PHOTOIONIZATION MODELS OF THE INNER GASEOUS DISK OF THE HERBIG BE STAR BD+65 1637

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ABSTRACT

We attempt to constrain the physical properties of the inner, gaseous disk of the Herbig Be star BD+65 1637 using non-LTE, circumstellar disk codes and observed spectra (3700–10500 Å) from the ESPaDOnS instrument on the Canada–France–Hawaii Telescope. The photoionizing radiation of the central star is assumed to be the sole source of input energy for the disk. We model optical and near-infrared emission lines that are thought to form in this region using standard techniques that have been successful in modeling the spectra of classical Be stars. By comparing synthetic line profiles of hydrogen, helium, iron, and calcium with the observed line profiles, we try to constrain the geometry, density structure, and kinematics of the gaseous disk. Reasonable matches have been found for all line profiles individually; however, no disk density model based on a single power law for the equatorial density was able to simultaneously fit all of the observed emission lines. Among the emission lines, the metal lines, especially the Ca II IR triplet, seem to require higher disk densities than the other lines. Excluding the Ca II lines, a model in which the equatorial disk density falls as $10^{-10} (R_*/R_d)^3$ g cm$^{-3}$ seen at an inclination of 45° for a 50 $R_*$ disk provides reasonable matches to the overall line shapes and strengths. The Ca II lines seem to require a shallower drop-off as $10^{-10} (R_*/R_d)^2$ g cm$^{-3}$ to match their strength. More complex disk density models are likely required to refine the match to the BD+65 1637 spectrum.

Key words: accretion, accretion disks – line: profiles – stars: emission-line, Be – stars: individual (BD+65 1637) – stars: pre-main-sequence – stars: variables: T Tauri, Herbig Ae/Be

1. INTRODUCTION

Herbig Ae/Be (hereafter HAeBe) stars are pre-main-sequence A- or B-type stars with emission lines and an excess in their infrared spectral energy distributions (SEDs). The emission lines, particularly the Balmer series of hydrogen, and the infrared excess can be attributed to circumstellar dust and gas, the likely remnants of the star formation phase (Herbig 1960; Finkenzeller & Mundt 1984; Waters & Waelkens 1998). Circumstellar dust distinguishes HAeBe stars from the classical Be stars, whose infrared excess is solely due to free–free emission from the ionized, dust-free gas in a circumstellar decretion disk (Rivinius et al. 2013).

Being the precursors to the debris disks, such as those around β Pictoris and Vega, HAeBe stars make interesting subjects for studying disk physics, as well as for understanding disk evolution in pre-main-sequence stars (Perez & Grady 1997). HAeBe stars are also an important link between low- and high-mass star formation. High-mass, O-type stars form at the centers of very dense clusters and involve complex environments. The formation of such stars is currently poorly understood (Larson 2003). In addition, such stars spend their pre-main-sequence life in a deeply embedded state before becoming optically visible as main-sequence objects, hence depriving us of the opportunity to observe the early phase of star formation (Zinnecker & Yorke 2007). In contrast, Herbig Be stars (HBe), despite forming in complex and dense environments, may become optically visible just before they reach the zero-age main sequence (ZAMS) because they stay comparatively longer in the pre-main-sequence (PMS) phase compared to their higher-mass counterparts. This not only aids in the understanding of the formation process of intermediate-mass HBe stars, but can also help to bridge the understanding of the star formation process between low-mass, T Tauri stars and high-mass, O-type stars.

Knowledge of the physical conditions in the disks around HAeBe stars has been steadily increasing. The disk material is inherited by the star from its parent molecular cloud. Near-infrared and millimeter interferometric observations (see the review by Kraus 2015 and references therein) have been instrumental in providing strong evidence for circumstellar disks around HAeBe stars. The disk can extend to 100 s of astronomical units, and disk temperatures can vary from a few 10 s K to 1000 s K (Dullemond & Monnier 2010). These disks have been studied extensively at far-infrared and millimeter wavelengths for cooler dust species such as PAHs (polycyclic aromatic hydrocarbons), iron oxide grains, and silicates (crystalline and amorphous) to understand the evolution of these species in the disk (Waters & Waelkens 1998). Near- and mid-infrared wavelengths have been used to study molecular gas and warm dust in regions closer to the star.

Vink et al. (2002), Mottram et al. (2007), and Vink (2015) have shown that there exists a difference in polarization between Herbig Ae (H Ae) and HBe stars, especially early B-type stars. Vink et al. (2002) first noticed that while all HAe stars show intrinsic linear polarization consistent with magneto-spheric accretion, most HBe stars show line depolarization that is consistent with disk accretion. HAeBe stars show photometric variability ranging from days to months to years (Herbig 1960; Finkenzeller & Mundt 1984), and various models

5 T Tauri stars are pre-main-sequence stars, with masses less than 2.5 $M_\odot$, that show Balmer emission lines in their spectrum and an excess in their infrared SEDs, interpreted as gas and dust in the form of a circumstellar disk. The most massive T Tauri stars will later become main-sequence A-type stars.
such as nonradial pulsation, accretion, and so on have been suggested for their occurrence (Catala 1994). van den Ancker et al. (1998) and Mendigutía et al. (2011) have shown that HAe stars show large to moderate variations in magnitude (>2\textsuperscript{m}5), while HBe stars show low to moderate variations (<0\textsuperscript{m}5). The differences between the variations has been suggested to be due to different accretion mechanisms. In addition, Cauley & Johns-Krull (2014) studied Hei (λ10830)\textsuperscript{6} in a sample of HAeBe stars and noticed that HBe stars show blueshifted absorption features, while HAe stars show both blue- and redshifted absorption features. This difference indicates that HBe stars show little evidence of infalling material, while HAe stars show a higher level of mass flow activity, suggesting the action of different mechanisms. A recent study by Fairlamb et al. (2015) of UV excess of a large set of HAeBe stars showed that early-type HBe stars cannot be modeled successfully using the magnetospheric accretion, again hinting of an alternate mode of accretion.

Alecian et al. (2008, 2013) studied a large set of HAeBe stars and found that less than 10% of them show evidence of large-scale magnetic fields. Possible causes for a lack of large-scale magnetic fields for the HAe and HBe stars are either a very small convective core or a completely radiative envelope, neither of which generate large-scale magnetic fields (Alecian 2014). Accretion via a magnetosphere is fairly well established for T Tauri stars (see reviews by Bouvier et al. 2007, p. 479B and Gómez de Castro 2013, p. 279), but whether or not the same mechanism applies to HAeBe stars is still an open question. With the differences in the polarizations and the lack of large-scale magnetic fields, the mechanism at work for accretion in HBe stars is still a mystery.

