The Be/X-ray Transient V0332+53: Evidence for a tilt between the orbit and the equatorial plane?

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ABSTRACT
We present optical and infrared observations of BQ Cam, the optical counterpart to the Be/X-ray transient system V0332+53. BQ Cam is shown to be an O8 – 9Ve star, which places V0332+53 at a distance of ~ 7 kpc. Hα spectroscopy and infrared photometry are used to discuss the evolution of the circumstellar envelope. Due to the low inclination of the system, parameters are strongly constrained. We find strong evidence for a tilt of the orbital plane with respect to the circumstellar disc (presumably on the equatorial plane). Even though the periastron distance is only \( \approx 10R_\odot \), during the present quiescent state the circumstellar disc does not extend to the distance of periastron passage. Under these conditions, X-ray emission is effectively prevented by centrifugal inhibition of accretion. The circumstellar disc is shown to be optically dense at optical and infrared wavelengths, which together with its small size, is taken as an indication of tidal truncation.

Key words: binaries: general – stars: emission-line, Be – stars: individual: BQ Cam – pulsars:general – infrared: stars – X-rays: stars.

1 INTRODUCTION
The hard X-ray transient V0332+53 (X0331+53) was first detected by the Vela 5B satellite during a bright outburst in 1973 (Terrel & Priedhorsky 1984). It was rediscovered ten years later by Tenma during a series of smaller outbursts (Tanaka et al. 1983). EXOSAT observations were used to determine that the source pulsates with a period of 4.4 s (Stella et al. 1985). Doppler shifts in pulse arriving times indicate that the pulsar is in a 34.25-d binary orbit with an eccentricity \( e = 0.31 \) (Stella et al. 1985). The optical counterpart was identified by Honeycutt & Schlegel (1985) as the heavily-reddened early-type star BQ Cam. This object was observed to display highly variable Hα emission (Corbet, Charles & van der Klis 1986, and references therein) and infrared excess (Coe et al. 1987). These characteristics are typical of a Be/X-ray binary.

In this subclass of Massive X-ray Binaries, the X-ray emission is believed to be due to accretion of matter from a Be star by a compact companion (see White, Nagase & Parmar 1995; Negueruela 1998). The name “Be star” is used as a general term describing an early-type non-supergiant star, which at some time has shown emission in the Balmer series lines (Slettebak 1988, for a review). 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 circumstellar disc. Most Be/X-ray binaries have relatively eccentric orbits and the neutron star companion is normally far away from the disc surrounding the Be star. Due to their different geometries and the varying physical conditions in the circumstellar disc, Be/X-ray binaries can present very different states of X-ray activity (Stella, White & Rosner 1986). In quiescence, they display persistent low-luminosity \( (L_x \lesssim 10^{36} \text{ erg s}^{-1}) \) X-ray emission or no detectable emission at all. Occasionally, they show series of periodical (Type I) X-ray outbursts \( (L_x \approx 10^{36} - 10^{37} \text{ erg s}^{-1}) \), at the time of periastron passage of the neutron star (e.g., A0535+26, Motch et al. 1991). More rarely, they undergo giant (Type II) X-ray outbursts \( (L_x \gtrsim 10^{37} \text{ erg s}^{-1}) \), which do not show clear orbital modulation. Some systems only display persistent emission, but most of them show outbursts and are termed Be/X-ray transients.

Like most other Be/X-ray transients, V0332+53 has shown both types of outbursts. The 1973 outburst lasted ~ 100 days and peaked at ~ 1.6 Crab near July 10. It was clearly a Type II outburst, even though Whitlock (1989)
found an underlying orbital modulation when the main trend was removed. On the other hand, the three weak outbursts separated by the orbital period observed in 1983 are Type I outbursts. During these outbursts, the pulsed fraction was small (10 – 15%) and the temporal behaviour was dominated by random rapid fluctuations (Makishima et al. 1990a). The spectrum was fitted with a power-law modified by cyclotron absorption. Unger et al. (1992) found that the pulse profile varied between a double-peaked and a single-peaked structure. The equivalent hydrogen column density remained relatively constant at \( \sim 1 \times 10^{22} \) atom cm\(^{-2}\). A prominent absorption feature at 28.5 keV, if attributed to electron cyclotron resonance, implies a magnetic field at the surface of the neutron star of \( \sim 2.5 \times 10^{12} \) G (Makishima et al. 1990b).

A new outburst was discovered by Ginga in September-October 1989. The source remained very bright for more than two weeks, indicating that this was a Type II outburst. A quasi-periodic oscillation, possibly implying the presence of an accretion disc, was detected (Takushima et al. 1994). V0332+53 has not been detected by the BATSE experiment since the CGRO satellite started operations in April 1991 (Bildsten et al. 1997). It is not detected with any significance by the All-Sky Monitor (ASM) on board RXTE either, according to the quick-look results provided by the RXTE/ASM team. Stella et al. (1986) interpret the lack of quiescence emission as an effect of centrifugal inhibition of accretion.

