A perplexing binary system containing a supergiant Be star

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We report on detailed studies of the absorption line spectrum and spectroscopic orbit of the binary BN2.5Ib star HD235679. We also give a preliminary report on our study of the Hα emission line profiles from this perplexing system. ***Hipparcos*** **and** ***Tycho2*** **astrometric data allow us to place limits on the distance to the system. The lack of a measurable reflection effect in the** ***Hipparcos*** **photometry allows us to rule out the possibility that the massive invisible star is cool and fills its Roche lobe. Thus, by process of elimination, the invisible star must be hot or a black hole. The properties of the Hα profiles suggest that the invisible star is somewhat hotter, and has a stronger wind than HD235679.**

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1 Introduction

HD235679 is a one of the most extreme of the OBN stars. These are stars characterized by unusually strong nitrogen lines and relatively weak carbon and oxygen lines compared to "normal" stars with similar helium and silicon line strengths (Walborn 1970, Walborn 1971a). According to Walborn (1971a), the spectral type of HD235679 is BN2.5Ib:. Walborn noted only one weak carbon line in the blue-violet spectrum and no oxygen lines. He also noted that the helium to hydrogen ratio is abnormally large. In addition to the peculiar absorption spectrum, there is strong emission at Hα, moderate emission at Hβ, and possible emission at Hγ, and weak emission has been reported in some helium lines.

HD235679 is a single-line spectroscopic binary with an unusually long period and exceptionally large mass function, P = 225 d and $f(M) = 5.90 M_\odot$ (Bolton and Rogers 1978). The large mass function indicates that HD235679 is one of the more massive binary systems in the galaxy. Several authors have used these results plus the presence of hydrogen emission lines to deduce that the visible star is accreting mass from a cooler more massive companion that fills its Roche lobe.

This seemed obvious to us twenty-five years ago. Since then we have undertaken two investigations to refine the model. These investigations have addressed four issues: 1) peculiarities in the absorption line spectrum, 2) the quality of the spectroscopic orbit solution, 3) the detectability of the secondary star, and 4) the properties of the hydrogen emission lines. The results of these investigations, which we summarize here, show that this model cannot be correct. We tentatively suggest a new model that can be tested by further analysis and modeling of our observations of Hα emission line profiles from this peplexing system.

2 Absorption line spectrum

In order to study the absorption line spectrum of HD235679, we digitized our seven best photographic spectra, which had an inverse dispersion of 12 Å mm^{-1}, with the PDS microdensitometer at the David Dunlap Observatory. Each density scan was reduced to wavelength calibrated intensity and normalized to unit continuum by the usual procedures. Since HD235679 is a faint star (B=9^m.21), the signal to noise of the individual spectra was low. Therefore each was processed with a 44 micron FWHM Gaussian noise filter. As a result, the final resolution is 0.5 Å. After processing, the individual spectra were aligned and co-added to form a spectrum covering the region from 3600 to 4919 Å. The signal to noise is about 75 over most of this region. For comparison purposes we used composite spectra of HD42087

Table 1: Comparison of the astrometric data for Cepheus OB1 and HD235679. The data for Cepheus OB1 are means for the nine brightest stars in the association. The parallax and proper motion components are in units of milliarcseconds.

Parameter	Cepheus OB1	HD235679
π (mas)	1.14 ± 0.19	0.27 ± 0.87
μ_α (mas)	-3.2 ± 0.8	-1.35 ± 0.86
μ_δ (mas)	-2.6 ± 0.8	-3.83 ± 0.75
V_r (km s^{-1})	-14.6 ± 1.3	-26.4 ± 1.5

(B2.5Ib) and HD207330 (B2.5III) (Walborn 1971b) processed in the same way as that of HD235679.

The hydrogen lines in the spectrum of HD42087 are a remarkable match to those in the spectrum of HD235679, except for Hβ, Hγ, and Hδ, which are filled in by emission to varying degrees in HD235679. But since HD235679 has a higher than normal He/H, *i.e.,* it is hydrogen deficient, which is most easily seen at the blend of H16 and HeI(25), it must have fewer electron donors and a lower particle density in its atmosphere. Thus its surface gravity must be higher than that of HD42087 in order to match the wings of the hydrogen lines. HD207330 has nothing in common with HD235679 and will not be discussed further here.

