THE EVOLUTIONARY STATE OF THE MASSIVE INTERACTING BINARY BD+36°4063

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ABSTRACT

We present a spectroscopic and photometric analysis of the remarkable massive binary system, BD+36°4063. We argue that the visible ON star is undergoing a rapid mass transfer episode that results in a thick and opaque disk that surrounds and renders invisible its massive companion. A comparison of the projected rotational velocity and the orbital semiamplitude of the visible star indicates a mass ratio near unity. Models for conservative mass transfer show that the equal mass state occurs at the point of minimum separation, and we argue that BD+36°4063 may represent the first system identified at this rapid and rare stage of massive binary evolution.

Key words: binaries: spectroscopic – stars: early-type – stars: evolution – stars: individual (BD+36°4063)

1. INTRODUCTION

Massive close binaries are destined to undergo extreme transformations once they begin to exchange mass and angular momentum (Langer et al. 2008). If mass transfer is conservative, then the system separation decreases as mass transfer progresses, and the orbit dimensions reach a minimum once a mass ratio of unity is reached. The system then experiences a critical phase where the mass transfer rates may exceed $10^{-4} M_\odot$ yr$^{-1}$ (Wellstein et al. 2001). Subsequently, the orbit will widen after the mass donor becomes the lower mass object, and a slower and more extended mass transfer stage will begin. The gainer accepts both mass and angular momentum, and it may quickly reach a state of critical rotation where gravitational and centripetal accelerations balance at the equator. This may limit further mass accretion and lead to the formation of a thick, opaque, and mass losing disk surrounding the gainer star (Nazarenko & Gazanuova 2006).

This stage of binary evolution is probably best represented by the W Serpentis class of massive binaries (Plavec 1980; Tarasov 2000). These binaries contain a visible, low gravity, donor star that fills its Roche lobe, while the higher mass, gainer star is invisible in the composite spectrum because it is immersed in a thick disk. The first direct image of such a disk around a gainer star was recently made with the CHARA Array for the best known member of the class β Lyrae (Zhao et al. 2008). The shortest period W Ser binary known is RY Scuti ($P = 11.1$ d). It consists of a 7 $M_\odot$, O9.7 Ibpe star and a 28 $M_\odot$ hidden companion (Grundstrom et al. 2007), and the entire system is surrounded by a 2000 AU wide gas and dust torus (Smith et al. 2002). The known W Ser systems are probably experiencing the slow mass transfer stage after mass ratio reversal, and no W Ser system has yet been identified at the close, rapid mass transfer stage.

The missing link may be filled by the subject of this paper, BD+36°4063. The star (ON9.7 Ib; Walborn & Howarth 2000) is located in the Cyg OB1 association (Humphreys 1978). It was noted by Mathys (1989) as a key example of an ON star, showing spectral features indicating the N-enrichment and C-depletion characteristic of CNO-processed elements (Walborn & Howarth 2000). Many ON stars are members of binary systems (Bolton & Rogers 1978) where mass transfer may remove the H envelope and reveal CNO-processed gas in the atmosphere. Thus, it is very pertinent that BD+36°4063 was discovered by Howarth (Walborn & Howarth 2000; Harries et al. 2002) to be a single-lined, spectroscopic binary with a period of 4.8 d. In a recent meeting contribution, Howarth presents radial velocity and light curves, and he shows that although the companion is massive, its absorption features are completely absent from the observed spectrum.

We obtained blue spectra of this and several other faint O-stars in a search for binaries, unaware at the time of Howarth’s detection of binary motion. Here, we confirm the orbital period and present preliminary orbital elements for the binary. We argue that the visible star is filling its Roche lobe and that the high rate of mass transfer results in a dense disk that blocks a direct view of the massive companion. We conclude with a brief discussion of system parameters and evolutionary status.

2. OBSERVATIONS AND ORBITAL ELEMENTS

Seven spectra of BD+36°4063 were obtained with the Kitt Peak National Observatory (KPNO) 2.1 m telescope from 2008 November 15 to 21. These observations made use of the Goldcam spectrograph with grating G47 (831 grooves mm$^{-1}$) in second order with a CuSO$_4$ order sorting filter. The detector was the T3KC CCD (a 3072 × 1024 pixel array with 15 × 15 μm pixels), and the resulting spectra have a resolving power of $R = \lambda/\Delta\lambda = 2400$ as measured from the HeNeAr comparison lines. Exposures were usually 600 s in duration, leading to spectra with a signal-to-noise ratio ($S/N$) = 200 per pixel in the continuum. The wavelength range is 3942–5032 Å with a wavelength calibration accuracy of ~5 km s$^{-1}$ based on the rms scatter of fits to comparison lines and on the variance of multilight measurements of the spectra of other stars. The spectra were extracted and calibrated using standard routines in IRAF$^5$ and then each continuum-rectified spectrum was transformed to a common heliocentric wavelength grid in log $\lambda$ increments.

