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A nebula around Nova BT Monocerotis

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Summary. We report the spectroscopic discovery of nebular Hα emission around Nova BT Monocerotis. The indicated expansion distance to this system is about 1800 pc.

1 Introduction

BT Monocerotis ($\alpha_{1950} = 6^h\,41^m\,16^s$, $\delta_{1950} = -1^\circ\,58'\,09''$, Nova 1939) was recently shown to be an eclipsing system with an orbital period of $8^h\,01^m$ (Robinson, Nather & Kepler 1982). On 1981 December 15 (UT) we obtained a series of spectra with the blue camera of the Hale 5-m telescope's double spectrograph (Oke & Gunn 1982) for the purpose of studying the radial velocity variations of the stellar emission lines. These results will be reported elsewhere (Wade & Oke, in preparation). Simultaneous exposures of the region around Hα, made at lower dispersion with the red camera of the double spectrograph, show the presence of an emission nebula of this discovery and derive a nebular expansion distance for BT Mon.

2 Observations and reduction of data

We acquired nineteen 900-s integrations of BT Mon near Hα using a Texas Instruments 800 x 800 pixel CCD as the detector. Observations were made through a 1.0 arcsec wide slit, oriented east–west at all times. The reciprocal dispersion at Hα was 6.04 Å pixel^{-1} and the angular scale along the slit was 0.58 arcsec pixel^{-1}. Seeing was 1–2 arcsec and light cirrus cloud was present throughout the night, becoming thicker towards dawn.

Standard procedures were used to correct the two-dimensional data frames for instrumental background and pixel-to-pixel sensitivity variations. At this stage it became clear that the spectrum near Hα was significantly extended in the direction perpendicular to the dispersion, so the corrected two-dimensional data were retained for further analysis,

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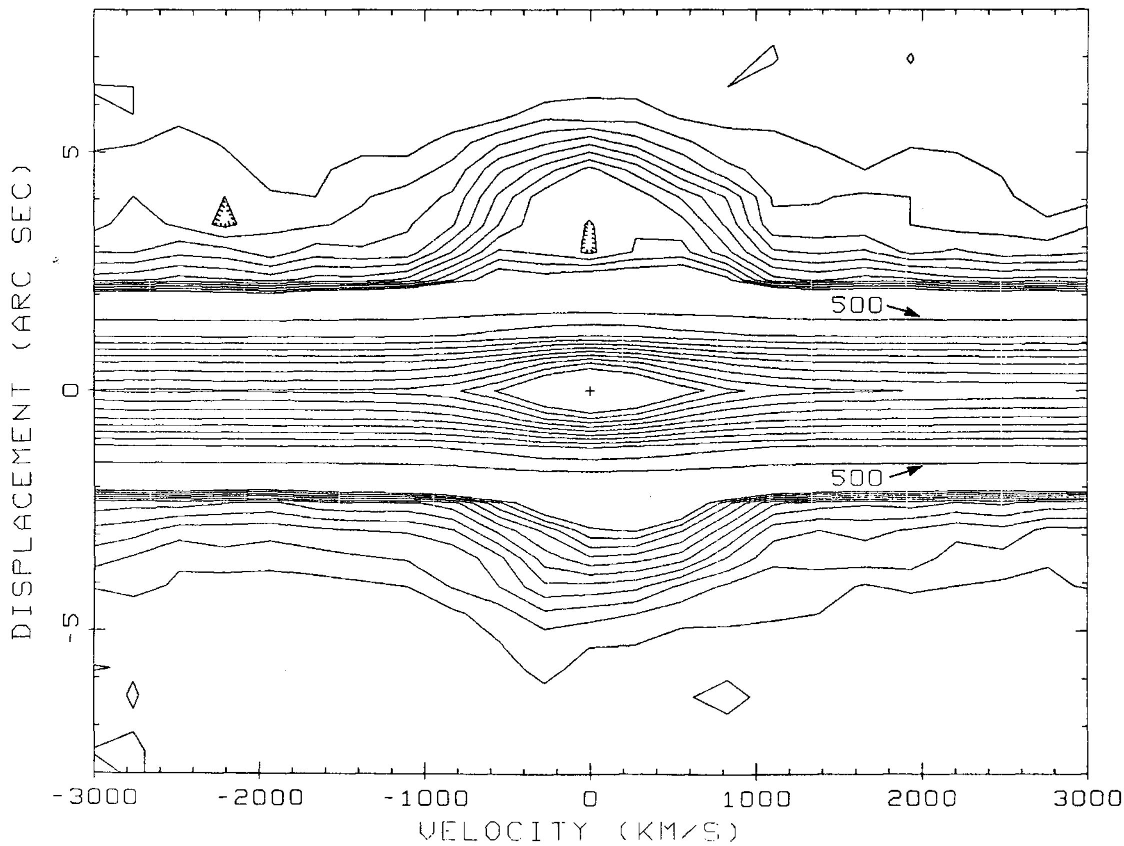

