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DISKS SURROUNDING MASSIVE STARS: WHEN COMPUTATIONAL MODELS ARE CONFRONTED BY OBSERVATIONS

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RESUMEN

Las estrellas masivas se encuentran insertas en materia gaseosa circunstelar; a veces también se encuentra polvo y moléculas. Aunque los discos son a veces demasiado pequeños para ser detectados directamente, este material puede ser detectado en el espectro de la radiación que observamos de la estrella. A menudo, el material circunestelar posee una distribución tipo disco, pero el proceso físico que forma y mantiene estos discos no es bien entendido. Las estrellas Be son un ejemplo de rotadores rápidos, estrellas calientes, cuyo espéctro en longitudes de onda óptica muestra ambas líneas de hidrógeno en emisión y frecuentemente, líneas de emisión de metales una vez ionizados, debido a la presencia del disco.

Hemos calculado modelos teóricos computacionales de discos circunestelares de estrellas Be, usando un código que incorpora un número de mejoras sobre tratamientos previos de la estructura térmica del disco, incluyendo una composición química realista. Estos modelos pueden predecir los perfiles de línea espectrales y anchos equivalentes, la distribución espectral de energía y la polarización del continuo. Los modelos con estructura térmica precisa y campos de radiación son esenciales para interpretar correctamente las observaciones. Estos modelos pueden también predecir imágenes en el plano del cielo en importantes longitudes de onda y por lo tanto están idealmente adecuados para compararlos con observaciones interferométricas. Demuestro que nuestros modelos pueden ser restringidos por comparación directa con observaciones interferométricas ópticas para la región que emite Hα y por perfiles de línea Hα contemporáneos. Las comparaciones detalladas de nuestras predicciones con interferometría y espectroscopía de Hα entregan ajustadas restricciones a los parámetros libres del modelo para estos sistemas estrella-disco.

ABSTRACT

Many massive stars are embedded within gaseous circumstellar matter; sometimes dust and molecules are also present. Though the disks are sometimes too small to be detected directly, this material can be detected in the spectrum of radiation we observe from the star. Often, the circumstellar material has a disk-like distribution, but the physical processes that form and maintain these disks are not well understood. Be stars are an example of rapidly rotating, hot stars, whose spectra at optical wavelengths show both hydrogen emission lines and, frequently, emission lines from singly ionized metals due to the presence of a disk.

We have computed theoretical models of circumstellar disks for Be stars, using a non-LTE radiative transfer code which incorporates a number of improvements over previous treatments of the disk thermal structure, including a realistic chemical composition. These models can predict spectral line profiles and equivalent widths, spectral energy distributions, and continuum polarization. Models with accurate thermal structures and radiation fields are essential to interpreting observations correctly. These models can also predict images on the plane of the sky in important wavelengths and are therefore ideally suited for comparison with interferometric observations. I will demonstrate that our models can be constrained by direct comparison with optical interferometric observations for the Hα emitting region and by contemporaneous Hα line profiles. Detailed comparisons of our predictions with Hα interferometry and spectroscopy place very tight constraints on the model free parameters for these star-disks systems.

Key Words: stars: emission-line, Be — stars: individual ($\boldsymbol{\chi}$ Ophiuchi, $\boldsymbol{\kappa}$ Draconis) — techniques: interferometric

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1. INTRODUCTION

Be (B-emission) stars are rapidly rotating B stars surrounded by a disk-like distribution of gas. The observed emission is due to radiative recombination within the gaseous disk. The variation of the width of these emission lines as a function of the stellar rotation velocity is consistent with the assumption that one is viewing an equatorially concentrated, rapidly rotating, slowly expanding, disk-like circumstellar envelope at a variety of inclination angles for different stars. These stars also have a high degree of linear polarization due to scattering of light off ionized matter, further evidence of a non-spherical distribution of circumstellar material.