2 OBSERVATIONS

We present data obtained as a part of the Southampton/Valencia/SAAO long-term monitoring campaign of Be/X-ray binaries (see Reig et al. 1997a), consisting of optical spectroscopy, infrared and optical broad-band photometry of BQ Cam, the optical counterpart to V0332+53.

2.1 Blue optical spectroscopy

The source was observed on August 14, 1997 using the 4.2-m William Herschel Telescope (WHT), located at the Observatorio del Roque de los Muchachos, La Palma, Spain. The blue arm was equipped with the Loral1 CCD and the R1200R grating, which gives a nominal dispersion of \( \sim 0.25 \) Å/pixel. A second observation was taken on November 14, 1997. On this occasion the blue arm was equipped with the R1200B grating and the EEV#10 CCD, giving a nominal dispersion of \( \sim 0.22 \) Å/pixel over \( \sim 900 \) Å. A composite spectrum is shown in Fig. 1. The signal-to-noise ratio (SNR) of the August spectrum is relatively low. The Loral camera introduces several artifacts in the range \( \lambda \sim 4150–4250 \) Å, where the spectrum could well be dominated by noise. A very strong spurious feature was present at the wavelength where He\( \text{II} \lambda 4200 \) Å should be found. Between \( \lambda 4320 \) Å and \( \lambda 4500 \) Å, where both spectra overlap, all the features look very similar and only the higher quality November spectrum is shown.
Table 1. Details of the Hα spectroscopy. The FWHM of Hα has been calculated by fitting a single Gaussian to the line profile and should therefore be taken only as an approximation. In the higher resolution spectra, however, this procedure gives values consistent with direct measurement to within 5%.

| Date of Observation(s) | Telescope | Dispersion (Å/pixel) | EW of Hα (Å) | FWHM (km s⁻¹) |
|------------------------|-----------|----------------------|--------------|---------------|
| Jan 28, 1990           | INT       | ~ 0.2                | ~ 4.5        | 250           |
| Sep 02, 1990           | INT       | ~ 0.8                | ~ 5.0        | 250           |
| Nov 14, 1990           | INT       | ~ 0.8                | ~ 5.7        | 260           |
| Dec 27, 1990           | INT       | ~ 0.4                | ~ 6.8        | 260           |
| Jan 27, 1991           | INT       | ~ 0.8                | ~ 6.5        | 240           |
| Aug 28, 1991           | INT       | ~ 0.4                | ~ 4.6        | 280           |
| Dec 14, 1991           | INT       | ~ 0.4                | ~ 4.8        | 270           |
| Aug 18, 1992           | PAL       | ~ 0.9                | ~ 3.1        | 230           |
| Nov 13, 1992           | PAL       | ~ 0.9                | ~ 3.8        | 290           |
| Dec 05, 1993           | PAL       | ~ 0.9                | ~ 6.8        | 280           |
| Aug 14, 1997           | WHIT      | ~ 0.4                | ~ 4.2        | 280           |
| Nov 14, 1997           | WHIT      | ~ 0.4                | ~ 3.9        | 270           |

2.2 Red optical spectroscopy

We have monitored the source since 1990, using the 2.5-m Isaac Newton Telescope (INT) and 4.2-m WHIT, both located at the Observatorio del Roque de los Muchachos, and the 1.5-m telescope at Palomar Mountain (PAL). A log of observations, together with some parameters measured, is presented in Table 1. The Palomar spectra have relatively low SNR and the error in EW, arising due to the difficulty of determining the continuum, is ~ 15%. The line shapes are also difficult to establish. In contrast, the INT and WHIT spectra have all relatively high resolution and errors in the EW of Hα are ~ 5%. The double-peaked structure of Hα is only clearly visible in the spectra with dispersions of 0.4 Å/pixel or better.

All the data have been reduced using the Starlink software packages CCDPACK (Draper 1998) and FIGARO (Shortridge et al. 1997) and analysed using FIGARO and DIPSO (Howarth et al. 1997).

Hα spectra normally show He i λ6678 Å as a very weak emission feature when the SNR is sufficiently large for it to be separated from the noise. An analysis of Hα variability in BQ Cam during 1990–1991 has been presented in Negueruela et al. (1998). Many of the spectra whose parameters are listed in Table 1 are shown in their Fig. 8, and are therefore not reproduced here. Negueruela et al. (1998) found that during 1990–1991, the Hα line presented V/R variability with a quasi-period of ~ 1 year, but this variability stopped late in 1991.

