HD 259440: THE PROPOSED OPTICAL COUNTERPART OF THE $\gamma$-RAY BINARY HESS J0632+057

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ABSTRACT

HD 259440 is a B0pe star that was proposed as the optical counterpart to the $\gamma$-ray source HESS J0632+057. Here, we present optical spectra of HD 259440 acquired to investigate the stellar parameters, the properties of the Be star disk, and evidence of binarity in this system. Emission from the Hα line shows evidence of a spiral density wave in the nearly edge-on disk. We find a best-fit stellar effective temperature of 27,500–30,000 K and a log surface gravity of 3.75–4.0, although our fits are somewhat ambiguous due to scattered light from the circumstellar disk. We derive a mass of 13.2–19.0 $M_\odot$ and a radius of 6.0–9.6 $R_\odot$. By fitting the spectral energy distribution, we find a distance between 1.1 and 1.7 kpc. We do not detect any significant radial velocity shifts in our data, ruling out orbital periods shorter than one month. If HD 259440 is a binary, it is likely a long-period (>100 d) system.

Key words: binaries: general – stars: emission-line, Be – stars: fundamental parameters – stars: individual (HD 259440, HESS J0632+057)
standard procedures in IRAF. All spectra were interpolated to a common wavelength grid and corrected for heliocentric radial velocity variations. The blue spectra were written to a common log wavelength scale for radial velocity analysis. The spectra were rectified in IRAF using emission line free continuum regions.

Two blue optical spectra were obtained at the KPNO 2.1 m telescope using the GoldCam Spectrograph on 2008 December 12–13. Grating G47 was used in the second order with a CuSO$_4$ blocking filter and a slit width of 1′′ to achieve $R \sim 2100–3100$. These observations cover a wavelength range of 3700–4900 Å. The exposure times were between 45 and 90 minutes long, yielding an $S/N$ range of 3872–6943 Å. The exposure times were between 45 and 90 minutes long, yielding an $S/N$ range of 3872–6943 Å. The spectra were zero-corrected, flat-fielded, and wavelength-calibrated using the standard procedures in IRAF. We corrected the spectra for heliocentric radial velocity variations and rectified them in IRAF using emission line free continuum regions.

We also observed HD 259440 seven times, twice in 2009 March and five times in 2009 October, with the SOPHIE cross-dispersed échelle spectrograph at the Observatoire Haute-Provence (OHP) 1.93 m telescope. These observations used the 52.65 1 mm$^{-1}$ R2 échelle grating to cover 39 orders in the high efficiency mode ($R = 40,000$) covering a wavelength range of 3782–6943 Å. The exposure times were between 45 and 90 minutes long, yielding an $S/N$ of 80–220. Additional spectra were obtained from the OHP archive, which were taken between 2007 October and 2008 February. These spectra had shorter exposure times of 5–15 minutes and $S/N$ as low as 40. The spectra were corrected for blaze, flat-fielded, wavelength-calibrated using ThAr lamp spectra taken within 2 hr of each observation, and corrected for heliocentric radial velocity variations. The observations are summarized in Table 1.

### 3. CONSTRAINTS ON ORBITAL PERIOD

We performed a cross-correlation of the He i λ4471 line in our CF data with a mean spectrum from that run to search for radial velocity, $V_R$, shifts. Due to the low $S/N$ of those spectra, the $V_R$ measurements had a standard deviation, $\sigma_{VR}$, of 20.1 km s$^{-1}$, and no significant shifts in $V_R$ were found. We also did not detect any gradual trend of increasing or decreasing $V_R$. The CF data set rules out orbital periods of $\sim 35$ d or less.

The He i λ5876 line in the échelle spectra from the OHP was also examined for $V_R$ variations, of which the results are presented in Table 2. These measurements had a $\sigma_{VR}$ of 6.7 km s$^{-1}$, which is close to the precision that we would expect to achieve due to the natural line width and line shape. Again, no significant shifts in $V_R$ were detected in this set of observations. Due to the significant instrumental differences and wavelength coverage between the CF, KPNO 2.1 m, and OHP runs, we hesitate to combine the $V_R$ over these data sets to investigate $V_R$ shifts. Crampton (1968) gives a radial velocity measurement of 7.6 km s$^{-1}$; however, the measurement is flagged for poor quality. Thus, we use only the sparsely sampled OHP spectra to constrain the orbital period further.