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$^4$ http://www.lowell.edu/workshops/Contifest/talks/Howarth.pdf.

$^5$ IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
We fixed the period at the photometrically derived value and then solved for the circular orbital elements: systemic velocity \( \gamma = -17 \pm 3 \, \text{km s}^{-1} \), velocity semi-amplitude \( K = 163 \pm 3 \, \text{km s}^{-1} \), and epoch of superior conjunction of the ON star \( T_{SC} = 2,454,787.26 \pm 0.03 \). Trial elliptical solutions did not improve the fit. The rms of the fit, 6.6 km s\(^{-1}\), is larger than the formal errors but comparable to what we find in observations of other O-stars from this run. The spectroscopic epoch occurs (0.3 \( \pm \) 0.2) d earlier than the prediction from the light curve ephemeris, which may indicate that the period is decreasing. The possibility of a measurable period change offers us an important diagnostic of the mass transfer rate that must be confirmed in future observations.

### 3. Binary Properties

The most surprising feature of the orbital solution is that the mass function is large, \( f(m) = (2.18 \pm 0.12) \, M_\odot \), suggesting that the companion is a massive star. However, there is no clear evidence of absorption lines of the companion in the individual spectra. The expected radial velocities for any companion lines depend on the assumed mass ratio. We can estimate the mass ratio by considering the projected rotational velocity \( V \sin i \) of the ON star. If we assume that the ON star fills its Roche lobe and rotates synchronously, then the ratio of \( V \sin i \) to semi-amplitude \( K \) is a monotonically increasing function of \( Q = M_1/M_2 \) (mass of the ON star divided by that of the hidden star; Gies & Bolton 1986)

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\frac{V \sin i}{K} = (Q + 1) \Phi(Q),
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where \( \Phi(Q) \) is the fractional Roche radius of the ON star (Eggleton 1983). Thus, we can use a measurement of \( V \sin i \) to determine the mass ratio. The resolution of our spectra is just adequate for this task. We made measurements of the FWHM of the deep and relatively unblended line of Si \( \text{iv} \) \( \lambda 4088 \), whose profile should be dominated by rotational broadening. The mean width of the line is FWHM = 2.95 \( \pm \) 0.11 Å, which is significantly larger than the instrumental broadening measured in comparison lines near this wavelength, FWHM = 1.90 \( \pm \) 0.02 Å. We then created synthetic spectra for a grid of test values of \( V \sin i \) by convolving the model spectrum with a rotational broadening function (Gray 2005) for a linear limb darkening coefficient of \( \epsilon = 0.37 \) (Wade & Rucinski 1985). It should be noted that varying the linear limb darkening coefficient even by a factor of 2 has no effect, within uncertainties, on \( V \sin i \) measurements. These model profiles match the observed FWHM for \( V \sin i = 126 \pm 15 \, \text{km s}^{-1} \). Although it is possible that some of the apparent line broadening is due to macroturbulence in the atmosphere, a test using a presumed macroturbulent broadening with \( \xi = 50 \, \text{km s}^{-1} \) (at the high end for similar supergiants; Ryans et al. 2002) resulted in the same \( V \sin i \) because the instrumental broadening is so much larger than the expected macroturbulent broadening. Then the relation above leads to a mass ratio \( Q = 1.02 \pm 0.17 \), i.e., the stars are about equal in mass.

We see no evidence of absorption lines moving in antiphase with a velocity comparable to that of the ON star. However, Figure 1 illustrates the orbital variations of the \( H\beta \) line in which an emission component does appear to share the orbital motion of the companion. We made a preliminary Doppler tomographic reconstruction of the two spectral components (Bagnuolo et al. 1994) assuming the mass ratio given above, and we found evidence of similar, antiphase moving emission lines in \( H\gamma \),

#### Table 1

| HJD 2,400,000 | Orbital Phase | \( V_r \) (km s\(^{-1}\)) | \( \Delta V_r \) (km s\(^{-1}\)) | \( O-C \) (km s\(^{-1}\)) |
|---------------|---------------|-----------------|-----------------|-----------------|
| 54785.624     | 0.660         | 126.7           | 2.4             | 5.1             |
| 54786.576     | 0.858         | 109.7           | 2.3             | 0.8             |
| 54787.557     | 0.062         | 61.9            | 1.9             | 16.7            |
| 54788.558     | 0.270         | \(-180.0\)      | 2.2             | \(-1.2\)        |
| 54789.567     | 0.480         | \(-36.7\)       | 1.8             | 0.7             |
| 54790.556     | 0.685         | 132.1           | 2.1             | \(-1.3\)        |
| 54791.559     | 0.894         | 77.9            | 2.1             | \(-6.8\)        |