The ratios of Si and He lines that define the spectral classification system of Walborn (1971b) for HD235679 are well matched with the ratios of the same lines in HD42087, even though the individual lines are stronger in the spectrum of HD235679. In place of the rich NII spectrum of HD235679, HD42087 has a rich OII spectrum along with some weaker NII lines. Both stars have lines of HeI, CII, MgII, SiII, and SiIII. HD235679 also has lines of AlIII, SII, SIII, AII, and FeIII, most of which are either not found in the spectrum of HD42087 or are very much weaker. This is almost certainly because the hydrogen deficiency in the atmosphere increases the ratio of the line opacity to the continuous opacity rather than to any overabundance of these elements.

3 Distance

Distance estimates for HD235679 have ranged from a low of 850 pc (Schild 1985)to a high of 6.5 kpc (Kimeswenger and Weinberger 1989). Neither is reasonable. Schild (1985) assumed that HD235679 is a member of Cepheus OB1, even though it lies somewhat south of the outer limits of the association and is more than four magnitudes fainter than the normal B2Ib star in the association. We compiled the *Hipparcos* parallaxes and *Tycho2* proper motions (Perryman et al. 1997) for ten stars listed as members of Cepheus OB1 in *The Bright Star Catalogue* (Hoffleit and Jashek 1982) to calculate a mean parallax and proper motion for the association. We also compiled radial velocities from Simbad. We dropped one star, HD209339, from the average because its parallax and space velocity show that it is not a member of the association. The averages for the other nine stars are shown in Table 1, where they are compared to the corresponding data for HD235679. Cepheus OB1 is located at a distance of 900 ± 150 pc. Table 1 shows that HD235679 lies beyond Cepheus OB1.

We can obtain an upper limit on the distance of HD235679 by assuming it has the same absolute magnitude and color as the normal B2Ib star in Cepheus OB1. This yields a distance of 3.5 kpc. We have already noted that the lower than normal He/H mean that the surface gravity of HD235679 must be greater than that of a normal B2Ib star. This means that its radius, hence luminosity must be lower than for a normal B2Ib star. However, the He/H line ratios and the strengths of other lines that are present because of the low continuous opacity suggest to us that the He/H ratio is not high by orders of magnitude. Therefore we believe it is probable that HD235679 is much closer to 3.5 kpc than it is to Cepheus OB1. It is a massive, luminous star, even if it is subluminous for its spectral type. It is definitely not a nearby, low mass Population II star.

4 The spectroscopic orbit

Since Bolton and Rogers (1978) had combined measures of radial velocities of the NII lines from spectrograms of widely different resolutions we thought it would be useful to recompute the orbital elements using only radial velocities measured from the moderate resolution spectrograms. We took six additional spectrograms with the same instrumentation as Bolton and Rogers (1978) in 1974-75 to improve the coverage of the velocity curve and provide enough moderate resolution spectra to allow us to investigate whether different line groups yield different orbit solutions.

We did a preliminary orbit solution using all of the NII radial velocity measures to determine the best value of the period, since these data cover a longer period of time than those used by Bolton and Rogers (1978). This yielded $P = 225.33 \pm 0.13$ d. When we checked the window function for this data set, we found that it has essentially no aliases for periods longer than one day. Hence the large mass function found by Bolton and Rogers (1978) cannot be due to an incorrect determination of the orbital period.

The spectroscopic orbital elements shown in Table 2 were obtained by fitting the radial velocities

Table 2: Spectroscopic orbital elements for major line groups with period fixed. Epochs of periastron are JD−2400000.