We cannot rule out the possibility that HD 259440 is a binary until we determine the probability that the system has an orbit with $V_R$ shifts too small for our observations to detect. We use a method similar to that outlined in Garmaly et al. (1980). For a binary system, the mass function of the primary is

$$f(m) = \frac{M_\star \sin^3 i}{q(1+q)^2} = 1.0355 \times 10^{-7} R_\star^3 P(1-e^2)^{3/2} \quad (1)$$

with

$$q = \frac{M_\star}{M_X}, \quad (2)$$

where $M_\star$ is the mass of the optical star in solar units, $M_X$ is the mass of the compact object in solar units, $K_\star$ is the velocity semi-amplitude of the optical star in km s$^{-1}$, $P$ is the orbital period in days, and $e$ is the orbital eccentricity. Assuming an
upper limit for $K_\star$ of $2\sigma_{\text{RV}}$, we can find the upper limit for the system inclination for a given value of $P$ at which we would fail to detect $V_R$ variations in our dataset:

$$\sin i \leq 9.392 \times 10^{-3} \sigma_{\text{RV}} \left( \frac{Pq(1+q)(1-e^2)^{3/2}}{M_\star} \right)^{1/3}.$$ (3)

If we assume a random distribution of orbital inclinations, the probability that $V_R$ is lower than our detection limit is

$$P(i < i_{\text{up}}) = \int_{0}^{i_{\text{up}}} \sin i \, di = 1 - \cos i_{\text{up}}.$$ (4)

We used the lower $\sigma_{\text{RV}}$ obtained from the OHP spectra and our measured mass of the Be star, $M_\star = 16 \, M_\odot$ (see Section 5). Secondary masses of 1.5, 2.0, and 2.5 $M_\odot$, consistent with a low-mass companion, and eccentricities of 0.0, 0.2, 0.4, and 0.6 were considered. The results are plotted in Figure 1. For a compact companion of 1.5 $M_\odot$, we would be unable to detect $V_R$ shifts for an orbital period greater than 50 days. The chance of detection improves for higher values of the secondary mass. However, for a 100 day orbit, there is still only a 50% probability that the system will have an inclination favorable for detecting $V_R$ shifts in our data. The chances of detection also decrease with orbital eccentricity. However, our method does not take into account that to detect the radial velocity shifts for an eccentric orbit, we would need to observe the system close to periastron. The system would only spend a small fraction of its orbit with $V_R$ shifts high enough for us to detect, decreasing our chances of observing $V_R$ shifts in systems of higher eccentricity. Therefore, we cannot rule out HD 259440 as a binary system with a long period.

4. CIRCUMSTELLAR DISK FEATURES

Our collection of red CF spectra provides an excellent tracer of the Be star’s disk emission over 35 nights. The mean equivalent width of the H\alpha emission line, $W_{\text{H}\alpha}$, is $-52.3$ Å, with a standard deviation of 0.7 Å. We find that $W_{\text{H}\alpha}$ is constant within our estimated 2% error due to noise and the continuum placement. We show in Figure 2 the H\alpha line profiles and a grayscale image of this line over the span of the observing run. Since the orbital period of HD 259440 is unknown, neither the line profiles nor the grayscale plots are folded by orbital phase, but rather they reveal true chronological variations in the line profile behavior as a function of Heliocentric Julian Date (HJD).
Figure 2. Upper plot shows the Hα line profile of HD 259440 over our continuous 35 nights of observation with the CF, sorted by the HJD, and the lower plot shows a gray-scale image of the same line. Since no period is currently known, the “arbitrary phase” goes from 0 at the start of the observing run to 1.0 at the end of the run. The intensity at each velocity in the gray-scale image is assigned one of 16 gray levels based on its value between the minimum (bright) and maximum (dark) observed values. The intensity between observed spectra is calculated by a linear interpolation between the closest observed phases.

We noticed some subtle temporal variations in the shape of the emission profile, so we subtracted the mean emission-line profile to investigate the residuals more carefully. The Hα emission residuals, and the corresponding gray-scales, are shown in Figure 3. These residual spectra reveal a partial S-shaped feature over the 35 nights of observation that suggest a characteristic period of ∼60 days. We attribute these variations to a spiral density wave in the circumstellar disk, common among Be stars (Porter & Rivinius 2003).