2.3 Optical Photometry

Optical photometry of the source was obtained on November 11, 1997, using the 1-m Jakobus Kapteyn Telescope (JKT) at the Observatorio del Roque de los Muchachos, La Palma, Spain. The telescope was equipped with the Tek4 CCD and the Harris filter set. Conditions were photometric. Instrumental magnitudes were extracted through synthetic aperture routines contained in the IRAF package, and transformed to the Johnson/Cousins system through calibrations derived from observations of a number of Landolt (1992) standard stars taken on the same night. The values measured are $U = 17.74 \pm 0.10$, $B = 17.29 \pm 0.02$, $V = 15.73 \pm 0.02$, $R = 14.69 \pm 0.02$ and $I = 13.27 \pm 0.08$. Errors in the $U$ and $I$ bands are dominated by calibration uncertainties (mostly in the colour correction equations). The smaller errors in $B$, $V$ and $R$ are dominated by measurement errors.

2.4 Infrared Photometry

Infrared observations of BQ Cam are listed in Table 2. They have been obtained with the Continuously Variable Filter (CVF) on the 1.5-m Carlos Sánchez Telescope (TCS) at the Teide Observatory, Tenerife, Spain, and the UKT9 detector at the 3.9-m UK Infrared Telescope (UKIRT) at the Mauna Kea observatory on Hawaii. The December 1994 observation was taken with IRCAM mounted on UKIRT and 540-s total exposure in each filter. Data for the period 1983–1986 have already been reported in Coe et al. (1987). The observations presented here extend for a further ten years. The long-term lightcurve is shown in Fig. 2.

3 RESULTS

3.1 Spectral classification

The spectrum of BQ Cam in the classification region is displayed in Fig. 1. We can see that Hβ is in emission, with a clear double-peaked structure (see also Fig. 3), almost to the continuum level. The He i lines at λλ 4713 & 5016 Å also show weak double-peaked emission, just above the continuum level. In contrast, Hγ only shows two very weak emission components on the wings of the absorption line.

The very strong diffuse interstellar lines are consistent with the high reddening of the object. The strength of the He ii lines clearly identifies the object as an O-type star. This is confirmed by the strong Si iv lines. Overall the spectrum is very similar to that of LS 437, the optical counterpart to 3A 0726–260 (Negueruela et al. 1996).

In Fig. 3, the spectrum of BQ Cam is compared to that of two MK standards from the digital atlas of Walborn & Fitzpatrick (1990), ε Orionis (O9III) and HD 48279 (O8V). Also shown is a high SNR spectrum of the Be star HD 333452 (O9Ie) from Steele, Negueruela & Clark (1999).

Points to be noted are:

- The Hδ and He i lines are weaker in BQ Cam than in any standard, due to the presence of circumstellar emission.
- BQ Cam must be later than O7, since He i λ4471 Å > He ii λ4541 Å.
- The presence of He i λ4026, 4144 Å, the strength of the Si iv doublet, C ii λ4072 Å and He i λ4388 Å all point to BQ Cam being no earlier than O8.
- The main luminosity criterion, namely, the strength of the Si iv λλ 4089, 4116 Å doublet is difficult to judge in BQ Cam, because He i λ4412 Å is not present (presumably filled-in by emission) and the quality of the spectrum is low at that end.
- The Mg ii λ4481 Å line is visible at this resolution in both evolved O9 stars, but it is absent in BQ Cam, indicating a lower luminosity class. Similarly, N iii λλ 4511–4515
Figure 2. Infrared lightcurves of BQ Cam during 1983–1995. $J$ magnitudes are represented by open squares, $H$ by stars, $K$ by filled squares and $L'$ by triangles. Error bars have been removed for clarity (see Table 2 for details).

Â is much weaker in BQ Cam than in the giants. This line is also stronger in HD 48279, but Walborn & Fitzpatrick (1990) warn that this object is N-enhanced.

- The N$\text{iii}$ lines are only seen in absorption in the O8–O9 range in main-sequence stars (Walborn & Fitzpatrick 1990). N$\text{iii}$ $\lambda\lambda$ 4379, 4642 Â and possibly N$\text{iii}$ $\lambda$4511 Â are visible on the spectrum of BQ Cam.
- The equivalent width (EW) of He$\text{ii}$ $\lambda$4686 Â in BQ Cam (0.6 Â) is inside the range typical for O8–O9 stars (Conti & Alschuler 1971).
- The O$\text{ii}$ $\lambda$4367 Â line, which can be seen in the spectra of the two O9 stars is also visible in the spectra of the O9V standards 10 Lac and HD 93028 at this resolution, hinting that BQ Cam could be earlier.
- The complete absence of C$\text{iii}$ $\lambda$4650 Â in BQ Cam is surprising. In main sequence stars, it is clearly visible as early as O8 (Walborn & Fitzpatrick 1990). This line is also absent in LS 437. There is no reason to think that BQ Cam is carbon deficient, since C$\text{iii}$ $\lambda$4072 Â is present and there is no sign of N-enhancement. One possible explanation is that the inner regions of the circumstellar discs of Oe stars are hot enough to produce C$\text{iii}$ emission, which would be filling in the $\lambda$4650 Â line.

From all the above, it is clear that BQ Cam is an un-evolved star in the O8–9 range. An O8.5V classification is very likely, but, since the presence of emission affects the main classification criteria, we prefer to be cautious and give an spectral type O8-9Ve.

