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The shell spectrum of the optical counterpart of GX 304 – 1 (4U 1258 – 61)

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Summary. A high-resolution spectrum of the shell star associated with GX 304 – 1 (4U 1258 – 61) has been obtained. The star is of spectral type B2 Vne. It is rotating at near break-up velocity and losing mass, probably via an expanding equatorial disc $\sim 2–5 R_*$ in size. A distance of 2.4 ± 0.5 kpc is derived.

1 Introduction

In a previous paper (Mason *et al.* 1978) we reported the discovery of a fifteenth magnitude Be star within 20 arcsec of the best X-ray position for the flaring X-ray pulsar GX 304 – 1 (4U 1258 – 61). Since then a refined *SAS-3* error circle has become available (Dower *et al.* 1978). The Be star lies only 10 arcsec from the centre of this 30-arcsec radius error circle, so the identification has been strengthened.

The low-resolution 4000–8000-Å spectrum obtained in 1977 February and discussed in Mason *et al.* (1978) indicated that the star belonged to the Be star subset known as shell stars. The evidence was (1) Hα in emission, and (2) the strength of the He I λ 5015-Å and O I λ 7774-Å absorption lines (see also Thomas, Morton & Murdin 1979). A shell star is one showing sharp deep absorption lines characteristic of a cool dense extended envelope (or shell), as well as emission lines from the circumstellar material and absorption lines from a hotter underlying star. Typically the underlying star is B-type and the underlying absorption lines indicate that it is a rapidly rotating dwarf, so close to instability that material has been ejected to form an equatorially expanding shell around the star. Radiation pressure as well as the centrifugal effect probably plays an important role in the ejection mechanism (Hutchings 1976).

Modes of mass transfer already identified in X-ray binaries include Roche lobe overflow with consequent gas streaming, and stellar winds. Confirmation of the shell spectrum would identify a further mode of mass transfer.

Our previous spectrum did not show the underlying stellar spectrum. We have obtained a higher-dispersion spectrum to look for it and to confirm the nature of the star.

2 The spectrum

The observations were made on 1978 February 26 using the Image Photon Counting System (IPCS) together with the RGO spectrograph, at the $f/8$ Cassegrain focus of the 3.9-m Anglo-Australian telescope. A four-section spectrum between 3300 and 7000 Å was obtained at a dispersion of 33 Å mm^{-1}. These data are shown in Fig. 1.

The strong doubled Hα emission is confirmed. Many sharp, deep absorption lines are evident. Absorption lines of H I, He I, N II, O II, Mg I, Mg II, Si II, Fe II, Na I and Ca II and a number of diffuse interstellar features have been identified in the spectrum. The strength of the diffuse features suggests that there is a major interstellar component to the Ca II and Na D lines. The absorption lines represent a considerable range of stellar spectral types, from He I normally strong in mid-B stars, to Fe II and Mg I normally strong in A–F stars. The Fe II spectrum is very strong, in particular members of multiplets 27, 42, 48, 74; multiplets 28, 37, 38, 40, 55 are also weakly present.

We identify the narrow absorption lines as being from the shell. In Fig. 2 some of the data are shown on a different scale and heavily smoothed to emphasize broad features by reducing statistical noise. Broad dish–shaped lines typical of a rapidly rotating dwarf star can clearly be seen at Hγ and Hβ (the broad interstellar band at λ4882 Å may contribute weakly to the red wing of Hβ). Assuming that the star is a dwarf (because of its rotation), the strength of Hγ indicates that it is early B or early F. The lack of a broad component in the H and K calcium lines eliminates the later spectral type. The Hγ equivalent width is 5.0 Å and indicates that the spectral type of the underlying star is B1 to B3 (Balona & Crampton 1974). We thus classify the star as B2 Vne.

3 Model of the shell

The most widely accepted model for shell stars (see, e.g. Hutchings 1976) considers the shell or extended envelope to be a disc-shaped equatorial extension which is rotating so as to conserve angular momentum. In this model, the presence of strong shell absorption lines, as are seen in the spectrum of the 4U 1258 – 61 counterpart, indicates that the line of sight to the star lies essentially perpendicular to the star's rotation axis. In the present example, independent support for this conclusion is provided by the broad underlying stellar lines at Hγ and Hβ.