The high V sin i for this star (see Section 5) implies that the disk inclination must be nearly 90°. Therefore, we view the disk nearly edge-on. Since we do not resolve a double-peaked profile in Hα, the disk is likely optically thick out to several stellar radii (consistent with the very high W(Hα)). By contrast, Hγ shows a strong double-peaked emission profile. The disk also contributes a continuum flux to the line of sight which is added to the observed stellar spectrum, causing photospheric lines in the rectified spectra to appear too shallow. Bound-free emission will contribute a fraction of the stellar flux across all wavelengths, while free–free emission will increase at longer wavelengths. Indeed, we find evidence for such flux dilution in our blue spectra, discussed in the following section. We also observe an infrared excess in the SED for the system, which will be discussed in Section 6.

5. STELLAR PARAMETERS

Accurately determining the stellar parameters of HD 259440 is a challenging process due to the prevalence of emission features in the spectra. In order to minimize the impact of the disk emission on our analysis, we chose to focus on the Hé and H Balmer lines with λ ≤ 4000 Å, where the lines are predominantly in absorption. This approach required our analysis to use the lower resolution KPNO 2.1 m telescope spectra, as these covered a broader wavelength range than the KPNO CF data (Figure 4). In order to improve the S/N, we created a mean spectrum from the two observations. We then compared this spectrum to Tlusty OSTAR2002 (Lanz & Hubeny 2003) and BSTAR2006 (Lanz & Hubeny 2007) model grids, corrected for instrumental broadening, to obtain values for the effective temperature, T eff, surface gravity, log g, and V sin i of the optical star.

The Tlusty BSTAR2006 and OSTAR2002 model grids assume a plane–parallel stellar atmosphere. The BSTAR2006 models are available with temperatures ranging from 15,000 K to 30,000 K, with a grid spacing of 1000 K, and log g ranging from 1.75 to 4.75, with a grid spacing of 0.25. The OSTAR2002 models exist for temperatures between 27,500 K and 55,000 K, with a grid spacing of 2500 K. These models are available for log g between 3.0 and 4.75, with a grid spacing of 0.25. The OSTAR2002 models assume a microturbulence velocity of 10 km s⁻¹, while the BSTAR2006 models assume a microturbulence velocity of 2 km s⁻¹. We used models with solar abundances.

Initially, we tried fitting the mean spectrum of HD 259440 over the 3750–3950 Å range for T eff, log g, and V sin i, simultaneously. T eff was varied between 20,000 K and 40,000 K in increments of 1000 K (2500 K) to match the spacing of the BSTAR2006 (OSTAR2002) grid. We varied log g from 2.50 to 4.75 (3.0 to 4.75) in increments of 0.25 according to the
BSTAR2006 (OSTAR2002) grid spacings. We also increased $V \sin i$ from 300 km s$^{-1}$ to 500 km s$^{-1}$ in steps of 50 km s$^{-1}$. We computed the $\chi^2$ value for each combination of $T_{\text{eff}}$, log $g$, and $V \sin i$. However, none of the trials produced a satisfactory fit to the observed spectrum. The best fits from the two model grids produced divergent solutions for $T_{\text{eff}}$ and log $g$. Furthermore, a visual inspection comparing the model to the observed spectrum revealed the poor quality of these fits and they could not be used to constrain a $T_{\text{eff}}$ and log $g$ for the system.

The unusually shallow yet broad absorption lines seen in the spectra of HD 259440 are indicative of flux dilution, in that the continuum emission and scattering from the disk has effectively decreased the relative strength of absorption lines in the rectified spectra. The total observed flux is the sum of the flux from the disk, $F_{\text{disk}}$, and the star, $F_{\text{star}}$. Over a small wavelength range, we can assume a constant ratio $N = F_{\text{disk}}/F_{\text{star}}$. Using this assumption, we can correct for the disk continuum emission by adjusting the rectified spectrum

$$F_{R,\text{star}} = F_R(1 + N) - N,$$

(5)

where $F_R$ is the rectified observed spectrum and $F_{R,\text{star}}$ is the rectified spectrum of the star corrected for the disk continuum emission. Since the relative disk flux is unknown, we adjusted the observed spectrum for values of $N = 0.1$–0.9 and repeated the fitting procedure at each value.

