resolution spectral atlases (Dachs et al. 1992, Hanuschik et al. 1996) has resulted in great advances in the traditional analysis of the emission line profiles (Slettebak et al. 1992, Hummel & Vrancken 1995). The main conclusion reached is that, in spite of the multiplicity of line shapes (single, double or triple-peaked, with or without flank inflections, showing central self-absorption reversal and/or emission wings, etc) the most fundamental division of emission profiles in Be stars can be made into two main categories (Hanuschik et al. 1995):

(i). Symmetric profiles, generally presenting two peaks of similar intensity. These shapes only evolve very slowly (with time-scales of a few years) and can remain unchanged for years.

(ii). Asymmetric profiles with a higher degree of variability. These profiles undergo quasi-cyclic V/R variability (the ratio between the V(iolet) and the R(ed) peak changes regularly), with quasi-periods ranging from a few years to decades.

The symmetric profiles are believed to arise from stable quasi-Keplerian discs, while the asymmetric shapes are produced in discs with a perturbed density distribution. The perturbations are associated with the existence of global oscillation modes propagating through the envelopes (Okazaki 1991, 1996; Papaloizou et al. 1992). The only modes which can propagate in a nearly Keplerian disc are global $m = 1$ (where m is the azimuthal wave number) oscillations (Kato 1983). Theoretical line profiles calculated from models of quasi-Keplerian discs with $m = 1$ global oscillation modes are in agreement with observed profiles (Hummel & Hanuschik 1997, Hummel & Vrancken 1995, Okazaki 1996). The evolution of observed V/R variations in some Be stars can be readily explained by a progressing global mode (Telting et al. 1994, Reig et al. 1997a). As a consequence, it is now generally accepted that asymmetric line profiles in the spectra of Be stars are caused by an asymmetric matter configuration in their extended envelopes, due to the existence of progressing density waves (Hummel & Hanuschik 1997, Okazaki 1997). Hanuschik (1996) indicates that approximately two thirds of the bright Be stars in his sample show symmetric profiles at a given time. However, evolution is observed over long time-scales, and approximately two thirds of the Be stars which have been extensively monitored have displayed V/R variability at some time (Okazaki 1997).

2.2. Observations of Be/X-ray binaries

It has been traditionally believed that the presence of the neutron star in Be/X-ray binaries will not affect the dynamics of the Be envelope. Norton et al. (1994) could not detect any variability in the photometric or spectroscopic properties of the Be/X-ray system EXO 2030+375 during a Type I outburst. They deduced that the effects of the compact companion in the structure of the circumstellar envelope were, in general, negligible. Recently, however, it has been proposed (Reig et al. 1997b) that the optical components of Be/X-ray binaries form a distinct group inside the Be stars. Supporting this hypothesis, Reig et al. (1997b) call two observational facts. First, there seems to be a correlation between the maximum equivalent width (EW) of the Hα line which a system has shown and the orbital period of the neutron star. Second, Be stars forming part of Be/X-ray binaries have, on average, low Hα EW when compared to randomly selected sets of Be stars.

The presence of strongly asymmetric lines in the spectra of Be/X-ray binaries, similar to those observed in Be stars undergoing V/R variability has been noted in several occasions (e.g., Cook & Warwick 1987, Corbet et al. 1986a). However, the lack of long-term monitoring of the sources has not permitted to determine whether these asymmetric profiles were associated with cyclic changes or were due to some other process. In these complex systems, the presence of temporary sources of Hα emission, such as an accretion disc or a high-ionization region, heated up by X-rays, around the neutron star cannot be ruled out. These additional sources of Hα emission would add to the circumstellar emission and create complicated line profiles.

Until now, the evolution of emission lines during Type II events had not been studied due to their unpredictability. No observations were taken at the time of the only Type II outburst ever shown by EXO 2030+375 (Parmar et al. 1989) or 2S 1417−624 (Finger et al. 1996b) or any of the two Type II outbursts of V 0332+53 (Terrell & Priedhorsky 1984; Takeshima et al. 1994). Likewise, no optical coverage of the 1973 Type II outbursts of 4U 1145−619 exists. A bright outburst from this source in 1994 could have been of Type II. A strong disturbance of the envelope is discussed by Stevens et al. (1997), but their sparse observations do not allow us to determine if its V/R periodicity was affected. Asymmetric lines have been observed in the spectra of A 0535+26 on different occasions, but its previous Type II outbursts in 1975 and 1980 were not covered. The spectra of V635 Cas (4U 0115+634) during and after another Type II outburst in 1980 probably show asymmetric Hα profiles (Kriss et al. 1983), but their very low S/N ratio does not allow us to be certain. No evident changes in symmetry were associated with a Type II X-ray outburst in 1991 (Negueruela et al. 1997).

In this paper we show that Be/X-ray binaries display quasi-cyclic changes similar to those observed in isolated Be stars and present evidence indicating that Type II X-ray outbursts affect the V/R variability of the optical components. Two sources which have recently displayed X-ray activity are investigated in detail:

2.2.1. 4U 0115+634

The hard X-ray transient 4U 0115+634 is one of the best studied Be/X-ray binary systems (see Campana 1996; Negueruela et al. 1997, henceforth N97). It consists of a fast-rotating ($P_{\rm s} = 3.6$ s) neutron star in a relatively close ($P_{orb} = 24.3$ d) and eccentric ($e = 0.34$) orbit around the O9.5Ve star V635 Cas (see Tamura et al. 1992; Unger et al. 1997). Due to the fast rotation of the neutron star, centrifugal inhibition of accretion prevents the onset of Type I outbursts (SWR, N97). The system is the only known Be/X-ray transient that has solely been observed to display Type II activity, with long strong X-ray outbursts extending over more than one orbital period and showing no dependence on any orbital parameters. These giant outbursts are believed to be due to episodes of enhanced mass loss from the Be star, which are reflected in optical and infrared brightening events (SWR, N97).

A Type II X-ray outburst from 4U 0115+634 was detected by the BATSE experiment on board the *CGRO* satellite starting on Nov. 18, 1995 (Finger et al. 1995). Granat/*WATCH* measured the flux in the 8–20 keV band peak at 670 ± 60 mCrab on Nov. 25 (Sazonov & Sunyaev 1995), which remained at that level until early December. A second flare lasted into January 1996 (Scott et al. 1996). The outburst was the strongest during the last decade (see the X-ray lightcurve in N97).

2.2.2. A 0535+262

The Be/X-ray transient A 0535+262 consists of a neutron star orbiting the O9.7IIIe star HD 245770 in a wide and eccentric orbit ($P_{orb} = 110.3$ d, $e = 0.47$, Finger et al. 1994, 1996a). Due to its brightness, HD 245770 has been extensively monitored (see Motch et al. 1991, Giovannelli & Graziati 1992 for reviews). Clark et al. (1998a, henceforth Cl98) have presented the results of several years of multiwavelength observations and analysed the connection between the X-ray activity and the behaviour of the primary. They did not find any clear correlation. The source displays all three types of X-ray activities observed in Be/X-ray binaries. The X-ray flux in the 2 – 10 keV is normally in the range 5 – 10 mCrab during quiescence phases. Type I outbursts occur close to the periastron passage of the neutron star, but Type II outbursts ($F_{\rm x} \gtrsim 1$ Crab) are generally slightly delayed in phase. The last active period of the source occurred between March 1993 and September 1994. Type I outbursts were observed at all periastron passages, except on February 1994, when a Type II outburst took place (Finger et al. 1996a). The Type II outburst lasted 52 days and peaked on February 18, when it reached a flux of 8 Crab in the 20 – 40 keV band.