The Hα-emission profile (Fig. 3) is broad, strong and has a deep central absorption. Hutchings (1976) has presented theoretical Balmer-line profiles for a variety of expanding disc models for Be stars, and has computed the ratio of the red to violet emission components (R/V ratio) of the double emission line, and the separation of the two emission peaks for a variety of disc geometries, expansion velocities and i_*, where i_* is the inclination of the star's equatorial plane to the plane of the sky. The results of these computations can be applied to the Hα emission line from the 4U 1258 – 61 optical counterpart, for which $R/V = 1.33$, and the peak to peak separation is 300 km s^{-1}. Referring to Hutching's grid, this peak separation implies $i_* \sim 90°$, which is consistent with the value already inferred from the presence of the shell lines and broad stellar lines. $R/V = 1.33$ and $i_* \sim 90°$ implies an expansion velocity of ~ 50 km s^{-1}. Once again this is supported by observation, in as much as the average heliocentric velocity of the shell lines is -50 ± 4 km s^{-1}, whereas that of the Hα emission centre (which should closely represent the radial velocity of the

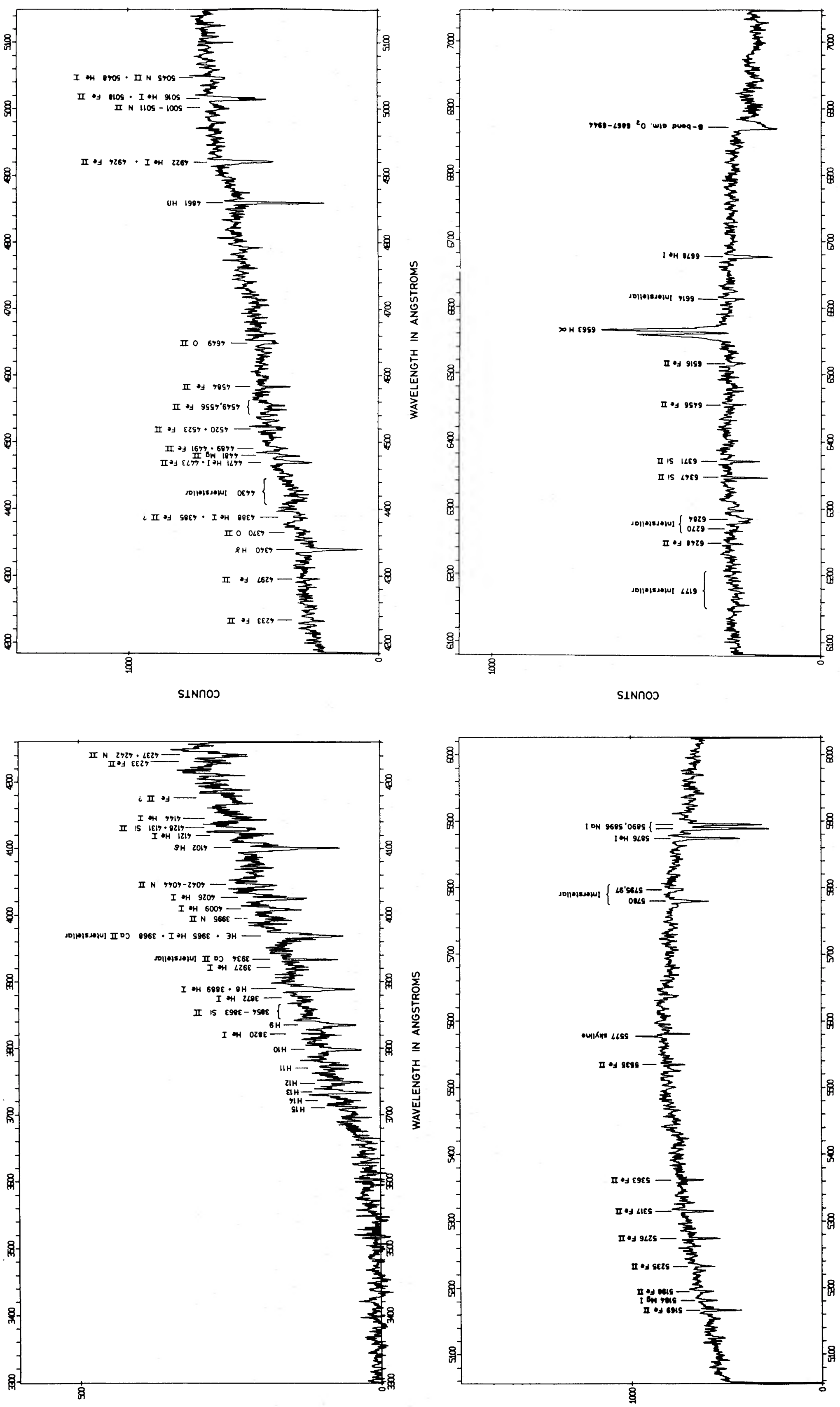

Figure 1. The four section spectral map of the optical counterpart of GX 304 − 1 (4U 1258 − 61), obtained on 1978 February 26 at a dispersion of 33 Å mm^{-1}