Despite decades of research, there are no models which successfully explain the existence of this circumstellar material. Struve (1931) proposed the first model which suggested that the presence of the disk is due to rapid stellar rotation. This general view of a flattened circumstellar disk has been confirmed for several stars by means of direct imaging of the circumstellar disk, using either optical, infrared, and/or radio interferometry. (See Quirrenbach et al. 1997). More recently, interferometric observations that can spatially resolve the disk are becoming available. See for example Chesneau et al. (2005); McAlister et al. (2005); Tycner et al. (2006). We know that Struve's model is too simplistic; many additional models have been proposed which combine rapid rotation with other mechanisms such as stellar pulsation (Rivinius et al. 2003), wind compressed disks (Bjorkman & Cassinelli 2003), and magnetically confined disks (Donati et al. 2001). None of these models have been completely successful (Porter & Rivinus 2003).

Many of the theoretical models used in the past to predict observables from these systems have, by necessity, required the use of a large number of free parameters, such as, disk opening angle, density distribution, temperature, and disk geometry. For the work presented in this paper, the non-LTE radiative transfer code of Sigut & Jones (2007) is used to predict the flux in the Hα emitting region, the Hα profiles, and the other predicted observables. The code has a number of improvements over previous disk models available in the literature. For example, the disk has a realistic chemical composition that is important for computing heating and cooling rates. This improvement combined with the enforcement of radiative equilibrium results in a self-consistent temperature distribution for the disk. It is crucial to determine the state of the gas accurately, so that observations can be interpreted correctly eventually leading to the development of successful dynamical models.

In this work, we assume a power-law density distribution within the disk in the radial direction, with R as the distance from the centre of the central star. This density distribution can be set by only two free parameters, the power-law index, n, and the assumed density at the stellar surface, ρ_o. The density distribution in the vertical direction (perpendicular to the equatorial plane), Z, is approximately hydrostatic. This simple density distribution is given by:

$$\rho(R,Z) = \rho_0 \left(\frac{R_\star}{R}\right)^n e^{-\left(\frac{Z}{H}\right)^2} , \qquad (1)$$

where H is the scale height in the Z direction. (Please see Sigut & Jones 2007 for greater detail).

Two-dimensional images of the predicted energy distribution in the plane of the sky can be produced in any wavelength regime of interest. These images can then be transformed for direct comparison with interferometric observations. These comparisons are used to place tight constraints on the density parameters, n and ρ_o.

Here, we present a review of our work for the Be stars, χ Oph (B2 Ve), and κ Dra (B6 IIIpe). The investigation for the disk of χ Oph resulted in a best-fit disk model to be selected by comparison with interferometry alone. However, for the case of κ Dra, a preferred model could not be selected on the basis of interferometry alone, and contemporaneous spectroscopy in the same wavelength regime is used to remove the degeneracy. This review aims to demonstrate, that although the information obtained from Hα spectroscopy and Hα interferometry is complimentary, additional new information can be obtained by combining the results of both of these techniques.

2. OBSERVATIONS

The interferometric observations were obtained at the Navy Prototype Optical Interferometer in Flagstaff Arizona in June 2006 for χ Oph, and in February and March 2007 for κ Dra. We have data for multiple baselines for each star, ranging in length from 18.9m to 53.2m. The contemporaneous spectroscopy was obtained at the Lowell Observatory's John S. Hall Telescope. Please see Tycner et al. (2008) and Jones et al. (2008) for greater details for χ Oph, and κ Dra, respectively.

3. RESULTS

For each star, hundreds of models are computed for pairs of n and ρ_o. Typically for Be star disks, the values of n cited in the literature are in the range

2 to 3.5. This expected range is based mainly on previous results based on models fitted to the IR continuum (Waters 1986). In order to ensure that our search includes all reasonable pairs of n and ρ_o, we construct our grids for n ranging from 1.8 to ~ 5 and with ρ_o from $\sim 10^{-12}$ g cm^{-3} to $\sim 10^{-8}$ g cm^{-3}. For example, the grid of models for κ Dra can be found in Jones et al. (2008), Figure 1.

The integrated model intensity for each model is computed over a 15nm spectral region centered at Hα for consistency with the interferometry. We note that this predicted intensity distribution is assumed to be axisymmetric with no over-dense or under-dense regions within the disk. Finally, the model intensities are Fourier transformed in preparation for comparison with the interferometry data. We use χ^2 values to assess the goodness of fit between the models and observations.