Only one set of spectral lines was readily apparent in these spectra, so we determined radial velocities by cross-correlating each spectrum with a model spectrum from the TLUSTY/SYNSPEC BSTAR2006 grid (Lanz & Hubeny 2007). We selected a model for \( T_{\text{eff}} = 28 \, \text{kK} \), \( g = 3.0 \), and microturbulent velocity of 10 km s\(^{-1}\), parameters that are typical for the star’s classification (Ryans et al. 2002; Martins et al. 2005), although small variations in these stellar parameters do not significantly alter the resulting velocities. We selected a N-enriched “CN” model to match better the line spectrum. The model spectrum was transformed to the observed grid by integration and was then convolved with functions to account for rotational broadening (Section 3) and instrumental broadening. A number of spectral regions that contain ISM features or emission lines were omitted from the cross-correlation sample (all hydrogen lines, the diffuse interstellar band at \( \lambda 4428 \), and He \( \text{ii} \) \( \lambda 4686 \)). Table 1 lists the date of observation, spectroscopic phase, radial velocity and error, and the observed minus calculated residual from the fit (below).

Our seven day time span is much too short to derive an accurate orbital period, so we estimated the period from the ellipsoidal variations in flux related to the tidal distortion of the star. Two sets of photometric measurements exist from all sky survey experiments. The first set of 111 Cousins \( I_C \) measurements were made between 2003 and 2007 by The Amateur Sky Survey (TASS\(^6\); Droege et al. 2006). The second set of 84 points were made in 1999 with the Northern Sky Variability Survey (NSVS\(^7\); Wozniak et al. 2004). Because the NSVS measurements record a broad spectral range (4500–10000 Å), we simply subtracted a constant value of 1.099 mag to bring their mean into coincidence with the mean of the \( I_C \)-band results. Despite differences in wavelength intervals, both the amplitude of variation and the ephemeris determined from each data set matched within uncertainties. A discrete Fourier transform of this combined time series immediately showed evidence of half the orbital period. A double sinusoidal light curve is exhibited in one orbit by tidally distorted stars, and for our data this yielded a period of \( P = 4.8126 \pm 0.0004 \) d and an epoch of ON star superior conjunction at \( T_{SC} = 2,452,448.60 \pm 0.08 \).

We then determined the remaining elements using a fit of the velocities made with the nonlinear, least-squares fitting program of Morbye & Brosterhus (1974). The weights were set to unity for most measurements (since they have comparable measurement errors), but we increased the weight of the single datum in the negative branch to four (to balance the four measurements in the positive branch) and we decreased the weight of the two conjunction phase measurements to 0.5.

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\(^6\) http://sallman.tass-survey.org/servlet/markiv/.

\(^7\) http://skydot.lanl.gov/nsvs/nsvs.php.
An emission component (bright in the gray-scale image) appears to follow the gray-scale image shows the relative velocity curve of the companion star. The backward S-curve in the gray-scale image shows the relative velocity curve of the companion star. An emission component (bright in the gray-scale image) appears to follow the velocity curve for the companion star.

He $\lambda$λ4387, 4471, 4713, 4921, and He $\mu$λ4686. We suggest that these emission features form in a disk surrounding the gainer star. Significant emission lines are also observed at Hz (see Howarth’s conference poster) and in the near-IR at He $\mu$ 2.058 $\mu$m and Br $\gamma$ 2.166 $\mu$m (Hanson et al. 1996; Tamblyn et al. 1996). A comparison of the line depths in the reconstructed spectrum of the ON star with those in the model indicates that the continuum flux from the disk is faint, $F_2/F_1 \approx 0.1$. Note that the absorption part of H$\beta$ appears deeper at conjunctions. The same deepening was observed in other lines that strengthen in slightly cooler atmospheres (Si $\mu$, O $\mu$). Similar changes are found in RY Scuti and are probably related to the tidal extension and gravity darkening of the donor star (Grundstrom et al. 2007).