Element	NII	Si	He	Hydrogen
P (d) fixed	225.33	225.33	225.33	225.33
K (km s^{-1})	61.1 ± 1.2	64.6 ± 2.3	58.0 ± 1.4	46.7 ± 2.6
e	0.075 ± 0.020	0.019 ± 0.037	0.105 ± 0.024	0.103 ± 0.053
$\omega\,(^\circ)$	13 ± 16	148 ± 93	357 ± 13	75 ± 32
T_{peri}	41895.4 ± 9.8	41978 ± 59	41886.3 ± 8.1	41936 ± 20
V_0 (km s^{-1})	-30.90 ± 0.89	-29.5 ± 2.0	-29.4 ± 1.0	-20.0 ± 1.6
$a \sin i$ (km)	$1.89 \pm 0.37 \times 10^8$	$2.00 \pm 0.70 \times 10^8$	$1.79 \pm 0.43 \times 10^8$	$1.44 \pm 0.80 \times 10^8$
$f(M)(M_\odot)$	5.29 ± 0.31	6.28 ± 0.66	4.48 ± 0.32	2.34 ± 0.39
rms (km s^{-1})	4.99	4.50	5.48	8.93

measured from the moderate resolution spectra only with the period fixed at the value determined in the preliminary solution. In these solutions, the radial velocities from the NII, Si, and He lines yielded results that are identical within the statistical errors. The mass functions, however, are somewhat lower than that found by Bolton and Rogers (1978). The orbital elements derived from the hydrogen line velocities are very different from those derived from the other line groups. The γ-velocity is red-shifted by 8 km s^{-1} and K is almost 15 km s^{-1} smaller. These effects are undoubtedly due to the effects of blending of the hydrogen absorption lines with the emission lines, which are approximately stationary but have somewhat variable profiles.

Table 3: Possible combinations of primary M_1 and secondary masses M_2 and average radius R_2 of the secondary's Roche lobe in solar units for the mass function derived from the NII line radial velocities for various orbital inclinations i.

i	90°		60°		50°	
M_1	M_2	R_2	M_2	R_2	M_2	R_2
5	10.9	174	14.3	196	18.4	218
10	14.5	186	18.6	205	23.2	226
20	20.2	202	25.2	221	30.8	240
30	24.9	214	30.7	232	37.1	251
40	28.9	223	35.5	242	42.6	260

5 The invisible star

Some possible combinations of primary and secondary masses [1] are shown in Table 3 for various several values of the inclination angle. We have also listed the average radius of the Roche lobe around the secondary star calculated according to the relationship Paczyński (1966), $R_2 = A[0.38 + 0.2\log(M_2/M_1)]$, where A is the major axis of the binary orbit in units of solar radii.

Table 3 shows the major difficulty with any model in which the invisible star is supposed to fill its Roche lobe, *i.e.*, the lobe is so large that the "invisible" star must be visible at some wavelength no matter what its temperature might be. If the invisible star has a temperature near 5000 K, then the smaller radii in Table 3 correspond to stars with $M_V \simeq -2^m.0$, which is probably 2 to 3 magnitudes fainter than the visible star. Larger stars would be even brighter. Thus it should be possible to detect the spectral lines from invisible star in the high S/N spectra of the red region of the spectra of HD235679. We have numerous spectra of the Hα region with continuum S/N$>$ 200 that show no signs of any lines of a cooler star. If the Roche lobe filling companion is cooler than 5000 K, its lines might not be visible at wavelengths less than 7000 Å, but it should be a strong infrared source. HD235679 has not been detected in any infrared survey.

Moreover, a system consisting of a cool, Roche-lobe filling secondary and a hot primary will display a sinusoidal photometric variation with the orbital period due to the reflection effect. When the primary is as hot as HD235679, this variation should be easily detectable at $i = 30^\circ$. The *Hipparcos* photometry covers five orbital cycles of HD235679. The star is variable with an amplitude of about 0.12 magnitude, but the amplitude of the variation that is periodic with the orbital period is only 0.0113 ± 0.0017 mag., and this variation is not statistically signficant according to the F-test. Thus if the model is correct, the inclination must be very low. This is possible only if the

[1] For brevity, we shall sometimes refer to the visible star as the primary and the invisible star as the secondary.

mass of HD235679 is very low and the mass of the visible star is very large, say $M_2 > 45M_\odot$. A very low mass for HD235679 is inconsistent with the distance limits discussed above, and such a high mass for an *invisible* secondary is hard to understand. We think these problems are enough to rule out the possibility that the secondary is a cool star, filling its Roche-lobe.