Figure 1. The averaged two-dimensional image of the spectrum of BT Mon, in the region near Hα. Contours are drawn at the 10(10)110 and 500(500)5500 unit levels; the 500-unit contours are labelled. The velocity zero-point corresponds to the laboratory wavelength of Hα. The nebula is visible as a faint extension of the stellar image perpendicular to the dispersion.

following the normal extraction of one-dimensional spectra. Of the 19 data frames, we have chosen to combine the 14 images that are of highest quality, i.e. least affected by clouds, bright sky background, or instrumental blemishes. In the subsequent discussion, we use the word 'column' to refer to a line of pixels parallel to the dispersed spectrum, and the word 'row' to refer to a line of pixels perpendicular to the dispersion (i.e. at approximately constant wavelength).

To combine the images, we first operated on individual frames as follows. We averaged the sky background row by row, rejecting dead pixels and cosmic ray 'hits' at the 3.5-sigma level, and subtracted the sky contribution from each pixel. Using spectra of comparison arc lamps for calibration, we corrected each data frame for a small tilt between the arc lines and the pixel rows. The tilt was due to a slight error in the orientation of the CCD's cold box with respect to the grating. We also corrected each frame for a slow but uniform drift in the wavelength zero-point, which was probably caused by flexure in the grating mounting. These corrections amounted to less than 1 pixel (at the edges of the image) for rotation and 2 pixels at most for zero-point drift. To complete the registration of individual spectra of BT Mon, the data frames were sheared (by about 2 per cent) and shifted (by 1 or 2 pixels) in order to align the dispersed stellar continuum accurately with one of the pixel columns. This step corrected for the cold box tilt, very slight differential atmospheric refraction, and displacement of the stellar image along the slit from one image to the next. The data are critically sampled along both columns and rows, so the smoothing introduced by the quadratic interpolation procedure we used is slight. The 14 registered images were averaged with equal weights to produce the image shown in Fig. 1.

3 Analysis of averaged spectrum

The 'stellar' Hα emission line has FWHM ≅ 1000 km s^{-1} and is approximately Gaussian in shape. At our resolution, about 12 Å, the line is not double-peaked. To remove the strong stellar continuum and Hα line we found the average image shape perpendicular to the dispersion in regions well away from the nebular image. This 'seeing profile', scaled to fit the values of the three central (highest) pixels in each row, was subtracted row by row to give the residual image of the nebula shown in Fig. 2. The scaling procedure introduces an error in the vicinity of the nebula because the flux in the three central pixels includes contributions from both star and nebula. The nebular contribution here amounts to only 1 per cent of the total flux, however, so that for displacements greater than about 2 arcsec from the stellar spectrum, the error amounts to perhaps 1 or 2 units. (One data 'unit' corresponds to about two detected photons per pixel. The contour interval in Fig. 2 is 10 units.) We believe that the nebular brightness measurements in Fig. 2 are trustworthy to better than 20 per cent for angular displacement outside ± 2 arcsec. Of course, the average value of the three central pixels has been forced to equal zero, and the one or two adjacent columns are also suspect. The (subtracted) sky background is the dominant source of noise (sigma ≅ 5 units) away from the central region.

The appearance of the nebula is that of a ring whose centre is displaced slightly from the stellar image. The seeing profile has FWHM ≅ 1.5 arcsec, so some of the thickness of the ring is artificial. The interpretation that we are viewing an expanding shell of gas, ejected during the nova outburst of 1939, follows easily.