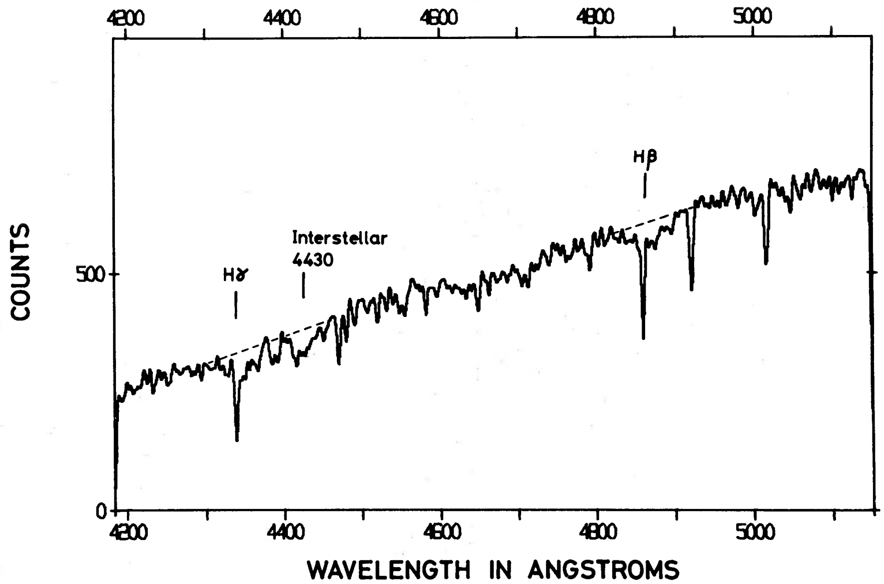

Figure 2. Part of the data of Fig. 1, heavily smoothed to emphasize the presence of broad absorption lines underlying the shell lines at Hγ and Hβ.

star) is -10 ± 5 km s^{-1}. In conclusion therefore, the disc model does explain the observed parameters with some consistency.

Whether the disc is rotating according to Kepler's law, or such that angular momentum is conserved in the outflow, the wings of the Hα line, which have velocities of ~ 600 km s^{-1}, will have been formed in the material closest to the star. The velocity is consistent with the

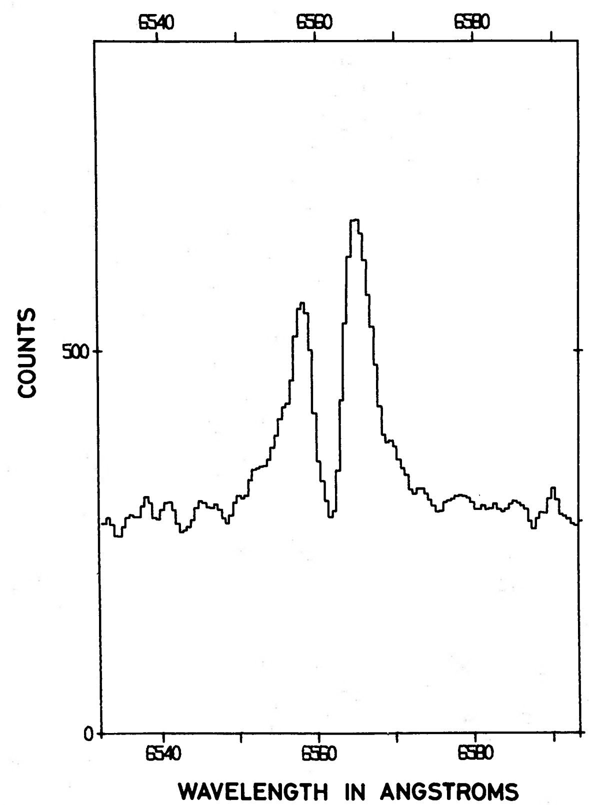

Figure 3. The Hα emission line profile.

break-up velocity of a star of type B2 V (Slettebak 1976). The radius of the line emitting envelope can be computed from the characteristic width of its Hα emission line (half width at half maximum ~ 250 km). Assuming rotation according to Kepler's law, $M_* \sim 10 M_\odot$ and $R_* \sim 6 R_\odot$ (Allen 1973) defines this radius to be ~ 5 R_*. Alternatively if the disc is rotating such that angular momentum is conserved in the outflow, the shell radius is ~ 2 R_*.