3.2 Distance

In order to obtain an estimate of the distance to the system, it is necessary to determine the interstellar absorption in its direction. This is complicated because Be stars present circumstellar reddening, due to the infrared continuum emission. The calculation by Kodaira et al. (1985) of $A_V = 7.4$ is a gross overestimate, since they took the infrared magnitudes measured in 1983 to be those intrinsic to the star, while our data show that the disc emission accounted for at least $\sim 0.8$ mag in $J$. Our $UBVRI$ photometry was taken at a time when the circumstellar disc was certainly small (see Sections 3.3 and 4). The small EW of H$\alpha$ at the time of the observations (see Table 3) should be accompanied by a small circumstellar reddening (see Dachs, Engels & Kiehling 1988).

Since the intrinsic colour of a late O-type star is $(B - V)_0 = -0.31$ for luminosity classes III–V (Schmidt-Kaler 1982), the measured $(B - V) = 1.56 \pm 0.03$ implies $E(B - V) = 1.87$. This value is almost identical to the
E(B − V) = 1.88±0.1 deduced from the strength of different interstellar bands by Corbet et al. (1986), though the photometric determination is more reliable. It is also compatible within the errors with the value of N_∞ derived by Unger et al. (1992) from EXOSAT X-ray data taken during the 1983 Type I outbursts, which implies E(B − V) ≈ 1.7 (Bohlin, Savage & Drake 1978). Since a very small amount of circumstellar reddening could be present, the derived distance should be taken as a lower limit. Zorec & Briot (1991) and Fabregat & Torrejón (1998) have noted that Be stars are on average 0.3 mag brighter than main-sequence objects (due to the added luminosity of the circumstellar disc). Though the disc surrounding BQ Cam must be small, some contribution to the absolute luminosity should be expected. However, we will use the absolute magnitude of a normal O8.5V star M_V = −4.5 (Vacca, Garmany & Shull 1996), once again taking into account that the distance calculated will be a lower limit.

Using the standard reddening of R = 3.1, we derive d = 7.6 kpc. However, using Schmidt-Kaler’s (1982) expression for the reddening to O stars, we find R = 3.3, which gives a distance of d = 6.3 kpc. Given the uncertainty in R and taking into account the above considerations, we will accept the distance d = 6 kpc as a lower limit (unless the reddening in that direction is exceptionally strong). An estimate of the different factors mentioned above, would indicate a range 6 < d < 9 kpc for the distance to BQ Cam.

We note that for an O9III star, M_V = −5.5 (Vacca et al. 1996) and the implied distance is d > 10 kpc, which would place the object well outside the galactic disc. This is taken as confirmation of the main-sequence classification for BQ Cam.

### 3.3 System parameters

The very low mass function of V0332+53, f(M) = 0.10 ± 0.03 (Stella et al. 1985) indicates that the orbit of the neutron star is seen under a very small inclination angle. Assuming a lower limit for the mass of an O-type companion M_4 ≥ 20M_☉ and the standard mass for a neutron star M_ν = 1.44 M_☉, an inclination angle i < 10°3 ±0°9 is obtained. Waters et al. (1989) have argued that the orbital plane of Be/X-ray binaries with close orbits should not be very inclined with respect to the equatorial plane in which the circumstellar disc is supposed to form.

We have used our high-resolution spectra from November 14, 1997 to measure the parameters of several emission and absorption lines, which are listed in Table 2, in order to estimate the rotational velocity of BQ Cam. This is particularly difficult given the presence of a circumstellar component. We have selected the two strongest He lines in the blue. He II λ4686 Å is not likely to be contaminated by any emission component from the disc, but can be affected by non-LTE effects. On the other hand, He I λ4471 Å is likely to be affected by circumstellar emission, which will reduce

