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# The optical and X-ray decline of V 0332+53 (X 0331+53, BQ Cam)

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**Summary.** We present optical spectra of the X-ray transient V 0332 +53 (BQ Cam). The equivalent width of the Hα emission line in the spectrum has declined by a factor ~2 compared with previous observations. This is interpreted as showing that V 0332+53 is surrounded by an evolving circumstellar envelope. EXOSAT observations failed to detect X-ray emission from V 0332+53 showing that the Hα emission decline has been accompanied by a cessation of the X-ray flaring previously observed. From measurements of optical I.S. bands we derive a reddening of $E(B-V) = 1.88 \pm 0.10$. We argue that the optical counterpart of V 0332+53 is a Be star viewed at a low inclination angle.

**Key words:** X-ray binaries – Be stars

## 1. Introduction

The transient X-ray source V 0332+53 was discovered by Terrell and Priedhorsky (1984) with the Vela 5B satellite. It was rediscovered by Tanaka et al. (1983) and subsequent EXOSAT observations (Stella et al., 1985a, hereafter SEA) showed V 0332+53 to be a 4.4s X-ray pulsator with an eccentric ($e = 0.31$) 34.25 day orbit. X-ray outbursts occur close to periastron passage. The pulsations show the presence of an accreting rotating magnetic neutron star in the system. An optical counterpart was found (Argyle, 1983; Kodaira, 1983; Honeycutt and Schlegel, 1983) which was thought to be a reddened B star. Bernacca et al. (1984, hereafter BIS) obtained low dispersion (250 Å/mm) optical spectroscopy of this star and reported Hα emission with, at least at times, a P-Cygni profile. Further, higher resolution, spectroscopy was obtained by Stocke et al. (1985) which showed broad H and He emission lines but without P-Cygni profiles. The lack of photospheric absorption and radial velocity variations led Stocke et al. to conclude that the optical continuum does not arise close to the primary star. Spectrophotometry of V 0332+53 (2.5 Å resolution) has been obtained by Honeycutt and Schlegel (1985, hereafter HS). Kodaira et al. (1985) also report spectroscopic and photometric observations.

In this paper we present medium dispersion (50–130 Å/mm) optical spectroscopy of the counterpart of V 0332+53. We compare our spectra with previous data and relate optical changes to the cessation of the previously observed X-ray flaring behaviour.

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We use our measurements of optical I.S. bands to estimate the reddening to V 0332+53.

## 2. Observations

### 2.1. Optical observations

Spectra of V 0332+53 were obtained at the 2.5 m Isaac Newton Telescope using the Intermediate Dispersion Spectrograph on the three occasions detailed in Table 1. Details of the spectra obtained are shown in Figs. 1 and 2. The detectors employed were the Imaging Photon Counting System (IPCS) and a GEC CCD. Channel to channel variability in detector response was corrected using data on a calibration lamp obtained at the end of each night. Wavelength calibration was from arc lamp exposures. The overall instrumental response of the IPCS was removed through observations of the flux standard HZ15 (Stone, 1977).

Emission is present at Hα in the two spectra of V 0332+53 covering this region. In no case do we see P-Cygni features or absorption components. Very weak emission may be present at Hβ but the signal-to-noise level prevents a definite identification. Interstellar lines due to Na I plus diffuse I.S. bands are also present. Measurements of the Hα line were made by fitting a Gaussian profile plus a quadratic continuum. This procedure produced good fits to the data. We measure a heliocentric velocity ($v_H$) of $-68 \pm 8\,\mathrm{km\,s^{-1}}$, E.W. $= 5.9 \pm 0.6$ Å and a FWHM of $250 \pm 20\,\mathrm{km\,s^{-1}}$ for the July spectrum (resolution $= 97\,\mathrm{km\,s^{-1}}$). For the lower resolution ($228\,\mathrm{km\,s^{-1}}$) Nov. spectrum we measure $v_H = -81 \pm 17\,\mathrm{km\,s^{-1}}$, E.W. $= 4.6 \pm 0.4$ Å and a FWHM of $302 \pm 22\,\mathrm{km\,s^{-1}}$. The quoted FWHM have been corrected for the instrumental resolution using measurements of the calibration arc lines. These widths are consistent with the BIS $300\,\mathrm{km\,s^{-1}}$ upper limit. The blue end of the IPCS spectrum is relatively noisy but Hγ absorption may be present (E.W. $= 1.0 \pm 0.37$ Å, $v_H = -25 \pm 40\,\mathrm{km\,s^{-1}}$). He I λ4387 may be weakly present (E.W. $= 0.64 \pm 0.26$ Å), but the lack of any visible line at He I λ4471 argues against this identification.