The absorption lines in the spectrum of HD 259440 are fairly broad, so we expect the star to have a high rotational velocity. At all values of $T_{\text{eff}}$ and log $g$, a $V \sin i$ of 500 km s$^{-1}$ provided the best agreement with the line profiles. Therefore, we chose to fix $V \sin i$ at this value. We then repeated our fits using the OSTAR2002 and BSTAR2006 models over the 3750–3950 Å region. At each $N$, we determined the best fit $T_{\text{eff}}$ and log $g$ by minimizing the $\chi^2$ from the model fits. Our quoted errors for $T_{\text{eff}}$ and log $g$ represent the 1σ significance levels from our best fit. For values of $N$ between 0.0 and 0.4, $T_{\text{eff}}$ and log $g$ are not well constrained, but the fit quality and agreement between the BSTAR2006 and OSTAR2002 models improve significantly for higher values of $N$. Therefore, we chose to focus on the results with $N \geq 0.5$, which are summarized in Columns 1–5 of Table 3.

A contour plot illustrating the 1σ, 2σ, and 3σ significance errors for the combined OSTAR2002 and BSTAR2006 model fits in the $N = 0.7$ case is shown in Figure 5. As can be seen from this figure and Table 3, the best values of $T_{\text{eff}}$ for both the OSTAR2002 and BSTAR2006 models lie near the boundaries of the model grids. Furthermore, the 1σ significance contours are not closed at the boundary between the models. Therefore, we determined the lower limit of $T_{\text{eff}}$ from the 1σ contour of the BSTAR2006 models and the upper limit from the 1σ contour of the OSTAR2002 models.

A Tlusty BSTAR2006 model spectrum with $T_{\text{eff}} = 30,000$ K, log $g = 4.0$, and $V \sin i = 500$ km s$^{-1}$ plotted against the mean spectrum of HD 259440 with $N = 0.7$ is shown in Figure 6. We generally find good agreement between the model and observed spectrum in the H Balmer lines, although the He i λ3819 line appears stronger than all of our model fits. HD 259440 has been classified as a star with peculiar abundances. It was marked as nitrogen-rich by Turner (1976) and may also be a helium-strong star. We cannot distinguish significant differences between the model fits with different values of $N$, hence some ambiguity in the physical parameters of this system.

As a further test of the validity of the fit, we compared the model fits to one of the few other photospheric absorption
lines in our blue spectra, the flux-corrected He I λ4471 line. Figure 7 shows good agreement over the core of the line with the BSTAR2006 fit and $N = 0.7$. There may be some excess emission in the line wings from the higher velocity regions of the disk, narrowing the line slightly. Using the OSTAR2002 fits, the flux-corrected He I λ4471 line is again stronger than the model, a result of the difference in microturbulent velocity between the two sets of models. Since HD 259440 may be He-strong, the fit of the He I λ4471 line does not help constrain the best fit any further. The quality of the fits for the values of $N$ considered in this paper were equally good, so we also cannot constrain the flux contribution from the disk any further.

We determined the mass, $M_\star$, and radius, $R_\star$, of the star using our best-fit values for $T_{\text{eff}}$ and log $g$ and interpolating between the evolutionary tracks of Schaller et al. (1992). The evolutionary tracks were published for non-rotating stars with solar metallicity and masses ranging from 0.8 to 120 $M_\odot$. The errors for $M_\star$ were calculated using the best value of log $g$ and using the 1σ limits for $T_{\text{eff}}$, while the errors for $R_\star$ were calculated using the best-fit values for $T_{\text{eff}}$ and using the 1σ limits for log $g$. Our measurements of $M_\star$ and $R_\star$ are presented in Columns 6–9 of Table 3. The rapid rotation of HD 259440 may result in an underestimation of the mass and introduce an additional systematic error into our measurements. Ekström et al. (2008) calculated evolutionary tracks for rapidly rotating stars. Comparing these models to the tracks from Schaller et al. (1992), we conclude that any discrepancy in the mass of HD 259440 would be about 5 $M_\odot$. We also calculated the critical velocity, $V_{\text{crit}}$, at the stellar equator for each $N$. Since HD 259440 is a rapid rotator, the stellar radius at the equator is 1.5 $R_\star$ in the standard Roche model. Therefore,

$$ V_{\text{crit}} = \sqrt{\frac{G M_\star}{1.5 R_\star}}. \quad (6) $$

The results are listed in Column 10 of Table 3. These results indicate that HD 259440 is rotating close to $V_{\text{crit}}$, which is plausible for Be stars and thought to contribute to the formation of the circumstellar disk (Townsend et al. 2004).