3. Observations

As part of the Southampton/Valencia/SAAO long-term monitoring campaign of Be/X-ray binaries, we have obtained Hα spectroscopy of a number of sources. The details of the programme are described in Reig et al. (1997c). Here we concentrate on the temporal evolution of the Hα line profile in search of the existence of V/R variability in these systems and the characteristics of this variability. Most of the data presented here have not been published previously, though some spectra have appeared in a previous paper (Clark et al. 1998a). The spectra have been obtained with the 2.5-m Isaac Newton Telescope (INT), the 4.2-m William Herschel Telescope (WHT) and the 1.0-m Jakobus Kapteyn Telescope (JKT), all three located at the Observatorio del Roque de los Muchachos, La Palma, Spain, and the 1.5-m telescope at Palomar Mountain (PAL). Different telescope configurations were used on different dates, some of which are discussed in the following sections.

3.1. *Observations of 4U 0115+634 (V635 Cas)*

3.1.1. X-ray observations

The All Sky Monitor (ASM) on board the Rossi X-ray Timing Explorer *RXTE* satellite consists of three wide-angle Scanning Shadow Cameras (SSCs) mounted on a rotating drive assembly, which scan ~ 70 % of the sky every 1.5 hours. A description of the satellite and its data acquisition procedure can be found in Levine et al. (1996). Observed intensities are determined by fitting the photon detections to the given positions of the sources listed as "active" in the ASM Source Catalogue. Sources with low ($\leq 2\sigma$) detections are eliminated from the fit and the process is iterated. When an appropriate fit is reached, the residuals are searched for new sources, not included in the original list. The data from each SSC are analyzed independently. Further, data from the three different energy bands ($1.3 - 3.0$, $3.0 - 5.0$ and $5.0 - 12.2$ keV) are also analysed separately. The analysis is performed by the ASM team at the Massachusetts Institute of Technology and made publicly available.

The lightcurves for 4U 0115+634 in the three energy bands, created with the software package XRONOS, are presented in

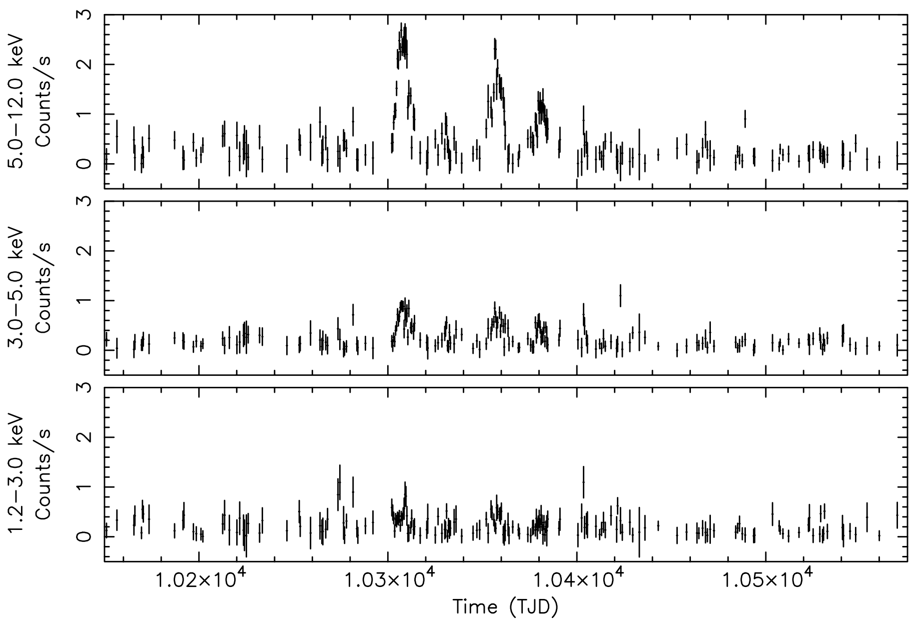

Fig. 1. X-ray lightcurves of the Be/X-ray binary 4U 0115+634 in three energy bands ($1.3 - 3.0, 3.0 - 5.0$ and $5.0 - 12.2$ keV), taken with the All Sky Monitor on board *RXTE*. Points represent 18-h averages of the individual dwell solutions.

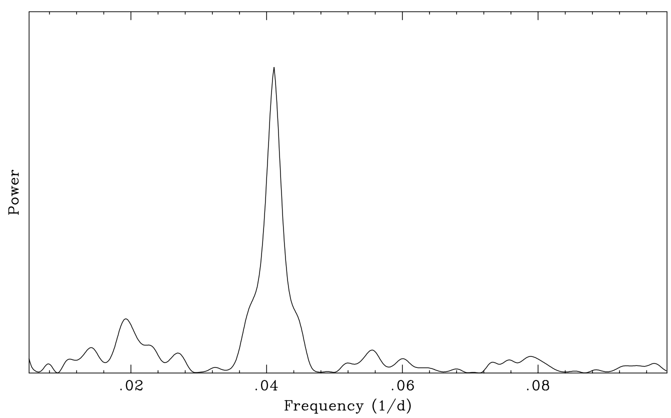

Fig. 2. Power spectrum for the ASM/*RXTE* high-energy band data in the interval TJD 10295 – 10451, calculated using the CLEAN algorithm (see text).

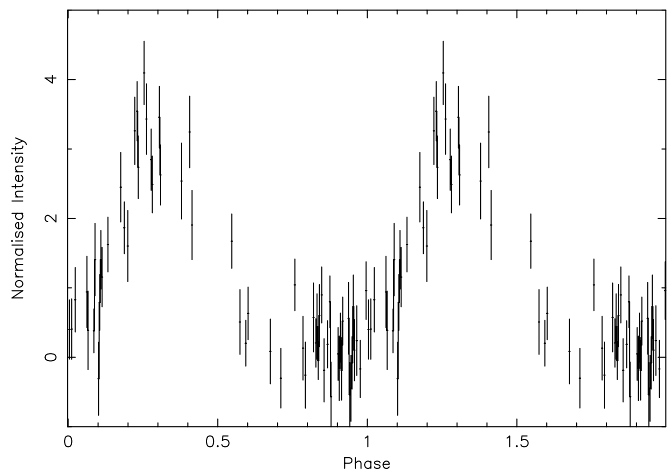

Fig. 3. Epoch folding of the high-energy ($5.0 - 12.2$ keV) data from the All Sky Monitor on board *RXTE* for the Be/X-ray transient 4U 0115+634 at the orbital period of the neutron star. Phase $\phi = 0$ is defined as the epoch of periastron passage on TJD 10300.36.

Fig. 1. All the data points used have been obtained from fitted solutions with a reduced $\chi^2 \leq 1.5$. Individual dwell data have been distributed into 64800-s (18-h) bins. The ASM began operations in January 1996, immediately after the end of the 1995 Type II outburst.