| Date     | TJD   | J    | H    | K    | L'    |
|----------|-------|------|------|------|-------|
| 1983 Nov 23 | 45662(U) | 11.39±0.03 | 10.70±0.03 | 10.31±0.03 | 9.6±0.05 |
| 1983 Dec 23 | 45692(U) | 11.39±0.03 | 10.60±0.03 | 10.20±0.03 | –      |
| 1984 Jul 22  | 45904(U) | 11.44±0.03 | –      | –      | –      |
| 1985 Jul 22  | 46269(U) | 11.60±0.03 | 10.94±0.03 | 10.53±0.03 | –      |
| 1986 Oct 10  | 46714(U) | 11.63±0.03 | 11.01±0.03 | 10.60±0.03 | 10.19±0.05 |
| 1986 Oct 23  | 46727(U) | 11.65±0.03 | 11.00±0.03 | 10.62±0.03 | 10.22±0.05 |
| 1987 Feb 25  | 46852(U) | 11.66±0.03 | 11.06±0.03 | 10.64±0.03 | 10.21±0.05 |
| 1987 Aug 18  | 47026(U) | 11.60±0.03 | 10.99±0.03 | 10.62±0.03 | 9.97±0.09 |
| 1987 Nov 05  | 47105(U) | 11.64±0.03 | 11.02±0.03 | 10.60±0.03 | 10.11±0.11 |
| 1987 Jan 03  | 47164(T) | 11.62±0.04 | 11.04±0.04 | 10.74±0.04 | –      |
| 1988 Jul 23  | 47366(U) | 11.44±0.02 | 10.78±0.02 | 10.42±0.03 | 10.02±0.08 |
| 1989 Dec 15  | 47876(U) | 11.47±0.01 | 10.84±0.01 | 10.46±0.01 | 10.09±0.08 |
| 1989 Dec 21  | 47882(U) | 11.42±0.01 | 10.80±0.01 | 10.42±0.01 | –      |
| 1991 Jan 22  | 48279(T) | 11.95±0.06 | 11.30±0.03 | 10.84±0.03 | –      |
| 1991 Aug 23  | 48492(T) | 11.97±0.04 | 11.40±0.03 | 10.97±0.03 | –      |
| 1991 Aug 25  | 48494(T) | 12.08±0.06 | 11.36±0.03 | 11.01±0.04 | –      |
| 1991 Aug 27  | 48496(T) | 11.80±0.05 | 11.28±0.04 | 10.96±0.04 | –      |
| 1991 Nov 04  | 48565(U) | 12.00±0.02 | 11.37±0.01 | 10.95±0.02 | 10.39±0.06 |
| 1991 Dec 01  | 48592(T) | 12.2 ±0.2  | 11.47±0.07 | 11.08±0.06 | –      |
| 1992 Jan 14  | 48636(U) | 12.05±0.01 | 11.46±0.01 | 11.06±0.01 | 10.44±0.04 |
| 1992 Feb 12  | 48665(U) | 12.16±0.04 | 11.67±0.05 | 11.40±0.06 | –      |
| 1992 Aug 17  | 48852(U) | 11.99±0.01 | 11.42±0.02 | 11.00±0.01 | 10.56±0.09 |
| 1993 Jan 15  | 49003(U) | 11.92±0.07 | 11.15±0.04 | 10.73±0.03 | –      |
| 1994 Nov 07  | 49664(T) | 12.16±0.06 | 11.61±0.03 | 11.21±0.05 | –      |
| 1994 Dec 14  | 49701(U) | 11.89±0.02 | 11.43±0.02 | 11.12±0.02 | –      |
| 1995 Jan 02  | 49720(T) | 11.97±0.14 | 11.28±0.05 | 11.04±0.06 | –      |

Table 2. Observational details of the IR photometry. Observations marked T are from the TCS, while those marked U are from UKIRT. The first five observations are taken from Coe et al. (1987).
we obtain

\[ v \]

\[ \text{we obtain} \]

\[ \text{ply} \]

\[ \lambda \]

we obtain

\[ \text{the Tek5 CCD on the red arm. From bottom to top, H} \]

\[ \text{and the R1200R grating and} \]

\[ \text{1997 with the WHT equipped with the R1200B grating and} \]

\[ \text{Emission lines in BQ Cam observed on November 14, 1997} \]

\[ \text{Huber and Kaiser (1988). Since the FWHM of H}_\alpha \]

\[ \text{correlation is due to the inclusion of measurements for stars} \]

\[ \text{to a relatively high degree. We note that the scatter in the} \]

\[ \text{relation between peak separation of H}_\beta \]

\[ \text{of the photospheric absorption and therefore below the continu-} \]

\[ \text{continuum. Note the similarity in shape, intensity and FWHM.} \]

\[ \text{its FWHM. Therefore any estimation of } v \sin i \text{ based on this} \]

\[ \text{line should be taken as a lower limit.} \]

\[ \text{From Buscombe’s (1969) approximation, the measured FWHMs correct-} \]

\[ \text{ed for instrumental broadening imply } v \sin i = 160 \text{ km s}^{-1} \text{ from the H} \]

\[ \text{He II line and } v \sin i = 130 \text{ km s}^{-1} \text{ from the H} \]

\[ \text{e I line. Similarly, using the correlation between FWHM of He I } \lambda4471 \]

\[ \text{Å and } v \sin i \text{ from Slettebak et al. (1975), we obtain } v \sin i = 135 \text{ km s}^{-1}. \text{The two values derived from the He I } \lambda4471 \]

\[ \text{Å are very similar and set a lower limit for } v \sin i. \]

\[ \text{A very different way of estimating the rotational velocity is by using the mean relation between FWHM of the H}_\alpha \]

\[ \text{emission line and } v \sin i \text{ for Be stars from Hanuschik, Kozok} \]

\[ \text{& Kaiser (1988). Since the FWHM of H}_\alpha \text{ in BQ Cam had not} \]

\[ \text{changed significantly during 6 years, we deduce that the disc is} \]

\[ \text{dynamically stable and the correlation can be trusted to a relative-} \]

\[ \text{ly high degree. We note that the scatter in the} \]