2. DISK STRUCTURE

2.1. Atomic Gaseous Disk

Close to the star, one expects regions with high temperatures that would destroy any dust and create a dust-free zone. Farther away, the temperature is cool enough for dust to exist, and in the region favorable for dust, one either finds a thick wall of dust, sometimes called a dust rim, or a smooth transition to a dusty disk at the dust sublimation radius (see Dullemond & Monnier 2010 for a review). Monnier et al. (2005) suggest that if an optically thin gas exists in the dust-free zone, a wall of dust is expected because direct radiation from the star will enhance the scale height of the dust rim or puff up the inner disk wall. If an optically thick gas exists, then the transition to dust is smoother.

As dust evaporates above ~1500 K, the portion of the disk closest to the star is likely to be completely gaseous, due to high temperatures resulting from the star’s UV radiation. Depending on the distance from the central star and the stellar radiation, HBe disks can be divided into atomic gas, molecular gas, and dust. The expected structure of such a disk is illustrated in Figure 1. The inner gaseous region extends from, perhaps, 0.1 AU to a few astronomical units (~100\textsubscript{R}\text{\textsubscript{\textcircled{e}}}) in size, and temperatures can reach 1000s K. Optical and near-infrared (NIR) atomic lines are used to study this hot, atomic gaseous region. The disk region beyond the gaseous disk receiving direct radiation from the star is expected to have a thin surface layer with atomic gas; hence, the emission seen in the spectrum can arise from a large extended area. In the region beyond the atomic gaseous disk, where the temperatures are cooler, molecular gas is expected. As the temperature decreases, the molecular gas condenses into dust, and a mixture of warm dust and molecular gas is expected. NIR molecular emission lines and NIR/mid-IR (MIR) interferometry is used to understand the structure of this region. Beyond this region, cooler gas and dust are detected using millimeter and submillimeter interferometry. The region beyond the atomic gaseous disk can range anywhere in size from 0.1 to 100s of AU, including the dusty disk. The outer, dusty region of the disk is well studied, but currently very little is known about the inner, gaseous region.

Several studies have suggested that HBe stars can be compared to classical Be stars (see Hamann & Persson 1992a; Mottram et al. 2007) in their circumstellar disk and structure. Hillenbrand et al. (1992) noticed that some of the HAeBe stars in their sample show a small IR excess, comparable to that seen in classical Be stars. Like early-type HBe stars, classical Be stars are known to show depolarization (see Rivinius et al. 2013). In addition, similarities such as the H\alpha equivalent width distribution, fast rotation speeds (i.e., high $v\sin i$), photometric variability, and slow outflow velocities further connect the classical Be and HBe stars (Böhm & Balona 2000). Hence, using models that have been well established for classical Be stars would make a good first step in understanding the inner, atomic gaseous disks of HBe stars.

2.2. Molecular Gas and Dust Disk

Several studies of molecular gas using tracers such as Br\gamma (Calvet et al. 2004; Mendigutía et al. 2011) and CO (e.g., Wheelwright et al. 2010; Ilee et al. 2014, 2013) have been conducted, probing the relatively warm region of the disk where these emission lines are thought to originate. Ilee et al.

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\textsuperscript{6} All wavelengths are in Å in this study unless otherwise stated.
studied CO overtone emission and strongly suggest that the emission originates from a small gaseous disk inside the dust sublimation radius that follows Keplerian rotation. This hints at the process of classical disk accretion where material is thought to be transferred from the disk directly onto the star through an equatorial disk.

Monnier & Millan-Gabet (2002) and Millan-Gabet et al. (2007) noticed that most HBe stars have a smaller dust sublimation radius \( r_{\text{sub}} \) than predicted by the luminosity–size \( r_{\text{sub}} \propto L^{1/3} \) relationship developed for the T Tauri and HAe stars. Monnier & Millan-Gabet (2002) suggest that the smaller size of the gaseous disk around HBe stars may be due to optically thick gas absorbing the UV radiation, allowing the dust to exist closer to the star. Eisner et al. (2004) was able to fit an inner rim model to a flat disk with optically thick gas to 2.2 \( \mu \)m observations for higher mass stars. Alonso-Albi et al. (2009) showed that the disks around HBe stars are 5–10× less massive than those of lower-mass counterpart HAe and T Tauri stars and proposed that strong UV radiation from the hot, central star evaporates and disperses the gas, leaving behind a small dusty disk. Finally, the gas in the circumstellar disk is seen to follow Keplerian rotation, as found by Mannings & Sargent (1997, 2000) using millimeter interferometric measurements.

2.3. Emission Lines

By definition, all HAeBe stars show emission lines in their spectra that can be used to trace the structure and processes in the disk. Hamann & Persson (1992a) show that the spectra of HAeBe stars are very similar to those of T Tauri stars; however, they note that the similarity of the spectra does not mean that the formation mechanism of the lines is the same. The higher stellar temperatures of the HAeBe stars can change both the mechanisms and the extent to which the gas is excited by the intense stellar radiation field experienced by the disk gas.

Only a few studies have qualitatively modeled the permitted emission lines seen in the visible and NIR part of the spectrum. Cohen & Kuhn (1979), Finkenzeller & Mundt (1984), Hamann & Persson (1992a), and Böhm & Catala (1995) investigated emission lines such as H\( \alpha \), the Ca II IR triplet \( (\lambda 8498, \lambda 8542 \& \lambda 8662) \), and several Fe II lines and interpreted them as revealing chromospheric and wind activity in these stars. More recently, He \( \alpha \) (\( \lambda 10830 \)) has been used as a tracer of mass flow activity by Cauley & Johns-Krull (2014). In addition to permitted emission lines, forbidden emission lines are found to be present in HAeBe stars, and Corcoran & Ray (1997a) have shown that these lines may arise from the winds and outflows.

Finkenzeller & Mundt (1984) showed that the H\( \alpha \) line in HAeBe stars can be divided into three groups based on the line profile morphology, namely single-peak, double-peak, and P-Cygni line profiles. More than 50% of the stars studied showed a double-peak H\( \alpha \) profile, while the rest were divided equally into single-peak and P-Cygni profiles. Finkenzeller & Jankovics (1984) note that all Balmer lines exhibit the same line shape as H\( \alpha \), with the strength of the line decreasing from H\( \alpha \) to H\( \gamma \). H\( \alpha \) has been widely used for wind diagnostics studies of Herbig Ae/Be stars (Finkenzeller & Mundt 1984; Corcoran & Ray 1997b) and polarization (Vink et al. 2002; Vink 2015).

Hamann & Persson (1992a, 1992b) investigated the Ca II triplet emission in HAeBe stars: 71% of their HBe stars showed the Ca II triplet lines in emission. They showed that if the excitation is same in all of the stars, Ca II requires denser and/or thicker regions in hotter stars (see their Figure 8). They also noted that, due to high stellar temperatures and the double-peaked line profiles, the formation of the Ca II lines would happen away from the stellar surface in a disk like those possessed by classical Be stars and in a very small, ring-like structure close to the star. They also showed that there is a correlation between Ca II luminosity and IR excess in these stars and concluded that the Ca II emission lines are somehow related to the presence of a disk.