3.1.2. Optical spectroscopy

We managed to observe the source immediately after the 1995 Type II outburst and again after the spring gap during which the source cannot be observed from La Palma (February – May). Hα spectroscopy was taken with the Intermediate Dispersion Spectrograph (IDS) on the 2.5-m INT. The telescope was equipped with the 235-mm camera + R1200Y grating which gives a nominal dispersion of 0.8 Å/pixel. The data have been processed using the Starlink package FIGARO (Shortridge & Meyerdicks 1996) and analysed with the Starlink package DIPSO (Howarth et al. 1996). Dates of observation and the measured equivalent widths (EWs) of the Hα line are listed in Table 1.

The equivalent width of the spectra are measured by selecting a continuum point on each side of the line and integrating the flux relative to the straight line between the two points using the procedures available in DIPSO. The measurements were repeated several times and the error estimated from the distribution of values obtained. This error arises due to the subjective selection of the continuum. Gaussian fitting to the shapes does not provide a better estimate since again the extended wings of the emission line and the presence of several atmospheric absorption features make the determination of the continuum very imprecise. The errors thus obtained are always $\lesssim 15\%$ and typically $\sim 10\%$. Due to the subjectivity, we prefer to use 15% as a conservative estimate of the error.

Table 1. Details of the Hα spectroscopy for V635 Cas.

Date of Observation(s)	TJD	EW of Hα(Å)[a]	Line shape
Jul. 03, 1995	9901	−3.6	Shell
Sep. 12, 1995	9972	−4.5	Shell
Jan. 12, 1996	10094	−11.3	Asymmetric
Jan. 31, 1996	10113	−8.0	Asymmetric
Jun. 20, 1996	10254	−7.0	Asymmetric
Jul. 09, 1996	10273	−6.5	Asymmetric
Aug. 26, 1996	10321	−8.0	Asymmetric
Feb. 01, 1997	10480	−3.6	Asymmetric

[a] Errors in EW are $\lesssim 15\%$, due to the subjective continuum determination. See Sect. 3.1.2

Table 2. Observational details of the IR photometry for V635 Cas.

Date of Observation(s)	TJD	J mag	H mag	K mag
Aug 02, 1995	9931	12.15±0.08	11.45±0.05	11.08±0.07
Oct 15, 1995	10005	10.81±0.04	10.21±0.04	9.78±0.04
Jan 12, 1996	10094	11.36±0.05	10.74±0.05	10.35±0.05
Jul 28, 1996	10293	11.50±0.04	10.89±0.04	10.65±0.04

3.1.3. Infrared photometry

Infrared photometry of V635 Cas was obtained with the Continuously Variable Filter (CVF) on the 1.5-m Carlos Sanchez Telescope (TCS) at the Teide Observatory, Tenerife, Spain. Data for the period under discussion are listed in Table 2.

Our data show that, as in previous occasions, the Type II X-ray outburst was preceded by the sudden brightening of the infrared magnitudes of V635 Cas, with an increase of ≈ 1.3 magnitudes in K in $\sim$ two months (August – October 1995), but the source faded quickly after the outburst.

3.2. Observations of A 0535+262 (HD 245770)

We re-analysed the spectroscopic dataset for HD 245770 presented by Cl98. All the raw observations from the period 1990 – 1993 were extracted from the original tapes when available or retrieved from the La Palma Archive (Zuiderwijk et al. 1994) and reprocessed. This allowed us to find some new spectra which had not been included in the work of Cl98. The dates of observation for the complete set of spectra are listed in Table 3, together with measurements of the equivalent width (EW) of Hα. The spectra are displayed in Fig. 5. The method followed to measure the EW was the same as for V635 Cas, and the comments on the uncertainty of the measurement also apply.

The spectra displayed in Fig. 7 are taken from Cl98, except for the 1994 March 25 spectrum, which was obtained with the JKT equipped with the R1200Y grating and has lower dispersion ($\approx$ 1.2 Å/pixel). These spectra were taken with the 2.6-m telescope at the Crimean Astronomical Observatory and have not been re-reduced (see Table 1 in Cl98 for details).

Table 3. Details of the Hα spectroscopy for HD 245770.

Date of Observation(s)	TJD	Telescope	EW of Hα(Å)[a]
Feb 7, 1990	7929	INT	−12.4
Feb 21, 1990	7943	INT	−10.9
Apr 9, 1990	7990	INT	−10.9
Nov 14, 1990	8209	INT	−9.9
Dec 27, 1990	8252	INT	−9.0
Jan 28, 1991	8284	INT	−8.8
Apr 16, 1991	8362	WHT	−7.1
Aug 28, 1991	8496	INT	−8.0
Dec 13, 1991	8603	INT	−10.6
Feb 18, 1992	8670	PAL	−10.6
Aug 17, 1992	8851	PAL	−7.5
Aug 18, 1992	8852	PAL	−7.3
Mar 8, 1993	9054	PAL	−13.6
Mar 10, 1993	9056	PAL	−13.6
Sep 23, 1993	9253	PAL	−10.3
Dec 5, 1993	9326	PAL	−14.0
Dec 6, 1993	9327	PAL	−13.7

[a] Errors in EW are $\lesssim 15\%$, due to the subjective continuum determination. See Sect. 3.1.2

3.3. Observations of V 0332+53 (BQ Cam)

Observations of BQ Cam, the optical counterpart to the Be/X-ray transient V 0332+53 have been carried out during our campaign. In this paper, we only report on Hα observations obtained during the period 1990 – 1991. These spectra were obtained with the IDS on the INT and different gratings, generally the R1200Y, and are displayed in Fig. 8. Further discussion of the properties of this system is left for a forthcoming paper (Negueruela et al., in preparation).

4. Results

4.1. 4U 0115+634

The X-ray lightcurve of 4U 0115+634 (Fig. 1) between January and July 1996 (TJD 10087 – 10294) is compatible with the complete absence of emission (no detections above the 2σ threshold according to the quick-look results provided by the *RXTE*/ASM team). However, starting in early August 1996, a succession of outbursts is clearly visible. The first outburst was also seen by BATSE (Scott et al. 1996), which on August 12, 1996 (TJD 10307) observed a pulsed flux in the 20 – 50 keV range of ~ 30 mCrab. Two other outbursts were weakly detected by BATSE (Finger, 1997, priv. comm.). These two outbursts are clearly visible in the ASM/*RXTE* lightcurve. There is indication of a weak outburst around September 4, 1996 (TJD 10330, one orbital period after the first outburst).