### 6. Spectral Energy Distribution

We compared the observed SED of HD 259440 with the model SEDs from the Tlusty BSTAR2006 and OSTAR2002 models to measure the distance to the star. We obtained ultraviolet broadband photometric fluxes from Wesselius et al. (1982), Johnson $UBV$ magnitudes from Neckel & Chini (1980), Johnson $I$ magnitude from Droge et al. (2007), Two Micron All Sky Survey (2MASS) $JHK_\alpha$ magnitudes from Skrutskie et al. (2006), and mid-infrared fluxes from Egan et al. (2003). The Johnson magnitudes were converted to fluxes according to Bessell et al. (1998), while the 2MASS photometry was converted to fluxes using Cohen et al. (2003). The Tlusty model spectra were binned in 50 Å bins to eliminate small-scale line features and simplify comparison with the observed fluxes. A reddening of $E(B - V) = 0.85$ (Friedemann 1992) and selective extinction of $R = 3.1$ were applied to the model SEDs using the extinction model of Fitzpatrick (1999). The observed photometric fluxes were
corrected for disk emission using each value of \( N \) and compared with the best-fit OSTAR2002 and BSTAR2006 models.

In our spectral fitting, we assumed that the disk flux ratio \( N \) is constant over a small wavelength range. Therefore, we compared the observed fluxes between 3000 and 5000 Å, corrected for \( N \), to the model SEDs to determine the angular diameter, \( \theta_R \):

\[
\theta_R = \frac{R_*}{d} = \sqrt{\frac{F_{\text{obs}}}{F_{\text{surf}}}} = \sqrt{\frac{F_{\text{tot,obs}}}{F_{\text{surf}}(1 + N)}},
\]

where \( F_{\text{obs}} \) is the observed flux produced by the star, \( F_{\text{surf}} \) is the flux at the stellar surface, \( F_{\text{tot,obs}} \) is the combined flux of the star and disk, and \( d \) is the distance to the star. Using our derived \( R_* \) with the calculated \( \theta_R \), we find that HD 259440 lies within the distance range \( d = 1.1-1.7 \) kpc. The errors in the distance presented in Table 3 give the standard deviation of the model SED and the broadband photometric flux points in the 3000–5000 Å range. As the quality of all our best fits is similar for values of \( N \) between 0.5 and 0.9, the actual error in \( d \) is more accurately reflected by the range of values presented. HD 259440 is listed by Voroshilov et al. (1985) as a member of the open cluster NGC 2244. A recent study by Bonatto & Bica (2009) places the cluster at 1.6 \pm 0.2 kpc from the Sun, a value consistent with previous studies and our measurements for HD 259440 (Ogura & Ishida 1981; Pérez et al. 1987; Park & Sung 2002).

We expect to see exorbitant infrared emission in the SED of HD 259440 due to the nearly edge-on circumstellar disk. This infrared excess can clearly be seen in Figure 8, which shows the observed broadband photometric fluxes with the BSTAR2006 model SED for \( T_{\text{eff}} = 30,000 \) K, \( \log g = 4.0 \), \( N = 0.7 \), and \( d = 1.30 \) kpc. At blue optical wavelengths, the disk contributes \( \sim 0.7 F_\nu \). In the mid-infrared, the disk continuum emission is \( \sim 22 \) times the flux of the star.

7. SUMMARY OF RESULTS

HD 259440 is a main-sequence B0pe star that may be He-strong. Due to continuum emission and scattered light from the disk contaminating the stellar spectrum, our measurements of its physical parameters are somewhat ambiguous. We find \( T_{\text{eff}} \approx 30,000 \) K and \( \log g \approx 4.0 \). From the evolutionary tracks of Schaller et al. (1992), our best model fits indicate that the star has a mass of about 16 \( M_\odot \) and radius of about 6.6 \( R_\odot \). We find an angular radius of 23.5–25.7 \( \mu \)as and a distance range of 1.1–1.7 kpc. Due to the non-detection of radial velocity shifts over our 35 nights of CF data, we can rule out the possible 35–40 d orbital period suggested by Falcone et al. (2010). However, longer period orbits would produce \( v_R \) shifts that would be lost in the noise of our data sets. Therefore, we cannot rule out HD 259440 as a binary with a period greater than 100 days, which would be consistent with the class of non-accreting X-ray binaries.

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