4 Interstellar features and distance

We used Herbig's (1975) calibration of the strengths of the diffuse interstellar features against reddening, to derive $E(B-V) = 1.7 \pm 0.2$ from the equivalent widths of the features at 4430, 5780, 5797, 6284 and 6614 Å. The intrinsic colour of a normal B2 star is $(B-V)_0 = -0.24$ (Morton & Adams 1968). Mason *et al.* (1978) give $B-V = 1.86$ for the shell star, implying a colour excess $E(B-V) = 2.10$. The value derived directly from the interstellar features is in good agreement with this.

Schild & Romanishin (1976) have concluded from a study of Be stars in clusters that $M_V = 4.15 \pm 0.4$ is representative of the B(0 – 2) (III–V)e stars. Adopting $m_V = 14.72$ (Mason *et al.* 1978) and $A_V = 3.3\, E(B-V)$ (Herbst 1975) implies the distance to the shell star is 2.4 ± 0.5 kpc; the error corresponds to the range of absolute magnitude given above. At this distance the average X-ray luminosity is $\sim 1 \times 10^{35}\,\mathrm{erg\,s^{-1}}$, with a maximum of $\sim 10^{36}\,\mathrm{erg\,s^{-1}}$ (Dower *et al.* 1978).

5 Conclusions

The spectrum of the shell star associated with GX 304 – 1 is consistent with it being a B2 dwarf rotating at near break-up velocity and with a period of ~ 5 hr. The star is losing mass, probably in the form of an expanding equatorial disc 2–5 R_* in size.

The presence of shell absorption lines, broad underlying stellar lines and the Hα-emission profile indicate that the line of sight to the star lies nearly perpendicular to its rotation axis. Limits have been placed on the orbital motion by McClintock *et al.* (1977) from an analysis of the X-ray pulses. Assuming the orbital plane of the X-ray emitting secondary is coincident with the shell star's equatorial plane, the constraints on the orbital parameters are $P \gtrsim 18$ days and orbital separation $\gtrsim 10 R_*$. This is larger than the characteristic size of the shell. In spite of the high density of matter in the shell ($n \sim 10^{12}\,\mathrm{cm^{-3}}$), the X-ray source is relatively weak, a factor of 100 below the Eddington limiting luminosity for an object at the Chandresekhar mass ($L_{\mathrm{crit}} = 1.6 \times 10^{38}\,\mathrm{erg\,s^{-1}}$). This suggests that the shell star is distant from its X-ray emitting companion. Thus the separation derived from orbital constraints may be very much a lower limit. X-ray observations may therefore not reveal X-ray eclipses even though the inclination of the orbit to the line of sight is low. However variable X-ray absorption around the orbit is likely. Moreover shell stars are well known for undergoing relatively quick and dramatic spectral changes. Such an event in this system would undoubtedly be accompanied by considerable changes in the X-ray source.

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References

Allen, C. W., 1973. *Astrophysical Quantities,* 3rd edn, Athlone Press, London.
Balona, L. & Crampton, D., 1974. *Mon. Not. R. astr. Soc.,* **166,** 203.
Dower, R. G., Apparao, K. M. V., Bradt, H. V., Doxsey, R. E., Jernigan, J. G. & Kulik, J., 1978. *Nature,* **273,** 364.
Herbig, G. H., 1975. *Astrophys. J.,* **196,** 129.
Herbst, W., 1975. *Astr. J.,* **80,** 498.
Hutchings, J. B., 1976. *IAU Symp. No. 70,* p. 70, ed. Slettebak, A., Reidel, Dordrecht.
Mason, K. O., Murdin, P. G., Parkes, G. E. & Visvanathan, N., 1978. *Mon. Not. R. astr. Soc.,* **184,** 45P.
McClintock, J. E., Rappaport, S. A., Nugent, J. J. & Li, F. K., 1977. *Astrophys. J.,* **216,** L15.
Morton, D. C. & Adams, T. F., 1968. *Astrophys. J.,* **151,** 611.
Schild, R. & Romanishin, W., 1976. *Astrophys. J.,* **204,** 493.
Slettebak, A., 1976. *IAU Symp. No. 70,* p. 123, ed. Slettebak, A., Reidel, Dordrecht.
Thomas, R. M., Morton, D. C. & Murdin, P. G., 1979. *Mon. Not. R. astr. Soc.,* **188,** 19.