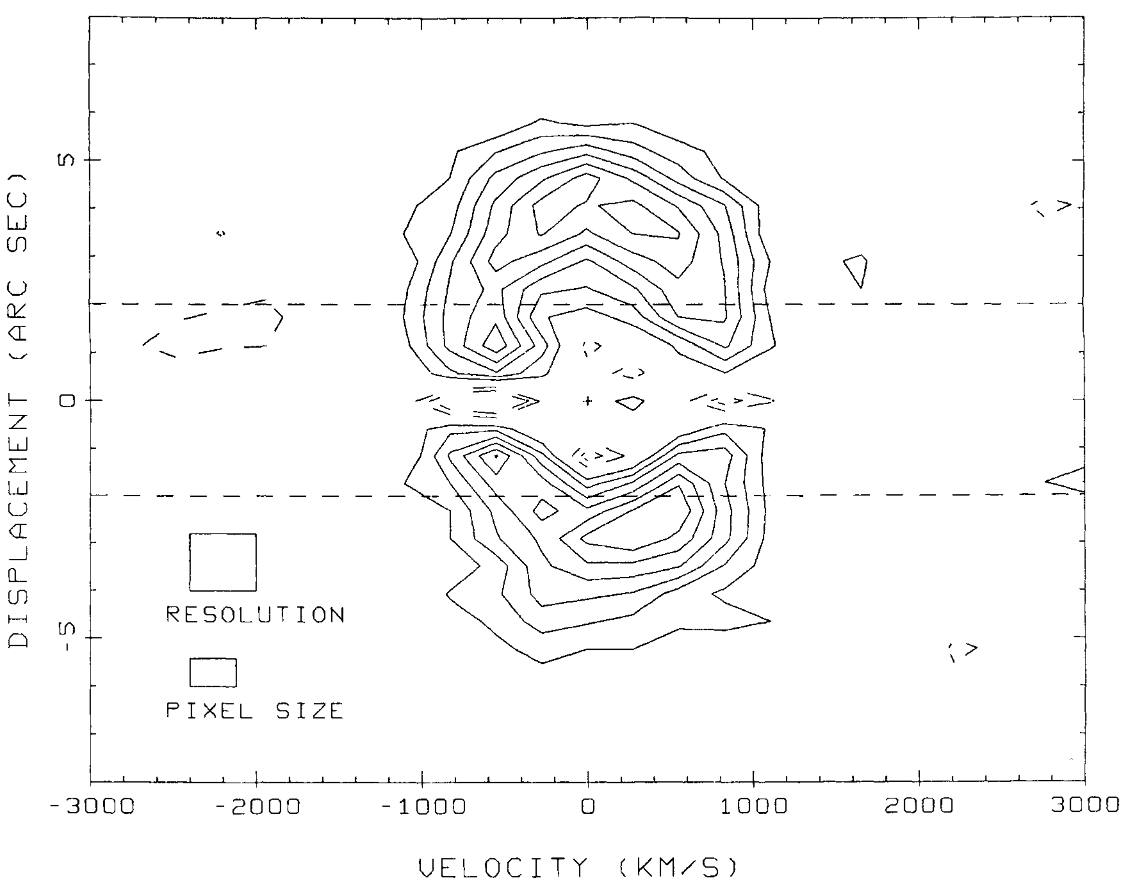

Figure 2. As Fig. 1, but with the 'stellar' contribution removed. Contours are plotted for −20, −10 and 10(10)60 unit levels (negative contours dashed). The dashed lines at ±2 arcsec indicate the approximate displacement beyond which the residual image should be trustworthy to better than 20 per cent.

Table 1. Parameters for the nebula.

	Angular diameter (arcsec)	Velocity diameter (km s^{-1})	Distance of BT Mon (pc)
Along ridge line	7	1500	1900
Along 10-unit contour	11	2100	1700

Table 1 summarizes measurements of the angular and velocity diameters of the nebula, measured along the ridge of maximum intensity and along the 10-unit contours. In each case the angular size is the better defined quantity, since the extreme velocities occur in the region of the subtracted stellar spectrum. Also shown in Table 1 are the nebular expansion distances for BT Mon, derived according to

$$d = (0.21 \text{ pc})\frac{v\Delta T}{\theta} \tag{1}$$

where v is the velocity diameter in km s^{-1}, θ is the angular diameter in arcsec, and ΔT is the time in years elapsed between the ejection of the shell (assumed to be 1939.7) and the epoch of observation (1982.0). Equation (1) assumes that the velocity of expansion is the same along and perpendicular to the line-of-sight. We have no indication whether this assumption is correct, so the expansion distances in Table 1 may be in error by a large amount. Additional observations of the nebula, both spectroscopically for different position angles and by direct narrow band imaging are required in order to establish whether our result is likely to be close to the truth. (See Baade 1940 for further discussion of the ambiguities inherent in the expansion distance technique.)