Böhm & Catala (1995) studied nonphotospheric lines such as the H\( \alpha \), the Ca II IR triplet, and He I \( (\lambda 5876) \). They concluded that the energy fluxes for these lines increase with the effective temperature and suggest that the origin of the emission in the lines is farther away from the layer between the disk and the stellar surface. Hernández et al. (2004) found that 33% of their sample showed emission in Fe II multiplets and also noticed that the equivalent width (EW) of one of the Fe II lines, the Fe II multiplet (42) \( (\lambda 5169) \), is correlated with the equivalent width of H\( \alpha \) and seems to be present only when [O I] \( (\lambda 6300) \) also appears in the spectrum.

2.4. Overview

Differences in polarization, magnetism, and spectral lines between HAe and HBe stars suggest the possibility of a different accretion mechanism at work. The accretion mechanism may be constrained by studying material very close to the star, determining its structure and kinematics. Because high temperatures are expected close to the star, we chose emission lines that form outside the stellar photosphere and require high temperatures to be excited. Modeling these lines and investigating what kind of disk density structure they require will allow us to qualitatively understand the regions close to the star.

In this work, we model emission lines thought to be produced in the inner gaseous disk of one HBe star, BD+65 1637, using observations from the Canada–France–Hawaii Telescope (CFHT) ESPaDOnS instrument. Section 3 describes the observations, reduction methods, and the emission lines found in the spectrum. The details of the models can be found in Section 4, and the results of the modeling for each emission line can be found in Section 5. The uniqueness of the models is discussed in Section 6. The paper concludes with a discussion in Section 7 and a summary of key findings in Section 8.

3. BD+65 1637

BD+65 1637 \( (V^* V361 \text{ Cep}) \) is a B2e star of visual magnitude 10.83 in the young cluster NGC 7129 (Stražys et al. 2014; Dahm & Hillenbrand 2015). BD+65 1637 was identified as a HBe star by George Herbig in his first paper on Herbig stars (Herbig 1960) and was noted to have a spectrum very much like that of a classical Be star. Hillenbrand et al. (1992) studied the star’s SED, which showed a small infrared excess, and they classified it as very similar to classical Be stars. The assigned spectral type has varied in the literature from B2 to B5 (see Herbig 1960; Strom et al. 1972; Finkenzeller & Mundt 1984; Finkenzeller 1985; Hillenbrand 1995). Here, we will adopt the stellar parameters and their uncertainties from Alecian et al. (2013), reproduced in Table 1.
3.1. Observations

The observational data were obtained in 2006 (HJD-2453898) using the high-resolution spectropolarimeter ESPaDOnS at the Canada–France–Hawaii Telescope. Additional spectra are also available from the Narval spectropolarimeter at the Telescope Bernard Lyot, obtained in 2009 (HJD-2455099). Both spectropolarimeters cover the wavelength range from 3700 to 10500 Å with a spectral resolution of 65,000. The peak signal-to-noise ratio (S/N) per CCD pixel at 7300 Å was 237 for the ESPaDOnS spectrum and 276 for the Narval spectrum.

The CFHT spectrum of BD+65 1637 can be seen in Figure 2. The spectrum not only contains strong Balmer line emission, Hα and Hβ, but also emission in many metal lines, such as those from calcium, oxygen, and iron. In addition to the two strong Balmer lines, we will investigate one of the three Ca ii infrared triplet lines (λ5342), two Fe ii lines (λ5169 of multiplet 42 and λ5317 of multiplet 49), and one He i line (λ6678). The He i line is seen in absorption and is used to estimate stellar properties, such as the $\sin i$ of the star. A detailed profile of each line can be found in Figure 3.

The Balmer lines, Hα and Hβ, are the strongest emission lines in the optical/NIR spectrum of BD+65 1637, as illustrated in Figure 2. For BD+65 1637, the equivalent width of the Hα lines has been noted to vary from −45 Å to −28 Å (Finkenzeller & Mundt 1984; Fernández et al. 1995; Hernández et al. 2004 and Garrison & Anderson 1977). In the 2006 CFHT spectrum, the EW measured for Hα is −26.2 Å and for Hβ, −0.92 Å. The EW for the Ca ii IR triplet (λ8542) is measured to be −4.0 Å. The two Fe ii lines, λ5169 and λ5317, were chosen for this study as they are in different multiplets, and their EWs were measured to be −0.58 Å and −0.40 Å. Fe ii λ5169 is in multiplet 42 (αS − zP), and Fe ii λ5317 is in multiplet 49 (αG − zF), although it is blended with a weaker line from multiplet 48. Both of these lines have low excitation energy. He i (λ6678) is in absorption, and the EW was measured to be 0.33 Å.

A comparison between the CFHT and Narval spectra, taken approximately three years apart, can be seen in Figure 3. Some variation in the spectral lines is seen, most notably in the metal lines and violet-to-red (V/R) peak intensity ratio, with a strong red component in the Narval observations from 2009. The similarity in the He i (λ6678) absorption line, in contrast to variations in the Balmer and metal lines, confirms that the Balmer and metal emission lines arise from material outside the star and that the disk structure varies over time. For the analysis of this paper, only the 2006 CFHT ESPaDOnS data were used. Hα, Hβ, and both the Fe ii lines (λ5169 and λ5317) show double-peaked profiles, with a stronger red component (R) when compared to the blue component (V). All of the nonphotospheric lines included in this study show changes in the V/R ratio over time (see Figure 3). Classical Be stars are known to show V/R line variability, which is interpreted as being caused by a one-armed, global disk oscillation (for details see the review by Rivinius et al. 2013). This effect has not been included in the model here, and hence the synthetic line profiles cannot fit both peaks of a line profile simultaneously.

3.2. Reduction of Spectra

In order to compare the observed and modeled line profiles, the observed spectra needed to be continuum normalized. The unnormalized data obtained from CFHT (and Narval) were separated into specific wavelength windows that included the emission lines of interest. Each wavelength window was continuum normalized using IRAF. The function and order used for normalization varied from one spectral window to another; “Legendre” and “cubic spline” functions and low-order polynomials were generally used in the process.

The Ca ii infrared triplet lines (λ8498, λ8542, and λ8662) are blended with the hydrogen Paschen series. In order to compare with synthetic line profiles, the Paschen line must be subtracted from the Ca ii line. This was done by taking an average of the two nearest, unblended Paschen lines and then subtracting the average from the Ca ii line. Figure 4 illustrates all three lines before the process of subtraction (on the left) and after subtraction (on the right) in the CFHT spectrum. It can be seen that the subtraction process decreases the strength of the Ca ii line, and the resultant line profile is double-peaked with a stronger red peak.