### 2.2. X-ray observations

X-ray observations of V 0332+53 were made using the ME experiment on the EXOSAT observatory (Taylor et al., 1981) on the three occasions detailed in Table 2. Although all observations were made close to times of predicted X-ray maxima no emission

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**Table 1.** Optical spectroscopy of V0332+53

| Date | J.D. (−2440000) | Phase | Detector | Exposure time (s) | Spectral range (A) | Dispersion (A/mm) | Channel Size (A) |
|---|---|---|---|---|---|---|---|
| 1984 July 8.2 | 5889.7 | 6.94 | CCD | 1000 | 6300–7000 | 50 | 1.1 |
| 1984 Nov. 29.0 | 6033.5 | 11.14 | IPCS | 6150 | 4200–6100 | 67 | 1.0 |
| 1984 Nov. 30.1 | 6034.6 | 11.17 | CCD | 1800 | 5800–7400 | 131 | 2.9 |

*Notes*: Phases are taken from the ephemeris of Stella et al. (1985a) and are all ± ~0.05

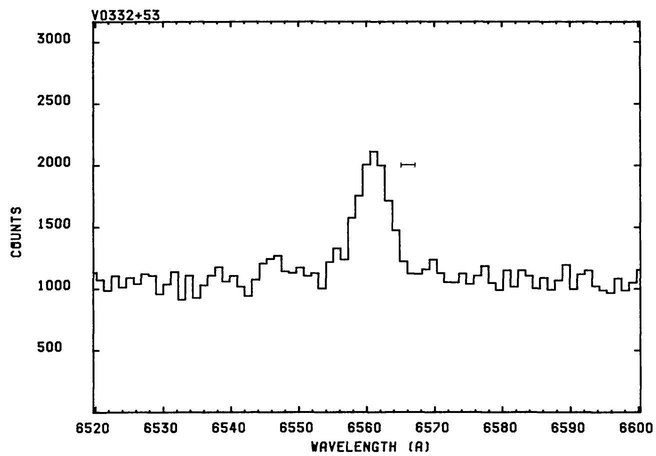


**Fig. 1.** 1984 July 8 spectrum of V0332+53 obtained with the INT Intermediate Dispersion Spectrograph with CCD showing detail of Hα. The horizontal bar indicates the FWHM instrumental resolution

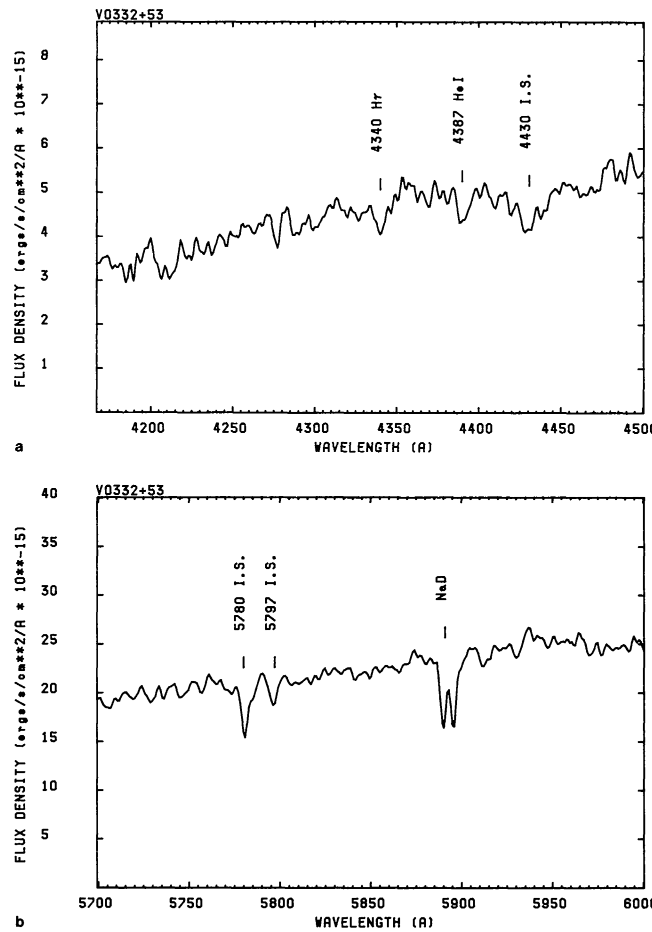


**Fig. 2a and b.** Details of 1984 November 28 spectrum of V0332+53 using the IPCS. The flux calibration is less accurate beyond ~5950 Å

was seen on any pointing with an upper limit of ~1 μJy in all cases (2–10 keV, $>3\sigma$ confidence).