The outbursts are clearly seen in the high-energy ($5.0 - 12.2$ keV) band, but hardly detectable in the low-energy band. Due to this large hardness ratio, in the following analysis we have only used the high-energy band data. The periodogram of the

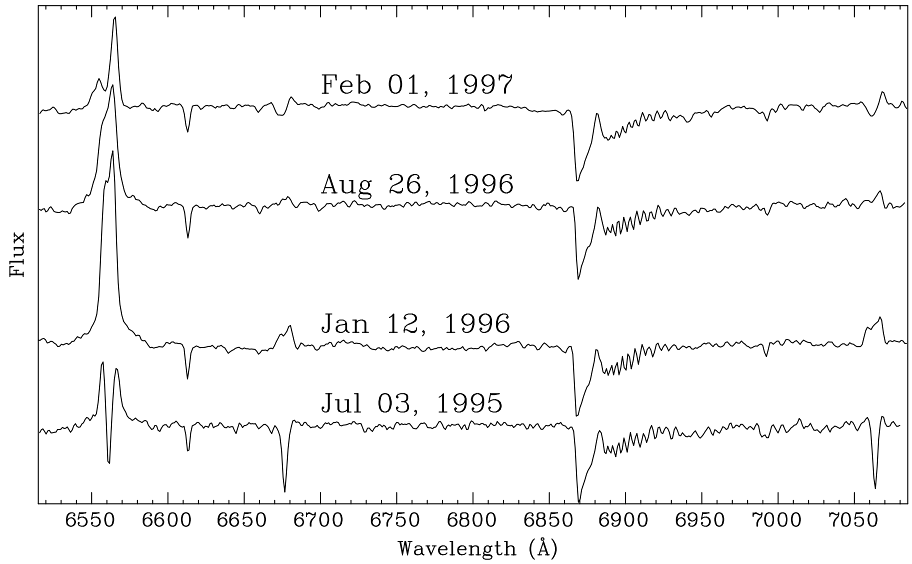

Fig. 4. Series of spectra showing the appearance of a global density perturbation, eventually leading to a global density wave, in the envelope of the Be/X-ray binary 4U 0115+634. Notice the parallel evolution of the He I $\lambda\lambda$6678, 7065 Å lines. The spectra have been divided by a spline fit to the continuum for normalisation and arbitrarily offset for clarity. The July 1995 spectrum is typical of the quiescent state of the source.

X-ray lightcurve was calculated using the CLEAN procedure from the Starlink PERIOD package (Dhillon & Privett 1997), with 10 iterations and a gain of 0.1 in each step (see Fig. 2). There is a single dominant peak corresponding to a period of 24.4±0.1 d, the orbital period of the neutron star. This result is also obtained when applying other period searching procedures such as SCARGLE (Lomb-Scargle normalised periodogram) or FT (discrete Fourier power spectrum). This is the first occasion in which the X-ray emission of 4U 0115+634 has displayed modulation of any kind. All the outbursts previously observed since the discovery of the source in 1969 had been of Type II and had not displayed any orbital modulation. The periodicity is not observed when only data from before TJD 10295 or after TJD 10450 are analysed, confirming that the modulation is due to the outbursts and not to any quiescence emission. A Fisher randomization test shows that no peak has a probability $\geq 60\%$ of being real and there are no peaks in the range 20 – 30 days.

The high-energy band ASM data for the time TJD 10295 – 10451 (the period of X-ray activity) were folded at the orbital period, using $P_{\rm orb} = 24.32$ d and epoch of periastron passage TJD 10300.36 after the model in N97. The folded lightcurve is shown in Fig. 3. The outbursts are seen to peak close to orbital phase $\phi \sim 0.3$, far away from periastron.

The optical counterpart, which had reached a peak in brightness just before the outbursts, faded steadily during this period, as can be seen in Table 2. As indicated in N97, it is difficult to define a photometric 'quiescent' state for this source. The J magnitude oscillates between ~ 10.8 and ~ 12.3. Whenever it has come close to $J \lesssim 11$, an X-ray outburst has taken place. The infrared colours remain relatively constant, as is usual in the system (N97), except for the July 1996 observations.

4.2. A 0535+262

The spectra displayed in Fig. 5 show that HD 245770 was displaying quasi-cyclic V/R variability during the period 1990 – 1993. As noted by Cl98, the shape of the spectra is too complex to attempt a Gaussian fitting to the profiles. In many spectra, very extended wings are apparent, which makes the determination of the continuum very imprecise. However, an attempt has been made to use the same criteria for all the spectra, so that the values measured on different spectra can be compared. Our values are in general agreement with those of Cl98. The intrinsic inaccuracy of the measurements, together with the reduced number of spectra, precludes the possibility of a proper search for periodicity. In spite of this and of the incompleteness of the coverage, due principally to the gap during which the source cannot be observed from the ground (May – July), a quasi-period of $\sim 18 \pm 1$ months can be deduced from visual inspection. It is noteworthy that this period is close to the 508-d period detected by Hao et al. (1996) in the photometric lightcurve of the source during the same epoch. Clark et al. (1998b) argue that this modulation does not seem to be coherent over long time-scales, but this behaviour is what should be expected of the quasi-periodicity of V/R cycles.

The continuation of the cyclic behaviour would imply a blue-dominated profile during early 1994, similar to those observed in January 1991 or August 1992. As can be seen in Fig. 7, the cyclic behaviour was broken in coincidence with the Type II outburst. Between February 17 and February 28 a strong red shoulder formed, changing the global shape of the emission line. This change was much faster than the variations associated with the cycle, as can be seen comparing Fig. 7 with Fig. 6, and must be of a different nature.

4.3. V 0332+53

Fig. 8 shows that V/R variability was present in BQ Cam during 1990, with a quasi-period of ~ 1 year, but it had disappeared by 1992. The variations in the lines are smaller than in the case of HD 245770, presumably because the star is seen almost pole-on. The mass function for the system implies $i < 15°$ (Corbet et al. 1986a) and the orbit is expected to be co-planar with the equatorial disc (Waters et al. 1989). No X-ray emission has

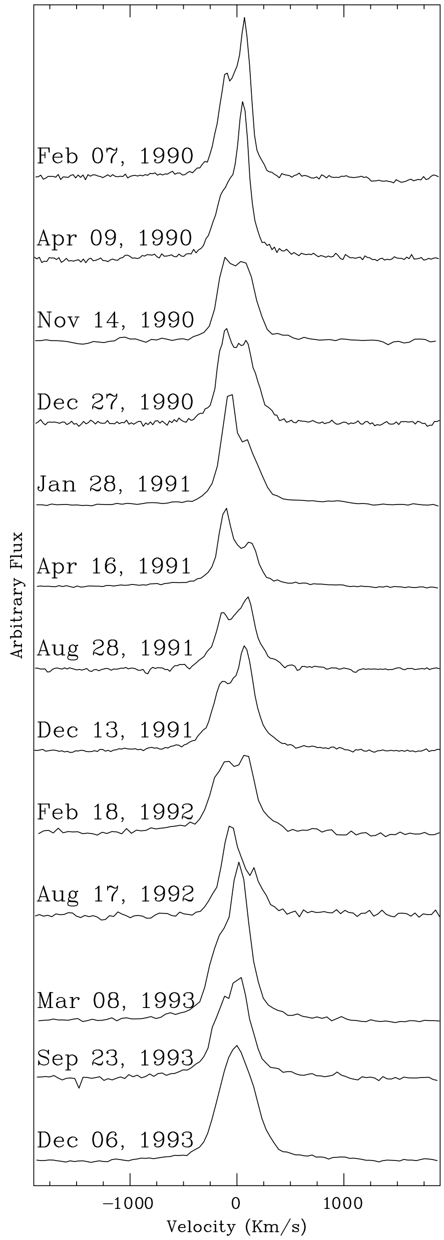

Fig. 5. Evolution of the shape of the Hα line in HD 245770 during 1990 – 1993. The observed profiles indicate the presence of a global oscillation with a quasi-period of $\sim$ 18 months. All the spectra have been smoothed with a Gaussian function ($\sigma = 0.8$ Å) to obtain a comparable resolution, divided by a spline fit to the continuum for normalisation and offset for display.

been detected from the source since late 1989 (Bildsten et al. 1997). The strength of Hα emission seems to have remained approximately constant, indicating that the cessation of the V/R variability was not associated with any major change in the size of the disc.