An example of the subtraction process is illustrated in Figure 5, where the average of Paschen 14 (P14, λ8596) and Paschen 17 (P17, λ8467) is subtracted from the blended Ca ii λ8542 line to extract the unblended Ca ii profile. For the rest of the paper, the resultant Ca ii line profile (seen in the right-hand panel of Figure 5) will be used. All of the lines are adjusted for the stellar radial velocity. The radial velocity required for the line shifts was measured using the center of He i (λ6678), which was measured to be −17.1 km s$^{-1}$ for the CFHT spectrum and −41 km s$^{-1}$ for the Narval spectrum. Both values are within the range of −26 ± 20 km s$^{-1}$ measured by Alecian et al. (2013).

4. MODELING

To calculate the thermal structure of the equatorial, non-accreting, gaseous disk surrounding the central B star, the Bedisk code (Sigut & Jones 2007) was used. This code calculates the temperature structure of the disk, given a user-defined density structure, by enforcing radiative equilibrium in a gas of solar composition. The energy input into the disk was assumed to be solely from the photoionizing radiation field of

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Table 1
Stellar Parameters for BD+65 1637

| Parameter          | Value       |
|--------------------|-------------|
| Spectral Type      | B2e         |
| $T_{\text{eff}}$ (K) | 10000       |
| log g (cgs)        | 4.0         |
| Radius ($R_\odot$) | 6.7 ± 0.7   |
| Mass ($M_\odot$)   | 8.11±0.24   |
| Distance (pc)      | 1250 ± 50   |
| $v\sin i$ (km s$^{-1}$) | 278 ± 27 |

Note. All of the values for the parameters as well as their uncertainties are taken from Alecian et al. (2013). The value of $T_{\text{eff}} = 10000$ is within the error 1000 K obtained by Alecian et al. (2013).
the central star. The microscopic rates of heating and cooling were balanced to determine the temperature at many grid points in the disk. The disk was assumed to be axisymmetric and in Keplerian rotation about the central star.\footnote{No wind from the central star has been included in the calculations.} BEDISK includes nine abundant elements (H, He, C, N, O, Mg, Si, Ca, and Fe) over many ionization stages in the determination of the radiative equilibrium temperatures. The atomic level populations, required for the calculation of the heating and cooling rates, as well as for use later in computing emission lines, were obtained by solving the statistical equilibrium equations in an...
The user-defined density structure of the disk \((g \, cm^{-3})\) was taken to be specified by the parameters \(\rho_0\) (base disk density) and \(n\) (radial power-law index) in the equation

\[
\rho(R, Z) = \rho_0 \left(\frac{R_0}{R}\right)^n e^{-\left(\frac{Z}{H}\right)^2},
\]  

where \(R\) and \(Z\) are the cylindrical coordinates for the disk, \(R_0\) is the stellar radius, and \(H\) is the disk scale height. In all our models, the disk extends from the stellar photosphere \((R\) starts at \(R_0\)) out to a radius of \(R_{\text{disk}}\).

If the vertical density structure of the disk is determined solely by gravitational equilibrium (the disk is rotationally

\[\frac{\partial^2}{\partial R^2} + \frac{1}{R} \frac{\partial}{\partial R} \left( R \frac{\partial}{\partial R} \right) + \frac{1}{R^2} \frac{\partial^2}{\partial Z^2} \rho(R, Z) = 0.\]
supported in the $R$ direction), then the scale height has the form
\[ H = \beta(T_{\text{HE}}) \left( \frac{R}{R_*} \right)^{3/2}, \]  
(2)
where
\[ \beta(T_{\text{HE}}) = \frac{2kT_{\text{HE}}R_*^3}{\sqrt{GM_*\mu M_H}}. \]  
(3)

Here, $M_*$ is the mass of the star, $\mu$ is the mean molecular weight of the gas in the disk (taken to be 0.68), and $T_{\text{HE}}$ is the hydrostatic equilibrium temperature assumed for the disk. This hydrostatic temperature is used solely for setting the vertical scale height of the disk, and typically in classical Be stars, one takes $T_{\text{HE}} \approx 0.6 T_{\text{eff}}$. A self-consistent treatment, in which the radiative equilibrium disk temperatures are used in the calculation of the vertical hydrostatic equilibrium, is possible (see Sigut et al. 2009), but that has not been used here. In the present work, varying $T_{\text{HE}}$ allowed the scale height of the disk to be varied. Finally we note that vertical gravitational equilibrium predicts a flaring disk, $H \propto R^{3/2}$.

The assumption of vertical hydrostatic equilibrium produces a very thin disk near the star. From Equation (3), it is easy to see that the ratio $H/R$ can be expressed as
\[ \frac{H}{R} = \frac{c_S}{V_K}, \]  
(4)
where $c_S$ is the local sound speed and $V_K$ is the Keplerian orbital velocity. As the orbital velocity is typically hundreds of km s$^{-1}$ while the sound speed is on the order of 10 km s$^{-1}$ for the disk temperature, the disk is predicted to be geometrically thin with $H/R \ll 1$. Such thin disks have been very successful in interpreting observables in classical Be stars, but their application to HBe stars is less clear. For this reason, we also considered disk density models with an enhanced scale height, achieved by setting the $T_{\text{HE}}$ temperature to be 5 $T_{\text{eff}}$, a factor of nearly 10 over the gravitational equilibrium value. We will refer to these models as thick disk models. Note that for the same disk density parameters, $\rho_0$, $n$, and $R_{\text{disk}}$, the thick disk models are a factor of $\sqrt{5}/0.6$ more massive because the total disk mass is proportional to the scale height.

Finally, we considered one additional modification to the basic disk model discussed above, although it is not an alteration to the density structure. In classical Be stars, there is some evidence that the $\alpha$ viscosity parameter required in hydrodynamical models of disk formation and dissipation is $\approx 1$ (Carciofi et al. 2012). One possible interpretation of this result is that of sonic turbulence in the disk, i.e., $\nu = \alpha c_S H \sim c_S H$. For this reason, we have also considered models in which the disk is assumed to have a microturbulent velocity equal to the local sound speed. Microturbulence is a concept from classical stellar atmospheres that represents the dispersion of an assumed Gaussian distribution of turbulent velocities on scales smaller than the unit optical depth. In this case, the turbulence acts to broaden the atomic absorption profile and hence is easily incorporated as an increase in the Doppler widths of radiative transitions. In our models, we assumed that the microturbulence value was either zero or equal to the local sound speed. These latter models will be referred to as turbulent disks.

The temperature structure and atomic level populations computed by BEDISK are input into the code BERAY (Sigut 2011), which can compute observables such as line profiles, SEDs, and monochromatic images in the sky. This is done by solving the equation of radiative transfer along a series of rays $(\approx 10^5)$ that pass through the star+disk system directed at the observer. Rays that terminate on the stellar surface use a Doppler-shifted photospheric (LTE) line profile for the initial boundary condition, while rays that pass entirely through the disk assume no incident radiation. Note that the BERAY calculation adds an additional parameter, namely the viewing inclination of the system ($i = 0^\circ$ for a pole-on star, face-on disk, and $i = 90^\circ$ for an equator-on, edge-on disk). Inclinations from $i = 18^\circ$ to $i = 75^\circ$ were computed. Finally, the computed spectral lines were convolved down to the instrumental resolution before comparing to the observed spectra.