## 3. Interstellar reddening

The I.S. bands seen in our spectra and their implied values for $E(B-V)$ are listed in Table 3. Excluding the 6284 Å band, to avoid problems due to blending with an $O_2$ band, we adopt $E(B-V)=1.88\pm0.10$ which implies $A_v=6.2$ (for $R=3.3$, Herbst 1975).

This reddening implies an X-ray H column density of 1.3 $\pm 0.3$ $10^{22}\,\mathrm{cm}^{-2}$ (Ryter et al., 1975). SEA measured $N_H$ to be between $0.6\pm0.2$ and $1.5\pm0.1$ $10^{22}\,\mathrm{cm}^{-2}$ which corresponds to $E(B-V)=0.9$ and 2.2 respectively (Ryter et al.). The absorption seen in the X-ray band is due to a combination of I.S. and variable material local to the X-ray source. The *lowest* $N_H$ seen is thus an *upper limit* to the I.S. absorption. The lowest X-ray $N_H$ value is thus lower than expected at $\sim 2\sigma$ significance which may indicate that there is an additional soft component in the X-ray spectrum. Alternatively there may be an unusual gas to dust ratio in the direction of V0332+53. This might indicate the presence of dust local to V0332+53.

## 4. Is the optical counterpart of V0332+53 a Be star?

If the primary is an early type star Hα emission implies a supergiant or Be classification. The orbital parameters imply that an OB star would underfill its Roche lobe and the X-ray pulsation period is much shorter than those of neutron stars accreting from the winds of supergiants (see e.g. Corbet, 1985). The orbital and pulsation periods of V0332+53 are typical, however, of those of Be star systems. The other X-ray properties of V0332+53 are also similar to those of other Be star systems: periodic flaring, long term on/off states and a very hard spectrum (Terrell and Priedhorsky, 1984). The optical counterpart of V0332+53 is thus almost certainly a Be star.

SEA derive an X-ray mass function of $\sim 0.1 M_\odot$. Assuming a neutron star mass of $1.4 M_\odot$ and a Be star mass of between 10 and $20 M_\odot$ an inclination angle ($i$) of 10 to 14° is implied. In Struve's (1931) Be star model emission lines originate in an equatorial envelope about a rapidly rotating B star. Be stars viewed at high $i$

**Table 2.** X-ray observations of V 0332+53

| Date | J.D. (−2440000) | Phase | Detector | Exposure time (s) |
|---|---|---|---|---|
| 1984 Sep. 14.2 | 5957.5 | 8.92 | EXOSAT ME | 12000 |
| 1984 Sep. 17.4 | 5961.4 | 9.03 | EXOSAT ME | 10800 |
| 1984 Oct. 18.6 | 5992.1 | 9.93 | EXOSAT ME | 9000 |

**Table 3.** Interstellar bands in V 0332+53 spectrum

| I.S. band | E.W. (Å) | $E(B-V)$ | |
|---|---|---|---|
| 4430 | 3.90 | 1.8 | |
| 5780 | 1.23 | 2.0 | |
| | | 1.6 | (S and VB) |
| 5797 | 0.50 | 2.1 | |
| 6284 | 3.2 | 2.75 | (B and N) |

*Notes*: Calibrations between E.W. and $E(B-V)$ are from Herbig (1975), except those marked (S and VB) and (B and N) which are from Snell and Vanden Bout (1981) and Bromage and Nandy (1973), respectively. For the 6284 band an approximate correction for blending with a telluric $O_2$ band has been applied

show double peaked emission lines whilst those viewed at low $i$ have only a single peak. In a binary system we may expect that the envelope and orbital planes will coincide. The single-peaked Hα line in the V 0332+53 spectrum is thus consistent with a low $i$.

Dachs et al. (1981) show that for Be stars with single Hα emission there is a strong correlation between line width and projected stellar rotational velocity. Hence we may use the width of the Hα line in the V 0332+53 spectrum to constrain $i$. We adopt: $v \cdot \sin(i) = (2(\log_e 2)^{1/2})^{-1}\ W(\alpha)$ from Dachs et al. (1981) where $W(\alpha)$ is the FWHM of Hα. Taking $W(\alpha) = 250\ \mathrm{km\,s^{-1}}$, from our higher resolution July spectrum, we obtain $i > 15°$ for $v < 600$ km/s (early B stars break-up speed, Allen, 1973).