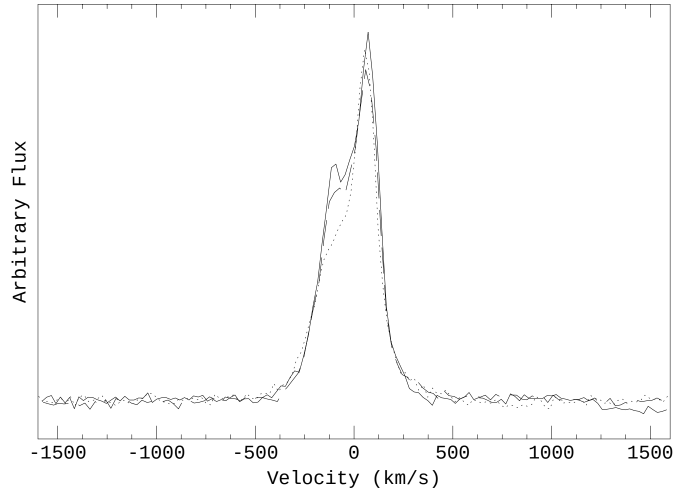

Fig. 6. Evolution of the Hα line profile in HD 245770 during February – April 1990. The slow decrease in the strength of the blue arm is typical of the speed of variation seen during the four years before the Type II outburst. The solid line represents the spectrum from February 7, the dash line, that from February 21 and the dotted line the spectrum from April 9. All the spectra have been normalised.

5. Discussion

5.1. A global change in 4U 0115+634

For the first time since its discovery in 1969, 4U 0115+634 has been observed to undergo a series of X-ray outbursts modulated with the orbital period. The outbursts did not peak near periastron but at phase ~ 0.3. The fact that we obtain such a strong modulation of the X-ray lightcurve at the orbital period with only three outbursts argues against the idea that the delay in the peak of the outbursts can be due to the mediation of an extended accretion disc, which would not be so regular. A more likely explanation would be that the neutron star repeatedly went through a region of very high density at some point of its orbit close to phase 0.3. The spectra from the summer of 1996 clearly indicate that the series of Type I outbursts was not associated with any major change in the size of the disc (as reflected in the EW). The infrared magnitudes of the source were close to its quiescence magnitudes during the first (and strongest) Type I outburst. All previous outbursts had been associated with much brighter infrared magnitudes (at least half a magnitude brighter than the August 1996 values). The only observed difference with previous quiescence states is the presence of asymmetric emission line profiles, which are indicating the existence of an asymmetric density configuration.

The spectrum of the source underwent a major change during or immediately before the December 1995 Type II outburst. The usual quiescence shell spectrum (see N97), which was observed only two months before the outburst, was replaced by strong asymmetric emission lines (see Fig. 4). The asymmetric profiles, characterised by a dominant red peak and a smaller blue peak were still present more than a year later, indicating that the circumstellar envelope has been strongly disturbed.

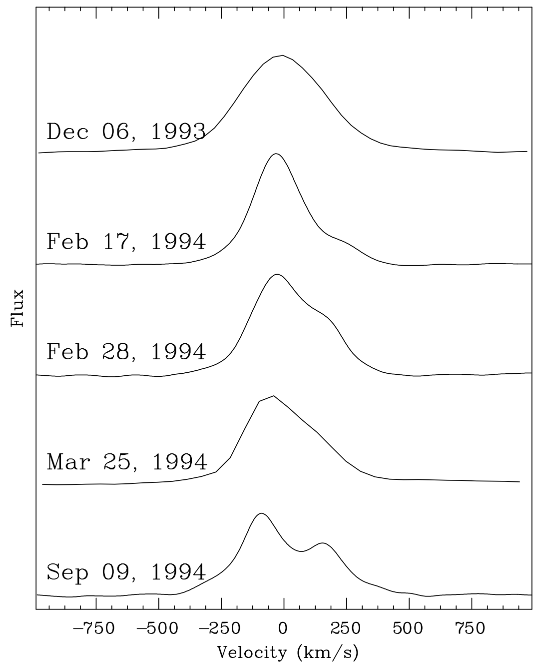

Fig. 7. Evolution of the Hα line profile of HD 245770 around the time of the Type II X-ray outburst peaking on February 18, 1994. The growth of a red shoulder in about ten days is clearly seen. All the spectra have been normalised and offset by a constant amount. The March 25 spectrum was taken with the JKT and has lower resolution. The higher resolution spectra have been smoothed with a σ = 0.8 Å Gaussian function.

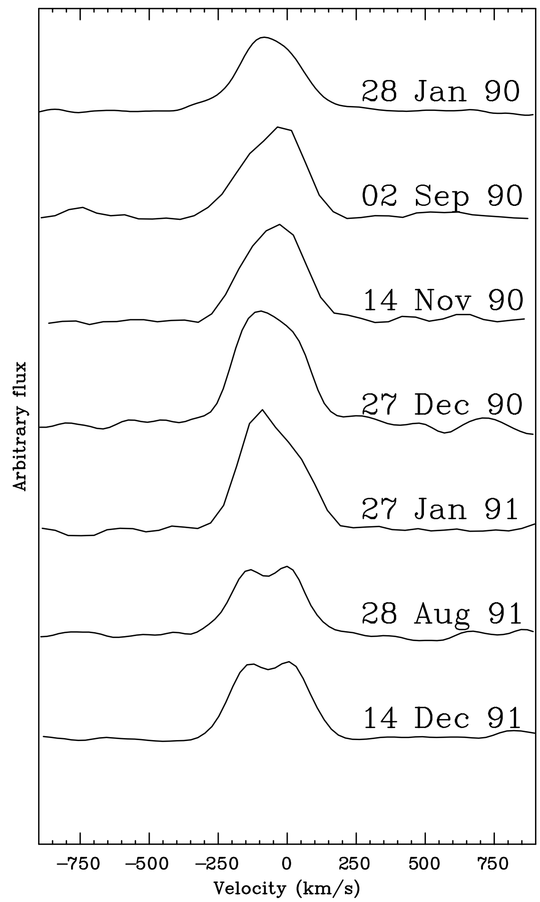

Fig. 8. Hα observations of BQ Cam, the optical counterpart of V 0332+53 during the period 1990 — 1991, showing the propagation and final disappearance of a density perturbation. The spectra have been divided by a spline fit to the continuum for normalisation.

Fast changes in the line profiles are not rare in this source (N97). However, this is the first time in which strongly asymmetric profiles, indicating a perturbed density distribution, have been observed. The asymmetric spectra of V635 Cas are very similar to those of V/R variable systems such as HD245770 or LS I +61°235 (Reig et al. 1997a). Fig. 9 shows the similarity of the Hα line profiles of V635 Cas and HD 245770 when their circumstellar envelopes have been perturbed.

The previous absence of Type I outbursts is explained by centrifugal inhibition of accretion due to the fast rotation and strong magnetic field of the neutron star (N97). The centrifugal barrier can only be overcome if the ram pressure of incoming material rises (SWR). The increase in ram pressure can be due to a higher density of the surrounding material or a higher relative velocity between the neutron star and the environment. The spectra do not show any evidence for enhanced mass loss during August 1996, but indicate that different regions in the envelope have different densities. This hints strongly at the possibility that the Type I outbursts are associated with the presence of a region of enhanced density in the envelope.