4.1. Classical Be Stars and the BERAY and BEDISK Codes

BEDISK and BERAY are non-LTE radiative transfer codes constructed specifically for classical Be stars and their ionized, gaseous decretion disks. Many studies, such as Silaj et al. (2010, 2014), have been able to successfully model the structure of the gaseous disk by comparing synthetic and observed H$\alpha$ lines. Sigut (2011) has shown that such models based on H$\alpha$ are also able to correctly predict observed Fe II lines in the spectra of these stars. These models have also been able to reproduce the observed correlation seen between H$\alpha$ and long-term variations in visual magnitude, which are interpreted as formation and dissipation of the disk over long periods of time in classical Be stars (Sigut & Patel 2013). Observed IR line fluxes (Jones et al. 2009; Halonen et al. 2008), as well as optical and near-IR interferometry (Jones et al. 2008; Tycner et al. 2008; Mackay et al. 2009; Grzenia et al. 2013; Sigut et al. 2015) computed with BEDISK and BERAY models, have been used to put constraints on the several classical Be star disks.

Several authors, such as Carciofi et al. (2006, 2007, 2009), studied the classical Be stars $\alpha$ Eri, $\zeta$ Tau, and $\delta$ Sco by fitting viscous decretion disk models to the observed Balmer lines, SEDs, and polarization measurements. Silaj et al. (2010) studied 56 Be stars and successfully fit the observed H$\alpha$ profiles to BEDISK models. Many individual stars, such as $\chi$ Oph (Tycner et al. 2008), $\kappa$ Dra, $\beta$ Psc, $\nu$ Cyg (Jones et al. 2008), and $\omega$ Aqr (Sigut et al. 2015), have been studied spectroscopically as well as interferometrically and are found to match a density model similar to the one adopted in this study. All of these mentioned studies, as well as several others, have fit the observed line profiles well with a power-law index ($n$) ranging from 2 to 4, typically 3.5, and the disk base density varying between $10^{-10}$ and $10^{-12}$ g cm$^{-3}$ (Rivinius et al. 2013).

Given the noted similarities between HBe and classical Be stars (Hamann & Persson 1992a; Böhm & Balona 2000; Mottram et al. 2007), a good starting point for the modeling of the emission spectra of HBe stars is using codes that have successfully been able to reproduce emission lines from the gaseous disks of classical Be stars. The analysis can give insights on the regions where the lines are being formed, the
mass of the disk, and the temperature and density structure of the emitting regions.

5. RESULTS

Large libraries of synthetic line profiles were calculated for H\(\alpha\), H\(\beta\), the Ca\(\Pi\) IR triplet (\(\lambda\) 8542), Fe\(\Pi\) (\(\lambda\) 5169, \(\lambda\) 5317)\(^{11}\), and He\(\text{I}\) (\(\lambda\) 6678) for disks surrounding a B2 star using combinations of the disk density parameters listed in Table 2. Values of the disk base density parameter, \(\rho_0\), ranged from \(10^{-13}\) to \(10^{-8}\) g cm\(^{-3}\), and the power-law index \(n\) ranged from 0.5 to 3.0. Three different-sized disks were considered with \(R_{\text{disk}} = 25\), 50, and 100 R\(_{\odot}\); thus, the largest disk considered has an outer diameter of 3.1 AU. This range of disk density parameters and disk sizes includes the range of values typically found for classical Be stars, as noted above, but with an extension to more massive disks (i.e., higher \(\rho_0\) and/or lower \(n\)).

All synthetic line profiles were calculated at viewing inclinations of 18°, 45°, 60°, and 75°, which represent the centers of the first four bins of five equal-area bins in a random \(\sin i\) distribution.

Each observed line profile was compared to its synthetic library by computing a figure-of-merit, \(\mathcal{F}\), defined as

\[
\mathcal{F} \equiv \frac{1}{N} \sum_{i=1}^{N} \frac{F_{i,\text{Mod}} - F_{i,\text{Obs}}}{F_{i,\text{Obs}}},
\]

where \(F_{i,\text{Obs}}\) is the observed relative flux, \(F_{i,\text{Mod}}\) is the model relative flux, and the sum is over the \(N\) wavelength points spanning the line. In performing this sum, a range of small shifts to the observed wavelength scale was also tried, within the errors of the star’s radial velocity. The smallest value of \(\mathcal{F}\) was deemed to define the best-fit model for that feature, although all profiles with small values of \(\mathcal{F}\) were visually inspected. In addition, the disk density parameters of profiles that fit the observed profiles almost as well as the best-fit model were also examined, and this point, concerning the uniqueness of the fits, will be discussed in Section 6.

While the minimum of \(\mathcal{F}\) for a given line, say \(\mathcal{F}_{H\alpha}\), defines the best fit for that particular line, it is not guaranteed that the best-fit model for all lines will result in the same set of disk density parameters. A figure-of-merit defined by Equation (5) can be obtained for each line considered: \(\mathcal{F}_{H\alpha}, \mathcal{F}_{H\beta}, \), and so on. Therefore, it is possible to search for the best set of disk parameters that minimizes the sum of all of the line figures-of-merit, that is, the global, best-fit model.

For all the line profile matches performed in this study, the effort was made to fit to the blue peak of the emission line. When a reasonable fit was not found for the blue peak, the fit was computed for the red peak instead.

\(^{11}\) For Fe\(\Pi\) 5317, only the multiplet 49 component was included.

| Table 2 | Explored Model Parameters for the Disk of BD+65 1637 |
|---------|---------------------------------|
| Parameter | Range |
| Base Disk Density, \(\rho_0\) (g cm\(^{-3}\)) | \(10^{-8} - 10^{-13}\) |
| Power Law Index, \(n\) | 0.5 – 3.0 |
| Inclination, \(i\) (°) | 18–75 |
| Disk Radius, \(R_{\text{disk}}\) (R\(_{\odot}\)) | 25–100 |

We will now first discuss the best-fit models for each line individually and then consider the best global model.

5.1. Individual Fits

The best-fit models for all individual lines are listed in Table 3, and the best synthetic line profile fits to the individual observed emission lines are shown in Figure 6. With the freedom to chose the density model independently for each line, the observed line profiles can be reproduced quite well in strength, shape, and equivalent width by the models.

The best fit for H\(\alpha\) is a 50 R\(_{\odot}\) thin disk model with a disk density parameter \(\rho_0\) of \(3.2 \times 10^{-12}\) g cm\(^{-3}\) and power-law index \(n\) of 2.0 seen at an inclination of 60°. The observed and synthetic profiles are compared in Figure 6. The width of H\(\alpha\) at its base is underestimated, and a better fit might be possible by refining the viewing inclination, but we have not attempted this.