\[ \text{correlation is due to the inclusion of measurements for stars} \]

\[ \text{with dynamically unstable discs.} \]

\[ \text{Using} \]

\[ \log \frac{\text{FWHM}}{2(v \sin i)} = -0.2 \log W_\alpha + 0.11 \]

\[ \text{we obtain } v \sin i = 140 \text{ km s}^{-1}. \text{Similarly, using the mean relation between peak separation of H}_\alpha \]

\[ \text{and } v \sin i \text{ for Be stars (Hanuschik et al. 1988),} \]

\[ \log \frac{\Delta v_{\text{peak}}}{2(v \sin i)} = -0.4 \log W_\alpha - 0.1 \]

\[ \text{we obtain } v \sin i = 170 \text{ km s}^{-1}. \]

\[ \text{All the above estimates provide similar values. The esti-} \]

\[ \text{mates based on He I } \lambda4471 \text{ Å yield a lower limit for } v \sin i \geq 130 \text{ km s}^{-1}. \text{Averaging the four esti-} \]

\[ \text{mates gives a value of } \sim 150 \text{ km s}^{-1}. \text{The errors associated with this estimation} \]

\[ \text{are formally large. However, the shape and FWHM of H}_\alpha \]

\[ \text{are not compatible with a very low } v \sin i \leq (100 \text{ km s}^{-1}), \text{while a value approaching } v \sin i \approx 200 \text{ km s}^{-1} \text{ does not seem} \]

\[ \text{compatible with the comparatively small width (both at the base} \]

\[ \text{and at half-maximum) of H}_\alpha \text{ when a large population of} \]

\[ \text{Be stars are considered (see, for example, Hanuschik et al. 1996).} \]

\[ \text{Since all Be stars are believed to be fast rotators, this value of } v \sin i \text{ confirms that the star is seen under a} \]

\[ \text{small inclination angle. We note, however, that in order to show} \]

\[ \text{a } v \sin i \approx 150 \text{ km s}^{-1} \text{ with an inclination angle } i = 10^\circ, \text{the rotational velocity of the star should be } v \sim 900 \text{ km s}^{-1}, \text{well above the break-up velocity of a late O-type star} \]

\[ \text{(} \leq 600 \text{ km s}^{-1}). \text{Assuming an upper limit for the rotational velocity of } v = 0.8v_{\text{break}} \lesssim 480 \text{ km s}^{-1}, \text{still gives } i \gtrsim 19^\circ. \text{An orbital inclination of } i = 19^\circ, \text{would imply an enormously undermassive primary with } M_* = 5M_\odot \text{(the errors in the orbital parameters allow up to } M_* = 7M_\odot \text{ within 2-} \sigma). \text{Even if we assume that the O star is rotating at break-up velocity,} \]

\[ i = 15^\circ \text{ implies } M_* = 8M_\odot, \text{still undermassive by a factor } > 2. \text{We note the uncertainty in our estimate of } v \sin i, \text{but the constraints } v < 600 \text{ km s}^{-1} \text{ and } i \lesssim 10^\circ \text{ can only be} \]

\[ \text{compatible with } v \sin i \lesssim 100 \text{ km s}^{-1}. \text{This is not only far away from our estimate of } v \sin i, \text{but also very difficult to} \]

\[ \text{reconcile with the FWHM and shape of H}_\alpha \text{ (see Hummel 1994, Hanuschik et al. 1996).} \]

\[ \text{On the other hand, we have no strong reasons to expect a very undermassive optical star. The calculations by} \]

\[ \text{Vanbeveren & De Loore (1994) show that, under certain} \]

\[ \text{circumstances, mass transfer in massive binaries can lead to} \]

\[ \text{the formation of overluminous post-main-sequence stars with} \]

\[ \text{compact companions (e.g., Vela X-1). It is not clear how} \]

\[ \text{noticeable this effect will be as long as the star which has} \]

\[ \text{received mass remains in the main sequence, and whether this} \]

\[ \text{will affect } T_{\text{eff}} \text{ (and therefore, spectral class). Gies et} \]

\[ \text{al. (1998) have found evidence suggesting that the optical} \]

\[ \text{component of the Be + sdO binary } \phi \text{ Per is moderately under-}\]

\[ \text{massive, but no evidence exists for any main-sequence} \]

\[ \text{component of an X-ray binary being undermassive by a factor} \]

\[ > 2. \text{As a consequence, we believe that the discrepancy} \]

\[ \text{in the two values for } \sin i \text{ strongly suggests that the orbital} \]

\[ \text{plane is not exactly aligned with the equatorial plane of the} \]

\[ \text{Be star, even though the difference may be small (} \sim 10^\circ). \]

\[ \text{Hummel (1994) has shown that, for inclination angles} \]

\[ i < 30^\circ, \text{the profile of emission lines from Be stars is} \]

\[ \text{dominated by the flank inflections generated by non-}\]

\[ \text{coherent scattering, giving rise to what is known as the} \]