5.2. Fast V/R variations in A 0535+262

Between 1990 – 1993, HD 245770 was showing V/R variability with a quasi-period of ~ 18 months. Even though small changes in the EW of Hα are expected on short time-scales (since they are observed for most Be stars), there seems to be a cyclic variation associated with the V/R cycle, in the sense that the red-peak phases (or perhaps the symmetric phase that immediately follows them) show larger EWs than other phases of the cycle. This seems to be superimposed on a general trend: the values of the EW during the second observed cycle are systematically smaller than in the first cycle, but those from 1993 (third cycle) are consistently higher than in the previous years, which in the standard interpretation would indicate an increase in the size of the disc. It is noticeable that the source started its Type I X-ray activity during 1993. Unfortunately, there is a gap in the observations in the second half of 1992 that does not allow us to determine if the increase in the EW of Hα was gradual or a fast event. In any case, the V/R cycle does not seem to have been strongly affected by this (compare the very similar shapes of the line profiles in April 1990 and March 1993, which are separated by two complete cycles). Therefore the conditions in the disc must have remained relatively constant until the Type II outburst in February 1994.

As indicated in Sect. 4.2, the change in the shape of Hα that took place during the outburst was much faster than any changes associated with the cyclic V/R variability. It could not have been due to the existence of an accretion disc around the neutron star, because the structure of the line was basically unchanged a month later, when the X-ray outburst had finished and the neutron star was in a very different orbital position. Therefore the growth of the red shoulder must have reflected a global change in the structure of the disc, which took place as the same time as the Type II X-ray outburst.

This is confirmed by the fact that the spectra from late 1994 correspond to approximately the same phase of the V/R cycle as those at the beginning of the year (compare the spectrum from February 28 with that from September 9). Cl98 indicate that the quasi-period of V/R variability after September 1994 was approximately one year. The process that took place at the same time as the Type II outburst resulted in a change of both the period and the phase of the quasi-cycle. Since these parameters depend strongly on the density gradient in the disc, it must have implied a major perturbation of the physical conditions in the disc.

5.3. V/R cycles in other Be/X-ray binaries

Some Be/X-ray binaries have been known to display V/R variability for many years, showing quasi-periods in the same range as those observed in isolated Be stars. The Be star γ Cas, extensively studied over the years, is the optical component of the X-ray source 2S 0053+604, which is believed to contain an accreting white dwarf (Haberl 1995). It has shown V/R variability in many occasions, with quasi-periods between 4 and 7 years (Doazan et al. 1987). Since 1970, the V/R cycle has had a period of 5±1 years (Telting et al. 1993). Likewise, X Persei, the optical counterpart to 4U 0352+309, has been observed to undergo phases of V/R variability with quasi-periods ranging from 2 to 12 years (see Okazaki 1997 for references). These sources are not transients, but persistent low-luminosity X-ray emitters and it is believed that the orbits of the compact objects are very wide. Another source displaying V/R variability is LS I +61° 235, the optical component of the Be/X-ray binary RX J0146.9+6121. It shows a quasi-period of about three years (Reig et al. 1997a). This source was only discovered in 1991 and it is not certain yet whether it is a transient or a persistent source, though the second possibility seems more likely. Given the very wide orbits of the neutron star in these objects, we have no reason to suspect that their V/R variability is different at all from that seen in isolated Be stars.

Among the transients, BQ Cam, the optical component of V 0332+53, displayed V/R variability on a time-scale of weeks or a few months during a series of Type I outbursts in 1983 (see Corbet et al. 1986a and references therein). As shown in Sect. 4.3, it was displaying quasi-cyclic V/R variability soon after the 1989 Type II outburst. V801 Cen, the optical component of the southern Be/X-ray binary 4U 1145−619 showed large variability in both Hα and Hβ in one week during an X-ray outburst in January 1985 (Cook & Warwick 1987). Long-term V/R variability has also been observed in this object. Stevens et al. (1997) present data that could be explained by the existence of a quasi-cycle with a period ~ 3 years. Further observations confirm both the existence of quasi-cyclic V/R variability and faster variations (Stevens, 1997, priv. comm.).

There is no reason to believe that the behaviour of this perturbation cannot be explained by the theory of one-armed global oscillations. As in the case of 4U 0115+634 and A 0535+26, the profile shapes observed during these slow quasi-cyclic variations are not distinguishable from those seen during periods of fast variability.

5.4. Interpretation

We have presented observational evidence that most Be/X-ray binaries (persistent and transient sources) display V/R variability with quasi-periods which are not correlated at all with their orbital periods. These observations invalidate the model of Apparao & Tarafdar (1986), who suggested that the V/R variations in Be binaries were due to the presence of an emission region associated with the Strömgren sphere of the neutron star and should therefore be modulated with the orbital period.

The only case in which some evidence could support this model is 4U 1258−61 (GX 304−1). Corbet et al. (1986b) obtained spectroscopy of its optical counterpart, V850 Cen, between 1977 and 1983, during its active Be (and X-ray) phase. They observed V/R variability with a quasi-period of approximately 130 days, which is very close to the orbital period of the neutron star in the system (132.5±0.5 d). Their statistical analysis showed that the possibility that the V/R ratio was modulated at the orbital period is $\gtrsim$ 85%. However, our monitoring reveals no evidence at all of any modulation in the shape or strength of the emission lines with the orbital period in any of the Be/X-ray binaries included in the programme. The observed V/R variability can be readily explained with the existing models of one-armed oscillations developed for isolated Be stars. We believe that, if the coincidence between the orbital period and the V/R quasi-period reported for 4U 1258−61 is real, it is more likely to be explained by some kind of resonance than by the Apparao & Tarafdar model.

We have presented observational evidence that large density perturbations arose in the envelopes of the Be/X-ray binaries 4U 0115+634 and A 05353+26 in coincidence with Type II outbursts and that they strongly affected the dynamics of their envelopes. In the case of 4U 0115+634, the change from symmetric emission lines to asymmetric profiles has resulted in the commencement of V/R variability. In the case of A 0535+26, the existing pattern of variability was profoundly affected, with a shift in both the quasi-period and phase of the V/R cycle.

In both cases, the fast appearance of the density disruption during the X-ray outburst suggests that there is an association between the Type II outburst and the density perturbation. No isolated Be stars have ever been observed to go from symmetric profiles to clearly asymmetric ones in such a short time-scale. Moreover, this kind of fast variations has been seen to occur only during X-ray outbursts, when the neutron star is closer to the envelope, which again points to a connection between both events.