The secondary could be invisible because it is a black hole. There is no x-ray source at the position of HD235679. However, a wind-fed black hole will not be a strong x-ray source. In fact, it might not be an x-ray source at all in such a wide binary. Thus we can't rule out this possibility directly. On the other hand, this model does not seem to offer any opportunities to explain the more important properties of the hydrogen emission lines described below.

6 The Hα emission

Between 1991 and 1996, we obtained over two dozen moderate resolution CCD spectrograms of the Hα region of HD235679 using the cassegrain spectrograph on the 1.88 m telescope at the David Dunlap Observatory. These spectra have continuum S/N$\geq$ 200, and are well distributed in orbital phase. At this point we are able to report only preliminary results of our analysis of these spectra.

The Hα emission lines are extremely strong. The maximum intensities range from more than three to almost four times the continuum intensity. This is much stronger than the emission formed in a stellar wind of a star of this spectral type. The shapes, widths and velocities of the profiles below approximately twice the continuum intensity are constant. The velocity is approximately equal to the γ-velocity of the binary system, and the profile appears to have extended wings, like a Voigt profile. This stationary profile is blended with one or more sharper peaks whose shape and velocity change with orbital phase. If these features are measured without any correction for blending with the stationary emission they yield a velocity curve that is similar to the absorption line velocity curve, but the scatter is much larger. However, the blending with the stationary feature must produce large displacements in the positions of the peaks of the narrow features depending on their positions relative to the stationary feature. Therefore we think any attempt at interpretation is premature until some work has been done to disentangle the blending effects.

7 Discussion

Although we have been able to place some strong constraints on the nature of the invisible star, its true nature remains a mystery. We also need to explain the exceptionally strong, stable Hα emission lines, and perhaps, the unusual range of excitation in the absorption line spectrum of HD235679.

We have already noted that the Hα emission produced in the wind of a normal B2Ib is many times weaker than that of HD235679. The enhanced He/H in the atmosphere of HD235679 increases the line opacity in the Balmer continuum and reduces the continuum opacity in Lyman continuum. These factors could increase the mass loss rate and ionization over that of a normal B2Ib star. On the other hand, the greater surface gravity compared to a normal B2Ib star will tend to reduce the mass loss rate. Thus we think it is unlikely that there will be a dramatic change in the mass loss rate or the strength of the Hα emission compared to a normal B2Ib star.

The velocity stability of the main part of the Hα profile suggests that it arises in a cloud surrounding the entire binary system. This suggests that the emission is not produced by the wind from a single star. If it was, then the wind density, hence the emission intensity would be greatest near the star, and the emission line should yield a velocity curve very similar to that derived from the absorption lines of the other elements. On the other hand, if the cloud is produced by winds from both stars in the system, it might be possible to produce profiles like the ones observed. The broad, constant velocity Hα emission profile can be explained by the interaction of two stellar winds if it is possible to balance the mass ratio and ratio of mass loss rates simultaneously. In this model, the sharper features on the Hα profiles arise in the shock front where the winds collide between the stars.

Based on these arguments, we reject the model where the invisible star is a black hole, and argue that the strong Balmer emission lines seen in the spectrum of HD235679 are produced in the winds of two hot stars. We tentatively suggest that the invisible star has a stronger wind and a significantly higher temperature than HD235679. We believe this is necessary to explain some details in the Hα line profiles, which are not presented here. The hot secondary in our model must also be either a rapid rotator, or at least 2 magnitudes fainter than HD235679 in the blue-violet region in order to have avoided detection in our spectra.

What kind of object could this be? The most likely candidate is a star evolving from right to left in the H-R diagram following the Roche lobe overflow stage of mass transfer evolution. Alternatively, the invisble secondary might have become a luminous blue variable without filling its Roche lobe, lost mass via a stellar wind until it is less luminous than HD235679, and then started to evolve rightward on the H-R diagram at a lower luminosity than HD235679. In either case, we would expect that HD235679 is more massive than the invisible star. However, Table 3 shows that there is a very small part of the M_1–M_2 plane where this is possible: $M_1 > 20\ M_\odot$ for $i = 90°$, $M_1 > 32\ M_\odot$ for $i = 60°$, for example. It is far more likely that the invisible star is more massive than HD235679.

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