For H\(\beta\), the best match to the observed profile was found for a model with slightly smaller, thin disk of 25 R\(_{\odot}\) seen at 45° with disk density parameter \(\rho_0\) of \(1.0 \times 10^{-11}\) g cm\(^{-3}\) and power-law index \(n\) of 2. The overall strength and width of H\(\beta\) (including its absorption wings) are well reproduced by the model. We note that the V/R asymmetry cannot be reproduced by our assumed axisymmetric disk models.

At this point, we immediately see that the best-fit models for H\(\alpha\) and H\(\beta\) differ. Nevertheless, it should be kept in mind that, in addition to the best-fit model, there is a range of other disk models that fit each profile nearly as well. For example, there will be \(N\) models that fit H\(\alpha\) with a figure of merit within 25% of the best-fit model, and for H\(\beta\), there will be \(M\) such models. We will return to the question of the number of such models and how the disk density parameter ranges compare in Section 6.

For Ca\(\Pi\) \(\lambda\) 8542, the best-fit model to the observed line has a disk density parameter \(\rho_0\) of \(1.0 \times 10^{-10}\) g cm\(^{-3}\) and power-law index \(n\) of 2 seen at 60° for a 25 R\(_{\odot}\) thin and turbulent disk. We again note that the width and overall strength of the line are well reproduced.

For the two Fe\(\Pi\) lines, the figure of merit \(\mathcal{F}\) was computed by using only the red half of the line; that is, the blue peak was ignored in the fit. The Fe\(\Pi\) multiplet (42) \(\lambda\) 5169 line requires a disk density parameter \(\rho_0\) of \(1.0 \times 10^{-10}\) g cm\(^{-3}\) and a power-law index \(n\) of 3 seen at 45° for a 25 R\(_{\odot}\) thick and turbulent disk. The Fe\(\Pi\) multiplet (49) \(\lambda\) 5317 line requires a model with disk density parameter \(\rho_0\) of \(1.0 \times 10^{-9}\) g cm\(^{-3}\) and a power-law index \(n\) of 1.5 seen at 75° for a 25 R\(_{\odot}\) thick and turbulent disk. We note that the lines of Ca\(\Pi\) and Fe\(\Pi\) prefer the turbulent disk model as these models tend to produce broader and stronger lines.

To investigate what range of disk radii contribute to the formation of the lines considered, the cumulative intensity produced by each emission line was plotted against the radius of the disk for the models listed in Table 3, as shown in Figure 7. To do this, a face-on synthetic image (\(i = 0°\)) was produced using the best-fit disk density model for each line. For each \(i = 0°\) image, the intensity was integrated over the total width of the line. Then, the integrated intensity out to a disk radius of \(R\) can then be defined as

\[
C(R) = 2\pi \int_{R_{\odot}}^{R} I(R') R' \, dR',
\]
where \( I(R) \) is the wavelength integrated line intensity at distance \( R \), and \( R_\ast \) is the stellar radius, assumed to be the inner edge of the disk. Then \( C(R)/C(R_\text{disk}) \) can be plotted versus \( R \) to determine how the line intensity is accumulated by the disk. In the Figure 7, a solid black line shows the cumulative fraction of 0.9. It is important to keep in mind when looking at this figure that the disk density model particular to each transition has been used and not a single disk density model. This explains, for example, why \( C = 1 \) is reached at 50 \( R_\ast \) for \( \text{H}_\alpha \) but 25 \( R_\ast \) for the remaining lines. In order to reproduce the strength of the \( \text{H}_\alpha \) emission, an extended emission region is required, reaching 90% of the emission at \( 40 R_\ast \). However, 90% of the emission for \( \text{Ca} \) and \( \text{Fe} \) \( (\lambda 5169) \) originates from the innermost 10 \( R_\ast \) of the disk, and \( \text{H}_\beta \) and \( \text{Fe} \) \( (\lambda 5317) \) are intermediately reaching 90% complete at \( \sim 20 R_\ast \).

This figure also illustrates how the disk might be structured in order to produce all of the line profiles by having the disk’s equatorial density vary in a more general way than as a single power law (see Section 7).

### 5.2. Global Fits

Given that different disk density models are required to best fit each observed profile for BD+65 1637, the next logical step was to see if a single disk density model could fit all of the lines in a reasonable (as opposed to optimal) manner. This will also assist us in deciding how to move forward in looking for a more general density model that would better describe the structure of the disk. To find the single best model, we minimized the sum of all the individual \( \mathcal{F} \):

\[
\mathcal{F}^{\text{total}} = \sum_{i=1}^{6} w_i F^i \tag{7}
\]

where \( i \) ranges over the six lines considered. Initially, we set \( w_i = 1 \) for all \( i \) to weigh all six lines equally. The model that

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**Table 3**

Best-fit Model Parameters for Individual Emission Lines and the Global Models with and without Ca II

| Emission Line          | Disk Density \( \rho_0 \) (g cm\(^{-3}\)) | Power Law Index \( n \) | Inclination \( i \) (°) | Disk Radius \( R_\text{disk} \) (\( R_\ast \)) | Model Type              |
|------------------------|-------------------------------------------|--------------------------|--------------------------|-----------------------------------------------|--------------------------|
| \( \text{H}_\alpha \)  | \( 3.2 \times 10^{-12} \)                | 2.0                      | 60                       | 50                                            | Thin                     |
| \( \text{H}_\beta \)   | \( 1.0 \times 10^{-11} \)                | 2.0                      | 45                       | 25                                            | Thin                     |
| \( \text{Ca} \) IR triplet (8542 Å) | \( 1.0 \times 10^{-10} \) | 2.0                      | 60                       | 25                                            | Thin & Turbulent         |
| \( \text{Fe} \) (5169 Å) | \( 1.0 \times 10^{-10} \)                | 3.0                      | 45                       | 25                                            | Thick & Turbulent        |
| \( \text{Fe} \) (5317 Å) | \( 1.0 \times 10^{-9} \)                 | 1.5                      | 75                       | 25                                            | Thin & Turbulent         |
| Global                 | \( 1.0 \times 10^{-10} \)                | 2.0                      | 45                       | 50                                            | Thin                     |
| Global (w/o Ca II)     | \( 1.0 \times 10^{-10} \)                | 3.0                      | 45                       | 50                                            | Thin & Turbulent         |

*Note. No best-fit model for the \( \text{He} \) (\( \lambda 6678 \)) absorption line is given because it is of photospheric origin.*
was found to best reproduce all the observed line profiles in this manner is listed in Table 3.