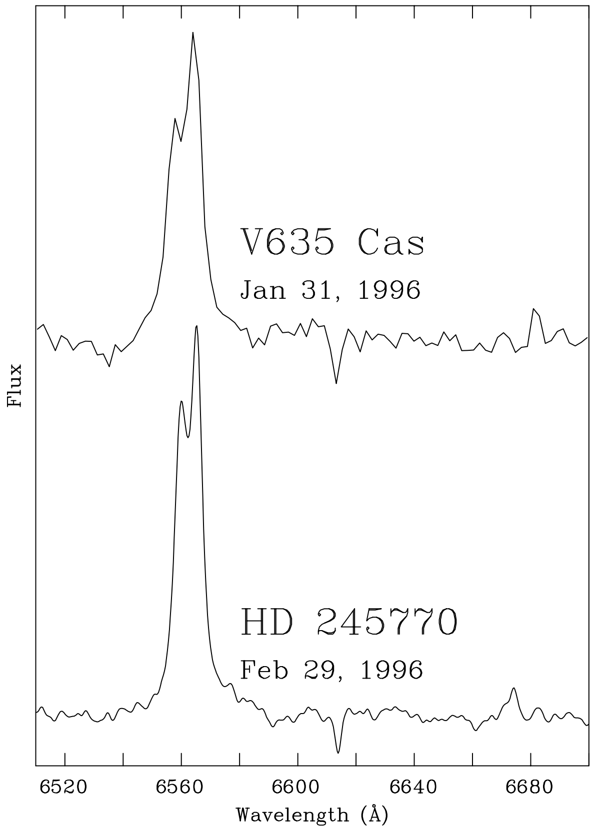

Fig. 9. Comparison of the Hα line profile in V635 Cas and in HD 245770 (A 0535+26) after a giant X-ray outburst. The HD 245770 spectrum was taken with the 1.0-m JKT in La Palma on Feb. 28, 1996, while the star was undergoing a V/R cycle. The spectra have been smoothed with a Gaussian filter of $\sigma = 0.8$ Å and had their continua normalised. Note that both stars are seen under a similar moderate ($\approx 40^\circ - 60^\circ$) inclination angle.

However, it must be noticed that we do not know how rapidly an instability develops into a global mode in an isolated Be star, but there are indications that it can be quite fast – less than a year in the Be star 66 Oph (Hanuschik et al. 1995). The direction of the causal connection between the two events, if any, cannot be deduced from the observations. It could well be that both the density perturbation *and* the outburst were caused by a common cause, such as violent asymmetric ejection of material from the Be star.

On the other hand, the association between Type II X-ray outbursts and major changes in the circumstellar envelopes of Be/X-ray binaries seems to be clear. Stevens et al. (1997) argue that a giant outburst of 4U 1145−619 in March 1994 was followed by a reduction in the strength of Hα by a factor of two. A similar reduction of the strength of Hα (by at least 30 %) took place after an X-ray outburst of A 1118−616 (Coe et al. 1994). The new observations confirm that the changes in the circumstellar envelopes at the time of Type II X-ray outbursts are global and profound, affecting their basic physical properties. The fact that the red shoulder in the Hα profile of A 0535+26 seems to have grown *after* the start of the X-ray outburst (the X-ray outburst peaked on February 18, while the spectrum taken just two days before shows the red shoulder beginning to appear) suggests that it is the X-ray outburst – or some physical process associated with it – which affects the dynamics of the envelope rather than the opposite.

Several objects have now been observed to display fast V/R variations (with a time-scale of days) and cyclic V/R variability with a time-scale of months. In a one-year V/R cycle, a phase such as the disappearance of the red peak illustrated in Fig. 6, would take about one month, if we can assume that the whole process happens at the same speed. The formation of a red shoulder seen in Fig. 7 was only a factor 3 – 4 faster than it would be in a normal V/R cycle. There is not an evident separation between the time-scales of fast changes and slow quasi-cyclic variability. Moreover, the shapes observed during these fast variations are not distinguishable from those observed during the V/R cycles. Therefore there is no longer any reason to suspect that the fast variations in the emission line profiles during Type II outbursts are caused by any other physical processes different from those involved in quasi-cyclic V/R variability. We propose that both types of variability are associated with highly non-axisymmetric density distributions in the envelopes. The rapid changes in the line profiles can be due to strong disruptions of the distribution of material in the envelopes taking place during very short time-scales, while the quasi-cyclic variability is due to the propagation of density waves in the discs, which originate slowly-moving disruptions. It is even possible that the global disruption events can act as original excitations giving rise to the global modes.

The observations of Hanuschik et al. (1995) and Hummel & Vrancken (1995) support the idea that the density perturbations in isolated Be stars expand outwards through the discs, from the neighbourhood of the central star. These perturbations would cover the whole radial span over a typical time-scale of the order of one year, in agreement with the calculations of Okazaki (1991). In the Type II outbursts of Be/X-ray binaries, the appearance of asymmetry in the Hα emitting region and the X-ray outburst – indicating a perturbation at the distance of the neutron star orbit – are almost simultaneous.

It must be stressed that all known Be/X-ray transients which have displayed V/R variability show very short quasi-periods of V/R variability, compared to isolated Be stars and to the predictions of one-armed oscillation models. Be/X-ray transients for which complete cycles have been observed are V850 Cen (quasi-period ≈ 4 months), HD 245770 (about one year), BQ Cam (about one year) and V801 Cen (about three years). In isolated Be stars, periods range from 2 years to decades, with an average of 7 years. Okazaki (1991) found that, in isolated Be stars, the periods of the oscillations are larger for larger discs or smaller density gradients in the discs. Waters et al. (1988) found that the density gradients in the envelopes of Be/X-ray binaries were in the same range as those calculated for isolated Be stars.

Recently, Okazaki (1997) has suggested that the higher radiation pressure could induce shorter quasi-periods for the earliest Be stars, but the observed quasi-periods in Be/X-ray binaries are still too short. Okazaki (1997, priv. comm.) suggests that the shorter periods could be due to denser envelopes. This systematic difference supports the idea that the presence of an orbiting neutron star is a major factor affecting the dynamics of the extended circumstellar envelopes of Be/X-ray transients, as has been proposed by Reig et al. (1997b) in order to explain the correlation between the *maximum* EW of Hα ever observed from a Be/X-ray binary and its orbital period. They suggested that the correlation exists because the continuous passage of the neutron star prevents the development of a large circumstellar disc by accreting material at periastron passage. A second possibility could simply be that the presence of the neutron star makes the discs unstable against density perturbations and the presence of these perturbations prevents their further growth.

An interesting point is the fact that the only series of Type I outbursts from 4U 0115+634 ever observed seems to be associated with the presence of a density perturbation in its envelope. This suggests the possibility that the existence of moving regions with enhanced densities and perturbed velocity fields causes the series of Type I outbursts observed from close Be/X-ray transients. The Be/X-ray transient 2S 1417−624 showed a series of Type I outbursts in 1995, after a giant outburst in late 1994 (Finger et al. 1996b), mimicking the behaviour of 4U 0115+634. The Type I outbursts peaked close to apastron, again suggesting that the density distribution was not symmetric. This behaviour would be easily explained if a global density perturbation in the envelope had been started at the time of the Type II outburst and the Type I outbursts were caused by the passage of the neutron star through the perturbed region. This explanation would also account for the large changes in relative velocity between the neutron star and the material in the envelope needed to explain the X-ray lightcurves of different outbursts without having to invoke enormous variations in the outflow rate from Be stars, which do not seem to be reflected in the observations. All the observed profiles can be explained by Keplerian movements, without any indication of mass outflow.