We have used our uneclipsed images and the spectrophotometry of Oke & Wade (1982) to estimate the Hα flux from BT Mon. We received about 2×10^{-15} erg cm^{-2} s^{-1} from the 1 arcsec wide slice across the nebula (integrated over velocity and accounting for the nebular flux lost by subtraction of the stellar spectrum). Depending on the shape of the nebula, its total flux in Hα is perhaps eight times larger. If $E(B-V) \cong 0.3$ mag (following Robinson *et al.* 1982) and $d = 1800$ pc, the nebular luminosity in Hα is about 1×10^{31} erg s^{-1}. The nebula is not seen at Hβ in our observations, but this is consistent with our expectation of a signal-to-noise ratio $\lesssim 0.1$ (per pixel), taking into account the Case B Balmer decrement, interstellar reddening, and the higher dispersion and larger readout noise of our blue spectra. The nebula is not present in the light of He I λ6678 or λ4471.

4 Discussion

Given our limited information about the nebula, we can derive only a preliminary and very tentative estimate of its mass. We assume that the gas has a low kinetic temperature, as observed for the DQ Her and CP Pup nebulae (Williams *et al.* 1978; Williams 1982). Adopting $T = 500$ K and assuming that the Hα emission arises from case B recombination, we find the emission measure of the nebula to be about

$$\text{EM} = \int n_e n_p dV \sim 1 \times 10^{54} \left(\frac{d}{1800 \text{ pc}}\right)^2 \text{cm}^{-3}.$$

The radius of the nebula is $R = 10^{17}$ $(d/1800$ pc) cm. We take the volume to be $V = 10^{51}$ cm^3, equivalent to that of a filled shell of thickness $\Delta R = fR \sim 0.1\,R$. In this volume we adopt, in the absence of definite information, a uniform gas density (clumping factor $\epsilon = \langle n_e^2 \rangle / \langle n_e \rangle^2 = 1$) and complete ionization of hydrogen ($x = n_{H^+}/n_{H\,(tot)} = 1$. Then the mass of the visible nebula is

$$M_{neb} \cong m_p \left(\frac{\mathrm{EM}\ V}{x^2 \epsilon}\right)^{1/2} = 3 \times 10^{-5} M_{\circledast} \left(\frac{d}{1800\ \mathrm{pc}}\right)^{5/2} \left(\frac{f/0.1}{x^2 \epsilon}\right)^{1/2}$$

Further sophistication is not warranted by our present knowledge. Plausible uncertainties are: $\times 3$ in the Hα flux (including the uncertainty in the extinction), $\times 3$ in the effective recombination coefficient which varies with temperature, $\times 2$ in f, $\times 100$ in $x^2\epsilon$, and $\times 2$ in d. Thus the nebular mass is uncertain by a factor of order 100. It is nevertheless interesting to note that M_{neb} for BT Mon falls within the range of nebular masses estimated for other novae (see, e.g. Cohen & Rosenthal 1983. They cite our discovery of the BT Mon nebula, but the preliminary values for expansion velocity and shell radius quoted by them are superseded by this paper; Schaefer & Patterson 1983 incorrectly attribute the discovery to Cohen.) A completely independent line of reasoning, based on an observed change in orbital period after the nova outburst, led Schaefer & Patterson to estimate a total ejected mass of $\sim 3 \times 10^{-5} M_{\circledast}$, similar to our value above. Additional observations of the nebula could substantially reduce the uncertainty in our shell mass estimate, making a significant comparison of the methods possible.

The nebular expansion distance we have derived agrees well with other indirect estimates of the distance of BT Mon and tends to confirm that the binary system is very luminous (see Robinson *et al.* 1982). Unfortunately, all of these estimates are uncertain by unknown and possibly large amounts. Here too, additional observations of the Hα nebula are perhaps the best way of improving our knowledge of this important datum.

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