Figure 8 shows all six synthetic emission lines produced for this model as compared to the observed line profiles. The density parameters are a power-law index $n$ of 2 and a disk density parameter $\rho_0$ of $1.0 \times 10^{-10}$ g cm$^{-3}$ with a 50 $R_*$ thin disk, as seen at 45°. As illustrated in the figure, the Balmer lines can be reproduced approximately in strength but are too narrow at the base; the metal lines are either too strong (Fe II lines) or too weak (Ca II IR triplet) compared to the observed emission lines. The mismatch of the shape of the Balmer line profiles, particularly in the wings, indicates that the material is not distributed correctly in the disk by a single power law. The synthetic line profile for the Ca II IR triplet $\lambda 8542$ is weaker in strength, as well as narrower in velocity, than the observed line profile. It does, however, produce a double-peaked shape. Both of the synthetic Fe II line profiles have approximately the same shape and strength when compared to each other; however, the width of the wings are different: Fe II (42) $\lambda 5169$, Fe II multiplet (49) $\lambda 5317$, and He I (\lambda 6678) for BD+65 1637, which were modeled using Béray. The global best-fit model parameters used for this figure can be found in Table 3.
regions may be required to reproduce the observed line (as seen in Section 5.1). Finally, He I shows absorption with some central emission, sometimes called a central quasi emission (CQE) feature (Hanuschik 1995). Because the star and disk system is seen at 45°, the CQE can be attributed to the disk partly blocking the direct stellar radiation.

Figure 9 illustrates where the intensity is produced by these lines for this single power-law model by plotting $C(R)$, Equation (6), as a function of disk radius. It can be seen that, in all the cases, 90% of the emission now is coming from inside 40 $R_*$ (or 1.25 AU). This figure also illustrates that the Ca II IR triplet ($\lambda 8542$) is produced in the innermost 10 $R_*$ of the disk; the H$\beta$ ($\lambda 4861$) and the Fe II multiplets ($\lambda 5169$ and $\lambda 5317$) produce most of their emission within 20 $R_*$, and H$\alpha$ emission is produced throughout the disk, with 90% coming from within 40 $R_*$. A comparison of Figures 7 and 9 shows that the Ca II IR triplet forms in the innermost part of the disk, while H$\alpha$ forms throughout the disk. The emission from H$\beta$ and Fe II multiplets are intermediate and emerge from the same region for the global model.

In addition to constraining the density distribution in the disk for a model that is consistent with the observations, the global model can be used to give insight to the temperature structure of the disk. Figure 10 illustrates the temperature distribution predicted by BEDISK in a thin disk for a model with a disk density parameter $\rho_0$ of 1.0 $\times$ 10$^{-10}$ g cm$^{-3}$ and a power-law index $n$ of 2. The upper plot illustrates the temperature structure in the entire disk, which generally ranges from 5500 to 10,000 K. The bottom log–log plot shows the region close to the stellar surface where temperatures in the disk can reach as high as 14,000 K. When combined with the density structure, this provides valuable information on the structure of the inner, gaseous disk. For example, even at 110 $R_*$, the coolest temperature predicted in the equatorial plane, $\approx$5500 K, is still above the dust sublimation temperature.

Finally, the disk density parameters can be used to estimate the total mass of the inner gaseous disk. The mass is estimated to be $9.3 \times 10^{26}$ gm ($5.7 \times 10^{-8} M_\odot$ or $4.6 \times 10^{-7} M_\odot$), while the scale height $H$ of the disk at the stellar surface was estimated to be $1.6 \times 10^{10}$ cm ($3.5 \times 10^{-2} R_*$ or 0.23 $R_\odot$).
It was noticed in the fitting process that the metal lines, especially the Ca II IR triplet, require a high disk density parameter \( \rho_0 \) with a low value of the power-law index \( n \). Ca II is generally not well reproduced by the models that otherwise are found to work reasonably well for a single power law. For this reason, we searched for global fits that exclude the Ca II line by setting \( w_i = 0 \) for \( F_{\text{Ca II}} \) in Equation (7). The result can be seen in Figure 11. The details for this model can be found in Table 3, and this model is able to reproduce the emission in the two Fe II lines reasonably well. The Balmer lines are not strong enough to match the strength of the observed profile. However, they match well when the width of the lines is considered. The same is the case for He I line. The Ca II IR triplet for this model shows hardly any emission, and this indicates that Ca II is likely formed in a different region, while all the other lines can be reasonably produced by a disk with a single power law with \( n = 3 \). The mass of this disk was estimated to be \( 4.8 \times 10^{25} \text{ gm} (2.3 \times 10^{-9} M_\odot \text{ or } 4.6 \times 10^{-7} M_\odot) \).

In order to illustrate where these lines are formed in this model that excludes Ca II, and if there is any similarity to the previous global model, Figure 12 was constructed. The plot shows H\( \alpha \) forming almost throughout the entire disk with 90% of the emission coming from inside the 30 \( R_\odot \). H\( \beta \), Fe II (\( \lambda 5169 \)), and Fe II (\( \lambda 5317 \)) can be seen forming within 15 \( R_\odot \).
When compared to the previous global fit model (Figure 9), all of the emission lines except H\(\alpha\) in this model are produced within half the radius.

Thus, from all three models considered, it can be concluded that the H\(\beta\) and the metal lines form in the innermost region of the disk, while the H\(\alpha\) forms in an extended region covering nearly the entire disk.

5.3. The Near-IR SED

As mentioned in Section 4, BERAY can also calculate continuum SEDs of the star-disk system. In order to assess how comparable these models are to the available observations, a SED was produced for the global disk model of Table 3 and compared to the observed SED for BD+65 1637 found in Hillenbrand et al. (1992). This is illustrated in Figure 13. The star’s continuum SED, i.e., in the absence of a disk, is also shown. As can be seen in the figure, the global disk model produces a brighter SED at longer wavelengths compared to the observed SED. This suggests that a thinner and less dense disk than those considered here is required in order to be comparable to the observed SED. However, it is important to note that the SED observations were taken more than 16 years prior to the observations of the emission lines used in the analysis here. H\(\alpha\) has been previously reported to be variable in EW (−45 to −26 A), so the comparison of the disks over a long period of time should be considered with caution.

6. UNIQUENESS OF DISK MODELS

As described in Section 5, the fitting procedure used the values of the figure of merit \(F\) for all of the lines, found by using Equation (7), to build a set of the global, best-fit models. In Section 5.1, it was noted that although one model is the best fit for each line profile, more than one model can fit a particular line profile within a certain range of \(F\). Table 4 gives the number of models for each emission line that have \(F < 1.25F_{\text{min}}\) (the top 25% best fits). It can be seen from the table that the number of models within this range varies from one model for Ca II to seven models for He I. Figure 14 illustrates where all these models fall in the explored parameter space of disk density \(\rho_0\) and power-law index \(n\). If a single model is found, it is represented by a point. For two models, a line connecting the two models is shown on the figure. For three models, a triangle is used. For more than three models, an ellipse is shown that encloses most of the models. For He I, a photospheric feature, the region that represents the models that reproduce no disk emission, is shown with an arrow. It is important to keep in mind that this figure represents only the values of the power-law index \(n\) and disk density \(\rho_0\); the rest of the parameters for the models (\(R_\text{disk}\) and \(i\)) are not distinguished. As the figure illustrates, some, but not all, of the models overlap, again illustrating that no common region is found where all of the lines can be well fit by a single power-law model. However, two general regions on the plot can be separated, one for the Balmer lines, which require relatively low densities, and another region of higher densities, dominated by the metal lines Fe II and Ca II. This figure confirms the earlier observation that the metal lines require higher densities.