The main unknown is the extent of the Hα emitting region. Okazaki (1997) has suggested that the global oscillations are confined to the inner parts of the discs due to the effect of radiation pressure. In most of his models, the perturbations would not extend to the distance of periastron passage of the companion. However, Hummel & Hanuschik (1997) have shown that the existing models, though qualitatively explaining the main characteristics of V/R variability, cannot be used to obtain accurate estimates of the perturbed density and velocity fields. The approximation of linear perturbations used in all existing models cannot reproduce the strength of asymmetry in observed profiles. If the perturbations could reach the distance at which the neutron star approaches (typically 8 – 12 R_* for the close-orbit transients), the series of Type I outbursts could be easily explained. It is evident from the observations that most of the Hα emitting region is affected by the perturbation. If the typical values of the outer radii of Hα emitting regions measured by Hummel & Vrancken (1995) for Be stars (7 – 30 R_*) can be extrapolated to Be/X-ray binaries, this is a likely possibility.

6. Conclusions

We have presented observational evidence showing that global disruptions are frequent in the extended circumstellar envelopes of Be/X-ray binaries. These perturbations are reflected in the asymmetric line profiles normally observed from these systems. V/R ratio variability is observed to occur with typical timescales ranging from a few days to several years. In at least two cases (the giant outbursts of A 0535+26 in February 1994 and 4U 0115+634 in December 1995), a major disruption seems to have originated in coincidence with the X-ray outburst. Further evidence of the association between fast changes in the line profiles and X-ray outbursts has been seen in most Be/X-ray transients.

We believe that all these observation suggest that the presence of the neutron star represents a major factor controlling the dynamics of the discs around the Be stars in X-ray binaries. This fact provides an explanation to the correlation between maximum Hα EW and orbital period found by Reig et al. (1997b). The frequent presence of major density perturbations in the envelopes of Be/X-ray binaries introduces a new element of complication in the modelling of these systems. Rather than assuming that the disc is static and homogeneous, new models should take into account the presence of global density waves and explore the possibility that the series of Type I outbursts are caused by the interaction of the neutron star with the regions of enhanced density which these waves generate.

Continued monitoring of Be/X-ray transients and careful optical coverage of future Type II outbursts will provide the only test for these hypothesis.

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References

Apparao K.M.V., 1994, SSRv 69, 255
Apparao K.M.V., Tarafdar S.P., 1986, A&A 161, 271
Bildsten L., Chakrabarty D., Chiu J., et al., 1997, ApJS 113, 367

Campana S., 1996, ApSS 239, 113
Chen H., Marlborough J.M., Waters, L.B.F.M., 1992, ApJ 384, 605
Clark J.S., Tarasov A.E., Steele I.A. et al., 1998a, MNRAS, 294, 165
Clark J.S., Larionov V.M., Larionova L.V.. et al., 1998b, MNRAS, in press
Coe M.J., Roche P., Everall C., et al., 1994, A&A 289, 784
Cook M.C., Warwick R.S., 1987, MNRAS 227, 661
Corbet R.H.D., Charles P.A., van der Klis M., 1986a, A&A 162, 117
Corbet R.H.D., Smale A.P., Menzies J.W., et al., 1986b, MNRAS 221, 961
Dachs J., Hummel W., Hanuschik R.W., 1992, A&AS 95, 437
Dhillon V.S., Privett G.J., 1997, Starlink User Note 167.5, R.A.L.
Doazan V., Bourdonneau B., Rusconi L., et al., 1987, A&A 182L, 25
Finger M.H., Cominsky L.R., Wilson R.B., Harmon, B.A., Fishman G.J., 1994, in Holt S., Day C.S., eds., AIP Proc. 308, The Evolution of X-ray Binaries, AIP, New York, p 459
Finger M.H., Scott M., Magedon K.,et al., 1995, IAUC 6266
Finger M.H., Wilson R.B., Harmon B.A., 1996a, ApJ 459, 288
Finger M.H., Wilson R.B., Chakrabarty D., 1996b, A&AS 120, 209
Giovannelli F., Graziati L.S., 1992, SSRv 59, 1
Haberl F., 1995, A&A 296, 685
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
Hao J.-X., Huang L., Guo Z.H., 1996, A&A 308, 499
Howarth I., Murray J., Mills D., et al., 1996, Starlink User Note 50.19, R.A.L.
Hummel W., Hanuschik R.W., 1997, A&A 320, 852
Hummel W., Vrancken M., 1995, A&A 302, 751
Kato S., 1983, PASJ 35, 249
Kriss G.A., Cominsky L.R., Remillard R.A., Williams G., Thorstensen J.R., 1983, ApJ 266, 80
Lamers H.J.G.L.M., Waters L..B.F.M., 1987, A&A 182, 80
Levine A.M., Bradt H., Cui W., et al., 1996, ApJ 469, L33
Motch C., Stella L., Janot-Pacheco E., Mouchet M., 1991, ApJ, 369, 490
Negueruela I., Grove E.J., Coe M.J., et al., 1997, MNRAS, 284, 859
Norton A.J., Chakrabarty D., Coe M.J., et al., 1994, MNRAS 271, 981
Okazaki, A.T., 1991, PASJ 43, 75
Okazaki A.T., 1996, PASJ 48, 305
Okazaki A.T., 1997, A&A 318, 548
Papaloizou J.C., Savonije G.J., Henrichs H.F., 1992, A&A 265, L45
Parmar A.N., White N.E., Stella L., Izzo C., Ferri P., 1989, ApJ 338, 359
Reig P., Fabregat J., Coe M.J., et al., 1997a, A&A 322, 183
Reig P., Fabregat J., Coe M.J., 1997b, A&A, 322, 193
Reig P., Coe M.J., Stevens J.B., et al., 1997c, in 2nd Integral Workshop, The transparent Universe, St. Malo, France, ESA SP-382, p. 175
Sazonov S., Sunyaev R., 1995, IAUC 6272
Scott D.M., Finger M.H., Wilson R.B., Prince, T.A., Vaughan B., 1996, IAUC 6450
Shortridge K., Meyerdicks H., 1996, Starlink User Note 86.11, R.A.L.
Slettebak A., 1988, PASP 100, 770
Slettebak A., Collins G.W., Truax R., 1992, ApJS 81, 335
Stella L., White N.E., Rosner R., 1986, ApJ 208, 669
Stevens J.B., Reig P., Coe M.J., et al., 1997, MNRAS, 288, 988
Takeshima T., Dotani T., Mitsuda K., Nagase F., 1994, ApJ 436, 871
Tamura K., Tsunemi H., Kitamoto S., et al., 1992, ApJ 389, 676
Telting J.H., Waters L.B.F.M., Persi P., Dunlop S.R., 1993, A&A 270, 355
Telting J.H., Heemskerk M.H.M., Henrichs H.F., Savonije G.J., 1994, A&A, 288, 588
Terrell J. & Priedhorsky W.C., 1984, ApJ 285, L15
Unger S.J., Roche P.D., Negueruela I., et al., 1998, A&A, in press
Waters L.B.F.M., Taylor A.R., van der Heuvel E.P.J., Habets G.M.H.J., Persi P., 1988, A&A 198, 200
Waters L.B.F.M., de Martino D., Habets G.M.H.J., Taylor A.R., 1989, A&A 223, 207
White N.E., Nagase F., Parmar A.N., 1995, in Lewin W.H.G., van Paradijs J., van den Heuvel E.P.J., eds., X-ray binaries, Cambridge University Press, Cambridge, p. 1
Zuiderwijk, E.J., Martin, R., Raimond, E., et al., 1994, PASP 106, 515