## 5. Variability

Our spectra show several differences from those of Stocke et al. (1985). In 1984 Jan. at $\phi \sim 0.0$ Stocke et al. measured Hα to have E.W. $= 9.0 \pm 0.1$ Å and a velocity of $-10\ \mathrm{km\,s^{-1}}$. Our Hα emission lines are weaker by a factor $\sim 2$ and are blue-shifted by $\sim 65\ \mathrm{km\,s^{-1}}$. Since all the spectra were obtained at similar phase ($\sim 0$) and Stocke et al. find no evidence for velocity changes on a time scale of days, orbital motion cannot account for the velocity shifts. Kodaira et al. (1985) also report that the velocity of Hα decreased by $\sim 70\ \mathrm{km\,s^{-1}}$ between 1983 Nov./Dec. and 1984 Feb. The decline in strength of Hα is almost certainly connected with the cessation of X-ray flaring. The last date SEA detected X-rays from V 0332+53 was 1984 Jan. 23. The probable presence of Hγ in our spectra is consistent with declining Balmer emission. The apparent radial velocity changes in Hα may be related to the "$V/R$" variability seen in those Be stars with double emission peaks in which the ratio of the strengths of the two peaks is variable (see e.g. Underhill and Doazan, 1982, Chap. 11).

The connection between optical line emission and X-ray production probably arises in two ways: a) X-rays ionize hydrogen which then produces emission lines by radiative recombination and b) the emission lines imply the presence of a circumstellar envelope from which the neutron star accretes to produce X-rays. Hα is still in emission when the X-ray flaring has ceased, indicating that an envelope is present. The envelope has presumably decayed, however, such that the neutron star's Alfvén radius is always greater than its corotation radius. Accretion thus cannot take place (cf. Corbet, 1984; Stella et al., 1985b).

HS give $B = 17.04$ on 1983 Nov. 27 and 28 ($\phi \sim 0.4$) whereas BIS report $B = 17.44$ on 1983 Dec. 4 ($\phi \sim 0.6$). This either indicates photometric changes on a timescale of days or calibration differences between the observations. The second explanation appears more likely as HS also give $B = 17.04$ on 1984 Feb. 21 ($\phi \sim 0.9$). HS measure $B-V = 1.62 \pm 0.06$ whereas BIS give $B-V = 2.31 \pm 0.04$. Assuming the I.S. reddening derived in Sect. 3 the first $B-V$ value implies a spectral class earlier than B3 whereas the BIS $B-V$ value implies an F type star, casting doubt upon their measurements (although the presence of a circumstellar shell might redden the colours beyond the interstellar value).

## 6. Distance

V 0332+53 lies within the galactic reddening layer for distances <4 kpc (Allen, 1973) since $b = -2°$. The NaD lines may thus be used as an approximate distance indicator. The E.W. of the sum of these lines is 2.04 Å implying a distance $\sim$ 2 kpc (Allen, 1973). The velocity variations of the Hα emission line mean that it cannot be used to calculate the distance. The low E.W. of Hγ implies contamination by an emission component and so it cannot be used either. Most Be stars in X-ray binaries have spectral types between B0 and B2 and (by definition) luminosity classes of III to V. A star within this range is expected to have $M_v = -2.5$ to $-4.6$ (Balona and Crampton, 1974). Assuming the value of $A_v$ derived in Sect. 3 and $V = 15.4$ (HS) a distance of 2.2–5.8 kpc is implied.

## 7. Conclusion

V 0332+53 is very likely a member of the Be/neutron star binary class in which a neutron star accretes from the extended envelope of an early type primary. This envelope is probably evolving on a time-scale of years. If the optical emission further declines a determination of the primary's spectral type should be possible.

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**Note added in proof:** After the acceptance of this paper we received a preprint from Iye and Kodaira (P.A.S.P., 1985, **97**, 1186) which also discusses H$\alpha$ variability in V 0332+53. They measure an H$\alpha$ E.W. of $\sim$1 Å in 1984 October and $\sim$3.5 Å in December. Combined with our measurements this shows that there is variability of a factor $\sim$5 in the strength of H$\alpha$ on time scales at least as short as one month.