Given that a single model is not able to reproduce the observed line profiles, understanding how different power-law indices and disk densities for the disk affect the overall line strengths is important. To this end, the EW for each line as a function of disk density parameter \(\rho_0\) was plotted for models with a 50 \(R_\odot\) disk size seen at an inclination of 45°. Figures 15 and 16 show the results for the four disk types considered here:
Figure 15. Equivalent width (Å) of each individual line as a function of disk density (log(ρ₀)) for three different power-law indices n for models of radius 50 Rₖ seen at a 45° inclination angle. The solid black line in each panel is the observed equivalent width. Panel (a) uses the thin and turbulent disk model. Panel (b) uses both thin and turbulent disk models.

(a) Thin disk model

(b) Thin & Turbulent disk model

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Figure 16. Equivalent width (Å) of each individual line as a function of density (log(\(\rho_0\))) for three different power-law indices \(n\) for models of radius 50 \(R_\odot\) seen at a 45° inclination angle. The solid black line in each panel indicates the respective observed equivalent width.

(a) Thick disk model

(b) Thick & Turbulent disk model

\(\text{H}\alpha\)  \(\text{H}\beta\)  \(\text{CaII} (8542 \text{ Å})\)

\(\text{FeII} (5169 \text{ Å})\)  \(\text{FeII} (5317 \text{ Å})\)  \(\text{HeI} (6678 \text{ Å})\)
thin, thick, and turbulent, and thick and turbulent. Models with disk density parameter $\rho_0$ of $10^{-13}$, $10^{-12}$, $10^{-11}$, $10^{-10}$, and $10^{-9}$ g cm$^{-3}$ and power-law indices $n$ of 1, 2, and 3 are shown. In each figure, the black line indicates the observed EW for that particular emission line in the CFHT ESPaDOnS spectrum from 2006.

Even as no single ($\rho_0$, $n$) combination is able to match the observed EW of all the lines, some models match the observed EW for more than one line. For example, in Figure 15(b) for a thin and turbulent disk, the EWs of two Fe II lines and the He I line match the observed EW for the disk density $\rho_0$ of $10^{-10}$ g cm$^{-3}$ and power-law index $n$ of 3. The EW of H $\alpha$ for the same model is very close to the observed EW. However, the EWs of H $\beta$ and Ca II ($\lambda 8542$) are weaker for the same model when compared to the observations.

In general, the EWs increase with disk density $\rho_0$ to a maximum value, and then decline as the lines become saturated while the continuum continues to increase, weakening the EW. A good example of this can be seen for the power-law index $n$ of 1, where a sharp increase to a peak and then decline can be clearly seen for each line. In general, the maximum EW moves to a higher disk density $\rho_0$ as the power-law index $n$ increases. Also illustrated in the plots, the addition of turbulence increases the strength of the lines. The thicker disk models generally show a large number of models with EW equal to or greater than the observed EW for all of the lines. For example, for a power-law index $n$ of 2, the models with thicker disks show stronger EWs and a stronger rise in the EW as the density increases.

7. DISCUSSION

Good matches for all of the observed individual emission-line profiles for BD+65 1637 have been found in the large library of synthetic models. However, the diversity of the models in Table 3, and the failure to find one global model that fits all the observed line profiles well, seems to indicate that the density distribution within the inner gaseous disk of BD+65 1637 cannot be of the simple form of a single power law (Equation (1)) with power-law index $n > 0$. The differences between the best fits for individual lines and global fits suggest that the structure of the disk is more complex than a single power law. The idea that different density structures might be at play is supported by Figure 7, which illustrates how the variations in the structure of the disk can produce all of the emission lines. In addition, the metal emission lines (Ca II and Fe II) seem to require a denser region for their formation as compared to the Balmer lines.

The SED of the best-fit, global model overpredicts the near-IR excess compared to the available observations. However, it is important to note that the SED is very sensitive to the underlying (assumed) stellar temperature in the optical/NIR and hence should be viewed with caution. In general, the line modeling serves as a more powerful tool in inferring the structure of the gaseous disk found close to the star. The comparison between the observed and computed SEDs was performed merely as a byproduct of the line modeling study performed here, and, perhaps most importantly, the SED and line spectra observations are separated by 16 years.

A general trend was noticed while manually searching for the best fit to the line profiles that the metal lines required higher densities compared to the Balmer lines in order to reproduce the observed line profiles. The addition of turbulence to these models made the lines stronger and broader.

Finally, the analysis of observed and synthetic line profiles and their fits suggest that BD+65 1637 is seen at an angle between 45° and 60°.

Decretion disks around classical Be stars are generally modeled with a single power law for the density structure, as mentioned in Section 4 and Sigut & Jones (2007). When hydrodynamic models are used, a more complex density structure is predicted (Carciofi 2011). As shown by the current work, HAeBe stars do not seem to follow a single power law for their disk structure, perhaps as expected. Thus, a disk with density described by several different power laws in different radial zones might be able to provide a better global fit to all the lines considered. Finally, we assumed that the disk extends all the way to the stellar photosphere, so another possible area of exploration would be to have the disk start farther away from the star. If the star is not actively accreting or has sporadic events of accretion, the disk may not extend all the way to the star. Many recent studies such as Vink (2015) and Vink et al. (2005) have suggested that it may be possible to constrain the presence of such an inner hole radius using polarimetry.

8. CONCLUSIONS

This study of the inner gaseous disk of the Herbig B2e star, BD+65 1637, by modeling the optical and near-infrared emission lines, has led to three key findings:

1. All of the observed emission lines considered in this study can be reproduced with models that use photo-ionizing radiation of the central star as the sole energy source for the disk.
2. Despite being able to reproduce the observed emission lines individually, no model based on a single power law for the equatorial density was able to reproduce all of the emission lines simultaneously. More complex density models are required to generate a consistent disk structure for this star.
3. The metal lines (Ca II, Fe II) require higher densities when compared to the Balmer lines.

In addition to testing more general disk density models and investigating the effect of an inner hole in the disk, we have three more B2-type stars and four B0-type stars in the database (Alecian et al. 2013). Applying the same modeling technique as in this work, we hope to further understand the overall geometry and structure of the disks around early-type HBe stars. For the next paper in this series, the B2-type stars HD 76534, HD 216629, and HD 114981 will be analyzed.

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