\[ \text{wine-bottle shape. Wine-bottle shapes are found for Be stars} \]

\[ \text{with } v \sin i < 250 \text{ km s}^{-1} \text{ and Hanuschik et al. (1996) esti-} \]

\[ \text{mate that flank inflections are visible for inclinations up to} \]

\[ i < 150^\circ. \text{However, the 1997 H}_\alpha \text{ profiles of BQ Cam have} \]

\[ \text{no sign of flank inflections (see Fig. 3). Since it is not rea-} \]

\[ \text{sonable to suppose that } i > 60^\circ \text{ for BQ Cam, we interpret} \]

\[ \text{the absence of flank inflections as proof that the envelope of} \]

\[ \text{BQ Cam is small and the optical depth in the vertical direc-}\]

\[ \text{tion is not large enough to produce the wine-bottle profile} \]

\[ \text{typical of non-coherent scattering. Therefore the peak sepa-} \]

\[ \text{ration of emission lines in November 1997 will reflect the} \]

\[ \text{actual extent of the disc.} \]

\[ \sim 0000 \text{ RAS, } \text{MNRAS} \text{ 000, 000--000} \]
Table 3. Details of several lines in the spectrum of BQ Cam, observed on November 14, 1997, with the WHT. Emission lines are shown in Fig. 2. The EW of Hα is only approximate, due to the contamination by the interstellar band at λ 4885 Å. Note that He i 4686 Å and He i A4471 Å are photospheric absorption lines, though the latter could be affected by a circumstellar emission component.

3.4 Disc evolution

Iye & Kodaira (1985) and Corbet et al. (1986) describe radial-velocity changes in the Hα emission line and investigate their possible connection with the orbital period. Our Hα spectroscopy shows that these changes were also present during 1990–1991, but Negueruela et al. (1998) have shown that these velocity variations can be explained by quasi-cyclic V/R variability with a quasi-period ~1 year. Similar cyclic variability is seen in many other Be/X-ray binaries (Negueruela et al. 1998). It is noteworthy that the system was displaying V/R variability in 1983–1984 when it showed a short span of X-ray activity and again in 1990, immediately after the 1989 Type II outbursts. The possibility of a causal connection between V/R variability and X-ray activity has been discussed in Negueruela et al. (1998).

The infrared lightcurves (see Fig. 2) of BQ Cam show a general fading trend, only interrupted by a brief brightening in 1988–1989. The brightest magnitudes observed are those from late 1983, when the source was active in the X-rays, coinciding with the highest EWs of Hα reported (~8 and ~10 Å; Kodaira et al. 1985; Stocke et al. 1985). The decline of the strength of Hα (Iye & Kodaira 1985) was accompanied by the fading of infrared magnitudes. Corbet et al. (1986) and Coe et al. (1987) interpret the decline as being due to the dispersion of the circumstellar disc of the Be star.

The infrared magnitudes remained stable during 1985–1987, but brightened again in 1988, reaching values similar to those of 1983. After the type II outburst in late 1989, the infrared magnitudes faded to a deeper minimum, where they have remained until 1995, though showing considerable short-time variability. There does not seem to be any corresponding systematic change in Hα EW (see Table 1). The variability in Hα during 1990–1991 can be associated with the V/R cycle seen at the time (Negueruela et al. 1998). Given the similarity between the relatively high-resolution spectra of 28 August 1991, 14 December 1991, 14 August 1997 and 14 November 1997, it seems unlikely that any significant V/R variability has been present after 1991.

It is noteworthy that, while the infrared colours have experienced large fluctuations (~0.8 mag in J and ~1.2 in K), the associated colours have remained much more stable (with (J – K) ~ 0.8 – 1.2). There is no clear correlation between the brightness and the colours. If, for instance, we compare the J magnitude with (J – K), we see that the faintest observations can be either very blue (TJD 48665) or relatively red (TJD 48494). The brightest observations are on average relatively red, but not more than some fainter points.

Using the correlations of Rieke & Lebofsky (1985), from the observed $A_V = R \times E(B - V) = 6.17$ we deduce $A_J = 1.74$ and $A_K = 0.69$, implying an interstellar reddening $E(J – K) = 1.05$. Using the fainter and bluer infrared observations (TJD 48665), we find $J_0 = J – A_J = 10.42$ and $K_0 = K – A_K = 10.71$, implying $(J – K)_0 = -0.29 \pm 0.07$, which is roughly compatible with Wegner’s (1994) average value of $(J – K)_0 = -0.18$ for O9V stars, if we consider the errors in his value and in the standard relations used. The measured $E(J – K) = (J – K) – (J – K)_0 = 0.94$ is, within the errors, compatible with the value for interstellar reddening found above and implies that no circumstellar reddening was present. This corresponds to a state in which the disc is optically thin at all infrared wavelengths and very little infrared emission is produced (see Dougherty et al. 1994). Brighter magnitudes with a similarly blue colour (as in TJD 49701) must represent a state in which the disc is producing a significant amount of infrared emission, but still remains optically thin, giving rise to no circumstellar reddening – a condition which could be associated with a very small disc (Dougherty et al. 1994). Very faint magnitudes with redder colours (as in TJD 49664) represent states in which little infrared emission is produced (see Dougherty et al. 1994). With an inclination angle $i \lesssim 10^\circ$, the orbital solution...
for V0332+53 implies $a_\ast \gtrsim 8.5 \times 10^{10}$ m. For a companion mass $M_* \gtrsim 20 M_\odot$, this implies a periastron distance $a_{\text{per}} \gtrsim 6.3 \times 10^{10}$ m $\approx 10 R_*$, where the radius of the optical star is assumed to be $R_* = 9 R_\odot$ (Vacca et al. 1996). Using our value for $v \sin i$ and Huang’s (1972) law