The example of RY Scuti shows that mass transfer to a thick disk can lead to systemic mass loss from the binary and the formation of circumbinary gas and dust structures (Smith et al. 2002). There is some indication that an infrared excess from such circumbinary material is present in the spectral energy distribution (SED) of BD+36°4063. We show in Figure 2 the available flux measurements based upon Johnson $UBV$ (Hiltner 1956; Colina et al. 1996), Strömgren (Crawford 1975; Gray 1998) TASS V, $I_C$, (Droege et al. 2006; Bessell et al. 1998), and Two Micron All Sky Survey (2MASS) $JHK_S$ magnitudes (Cohen et al. 2003; Skrutskie et al. 2006), plus mid-IR fluxes from the Spitzer/IRS post basic calibrated data archive (Houck et al. 2004). We fit these observed fluxes with the BSTAR2006 flux model to determine the reddening (Fitzpatrick 1999) $E(B-V) = 1.28 \pm 0.06$ mag and ratio of total-to-selective extinction $R_V = 3.50 \pm 0.10$ (consistent with previous reddening estimates; Patriarchi et al. 2003). The limb darkened, angular diameter of the ON star is $\theta_{LD} = 97 \pm 8$ $\mu$as (after correction for a companion flux contribution of $F_2/F_1 = 0.1$). The resulting radius–distance relationship is $R_1/R_\odot = (10.4 \pm 0.8)d$ (kpc). There does appear to be a flux excess in the SED at wavelengths greater than 8 $\mu$m that may result from systemic mass loss. Could stellar winds account for this excess? Because the BSTAR2006 grid does not take winds into account, we also fit an SED from a CMFGEN model atmosphere (Hillier & Miller 1998) with similar stellar parameters and a wind. The absolute fluxes from the CMFGEN model were systematically 5% higher than those from the BSTAR2006 SED over the optical to near-IR range. However, there is no evidence of a marked IR excess near 10 $\mu$m from the wind in the CMFGEN model SED. This suggests that the observed excess may result instead from binary mass loss.

We summarize the available constraints on the masses of the stars in Figure 3. The mass ratio range derived from $V \sin i/K$ is indicated by the lines of constant slope. Next, we can use the observed light curve to constrain the orbital inclination. The ON star probably fills out its Roche surface, and consequently the photometric variations are due to the star’s tidal distortion.
(geometric shape and gravity darkening). The amplitude of the ellipsoidal light curve depends on the degree of Roche filling (assumed complete) and the orbital inclination (larger at higher inclination). Ideally, we would create a model that includes both a Roche distorted mass donor and a disk surrounding the gainer (Djurašević et al. 2008), but given the small flux contribution of the disk and the relatively large errors in the photometric data, we made an approximate model assuming that the companion is a small spherical object (with the same temperature as the ON star) that acts only as a mild flux dilution source in the light curve of the tidally distorted ON star. We used the GENSYN binary code (Mochnacki & Doughty 1972) to create model $L_C$ light curves for a grid of orbital inclinations, assuming that the ON star fills its Roche surface and that the companion has a modest fraction of its original mass so far. BD+36°34063 (Djurašević et al. 2008), but given the small flux contribution of a Roche distorted mass donor and a disk surrounding the gainer (assumed complete) and the orbital inclination (larger at higher ellipsoidal light curve depends on the degree of Roche filling, synchronously rotating, ON star) to form a distance–inclination relation, $\sin i = (1.15 \pm 0.16)/d$ (kpc). The inclination range shown in Figure 3 corresponds to distance range of 1.37 kpc ($i = 5^\circ$) to 1.76 kpc ($i = 41^\circ$), which agrees well with distance estimates for the Cyg OB1 association, $d = 1.25\sim 1.83$ kpc (Uyaniker et al. 2001). We can also associate a stellar luminosity with any specific distance (or inclination) from the radius–distance relation. In the absence of mass transfer, we would expect the luminosity to agree with the mass–luminosity relation for single stars of its temperature (Schaller et al. 1992), so that one position along the constant inclination locus would be preferred. However, stars in binaries that suffer mass loss may appear overluminous for their mass, so in practice there is an upper limit along the inclination track where the star becomes more massive than expected for the luminosity. These terminal points are indicated in Figure 3. Because the Schaller et al. (1992) models do not account for rotation and because rapidly rotating stars may appear more luminous (Ekström et al. 2008), these end-point values should be taken as upper limits. The gray shaded region shows the preferred mass ranges that fulfill all the constraints, and the optimal fit occurs for $M_1 \approx M_2 \approx 21 M_\odot$.

The tentative picture that emerges from the spectroscopic analysis is that the ON star is transferring gas to a relatively faint disk that surrounds and obscures the companion star. The ON star must be very close to filling its Roche surface since we observe evidence of its tidal distortion in the light curve and in the deepening of lines at conjunctions. The emission features that follow the orbital radial velocity characteristics of the hidden mass gainer probably form in the thick disk. Thus, BD+36°34063 shares many features in common with the W Ser class of interacting binaries, but since the orbital period is much shorter and the mass ratio closer to unity than that found in other W Ser systems, we suggest that BD+36°34063 represents an earlier and faster mass transfer stage of evolution. If the system is coeval with the stars of Cyg OB1 (with an age of approximately 7.5 Myr; Uyaniker et al. 2001), then the mass–radius–age relations for single star evolutionary tracks (Schaller et al. 1992) suggest that the ON star probably began life with a mass of 25 $M_\odot$ or less. Thus, the ON star has probably lost only a modest fraction of its original mass so far. BD+36°34063 offers us an important glimpse of binary evolution at its most intense stage, and we encourage new observational efforts to probe the system and its environment.

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