$$R_d = \left( \frac{2 v \sin i}{\Delta v_{\text{peak}}} \right)^2$$

where $v_{\text{peak}}$ is the separation between the peaks of an emission line and Keplerian rotation of the envelope is assumed (which gives upper limits), we obtain outer emission radii $R_d = 4.0, 2.5$ and $1.8 R_*$ for Hα, Hβ and Heα A6678Å in November 1997. This clearly shows that the neutron star does not come close to the dense regions of the circumstellar disc in the present situation. The neutron star is only reached by the low-density outer envelope and accretion is centrifugally inhibited (Stella et al. 1986). The reduced size of the circumstellar disc strongly points at the possibility of disc truncation by the neutron star, an idea advanced by Okazaki (1998) and supported by the results of Reig, Fabregat & Coe (1997b).

This truncation would explain why we observe instances of a small disc which is optically thick at all wavelengths, implying a very high density. We note that V635 Cas shows large brightness variations with little change in the associated colours (Negueruela et al. 1997), a behaviour that could be associated with a very optically thick disc (Dougherty et al. 1994). This variability extends to the $B$ band, which can change by at least 0.6 mag. It seems likely then that the disc in BQ Cam is not so optically thick as that in V635 Cas at optical wavelengths, but can be very optically thick in the infrared. Roche et al. (1999) find that optical and infrared observations of the Be/X-ray transient Cep X-4 are also best explained with a truncated dense disc.

We have established that the orbit of the neutron star is likely to be inclined with respect to the equatorial plane of the Be star (in which the disc is suppose to lie while it is dynamically stable). This is in contradiction with the general argument presented by Waters et al. (1989), but it is in not unexpected. We note that the Be + neutron star system PSR B1259−63, which is believed to be a representative of the class of systems which will evolve into Be/X-ray binaries, is likely to have a tilted orbit with respect to the equatorial plane of the Be star (see Ball et al. 1999 and references therein), and the B + neutron star system PSR J0045−7319, which must have formed in a way analogous to Be/X-ray binaries, has been shown to have a rotation axis misaligned with the orbit (Kaspi et al. 1996). The relevance of this misalignment to the formation and evolution of binary systems containing neutron stars has been discussed by van den Heuvel & van Paradijs (1997) and Iben & Tutukov (1998).

Corbet & Peele (1997) have suggested a possible 34.5-d period for the Be/X-ray binary 3A 0726−260. If this period was to be confirmed, the comparison between V0332+53 and 3A 0726−260 would be most interesting, since the two systems would have neutron stars orbiting Oe stars of almost identical spectral types with extremely similar orbital periods. In contrast, the X-ray activity of these two systems is completely different. V0332+53 is a transient, which spends most time in quiescence and shows very bright outbursts, while 3A 0726−260 seems to be a persistent low-luminosity source with small outbursts. The difference in pulse periods (4.4-s against 103.2-s) could be reflecting the very different behaviour of accreted material in magnetic fields of very different intensity. However, we note that the quiescent luminosity of 3A 0726−260 is almost identical to that of A 0535+262, which has almost the same spin period, but a much broader orbit. This, together with the fact that the source lies nowhere close to the $P_{\text{orb}}/P_s$ relationship for Be/X-ray binaries, casts some doubt on the orbital period until it can be confirmed using orbital Doppler shift in the arrival time of pulses.

5 CONCLUSIONS

We have presented long-term photometry and spectroscopy of the optical component of the Be/X-ray binary V0332+53, which indicate that it is an O8–9Ve star at a distance of $\sim 7$ kpc. We find evidence for a tilt of the orbital plane with respect to the equatorial plane. The lack of recent X-ray activity is explained by the fact that the dense regions of the circumstellar disc around the Oe star do not reach the orbit of the neutron star. The low inclination of the orbit allows us to determine a periastron distance $a_{\text{per}} \gtrsim 10 R_*$, while measurements from our high-resolution spectroscopy of emission lines set the outer radius of the Hα emitting region at $R_d \lesssim 4 R_*$. Under these conditions, centrifugal inhibition of accretion effectively prevents any X-ray emission.

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