3.1. χ *Ophiuchi*

This bright, nearby star has pronounced Hα emission and is therefore well suited for a study of its disk properties in this spectral region. The comparison of $\sim$ 500 pairs of n and ρ_o with interferometry using χ^2 values for χ Oph produced one model that was statistically better than all of the others. This best fit model has a reduced χ^2 value of 1.17 and corresponds to a model with $n = 2.5$ and $\rho_o = 2.5 \times 10^{-11}$ g cm^{-3}. The predicted Hα line profile, corresponding to this model, is shown in Figure 1. We note that the calculation of the Hα profile and the predicted visibilities were the result of the same model calculation. The predicted line profile was convolved with a Gaussian of FWHM of 0.656 Å to match the resolving power of the observation.

This best fit model is also compared with observations of the spectral energy distribution in the infrared previously reported in the literature. See Figure 8 of Tycner et al. (2008). The comparison shows reasonable agreement, especially considering the fact that χ Oph is known to be variable. Many Be stars are known to be variable on a variety of timescales (Porter & Rivinus 2003), and this serves to illustrate the need to obtain contemporaneous observations.

3.2. κ *Draconis*

A similar procedure, as described above, was followed for κ Dra. However, when the model predictions were compared with Hα interferometry we found that 25 models had reduced $\chi^2 < 2$. Therefore, further constraints were required to select a best

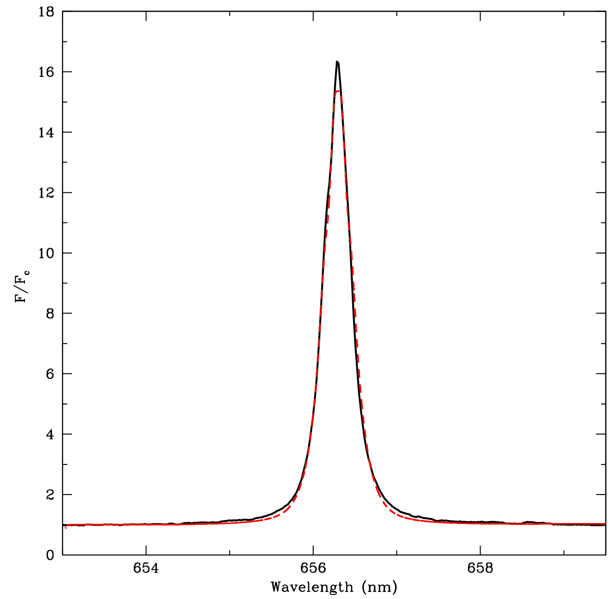

Fig. 1. Hα emission line for χ Oph. The observation was obtained on 2006 June 10 (solid line) and has an equivalent width of -7.1 ± 0.2 nm. The predicted line (dashed line) produced from the best fit model has an equivalent width of -6.6 nm.

fit model. For all of the models for κ Dra, we constructed Hα line profiles and computed their corresponding equivalent widths. There were 14 models with Hα equivalent widths within 2 Å of the contemporaneous Hα observations. Within this subset, 8 models had reduced $\chi^2 < 2$ from comparisons with interferometry. Therefore, this clearly illustrates that although 6 models had an Hα equivalent width that matched the observed equivalent width, these did not have the correct spatial distribution of gas for agreement with interferometry. The Hα line profiles for the subset of 8 were compared to the observed profile and we were able to select a best fit model based on both the spectroscopy and the interferometry comparisons.

Figure 2 shows the observed and predicted Hα lines for κ Dra for the 4 models that correspond to the best fit from both interferometry and Hα modeling. Please see Jones et al. (2008) for a discussion of the errors. We find that the model with $n = 4.2$ and $\rho_o = 1.5 \times 10^{-10}$ g cm^{-3} is the best fit in terms of both the spectroscopy and interferometry.

4. CONCLUSION

We have demonstrated by using detailed models and interferometric observations that the spatial disk density can be determined. Also, we showed that the process for finding the best-fit disk model

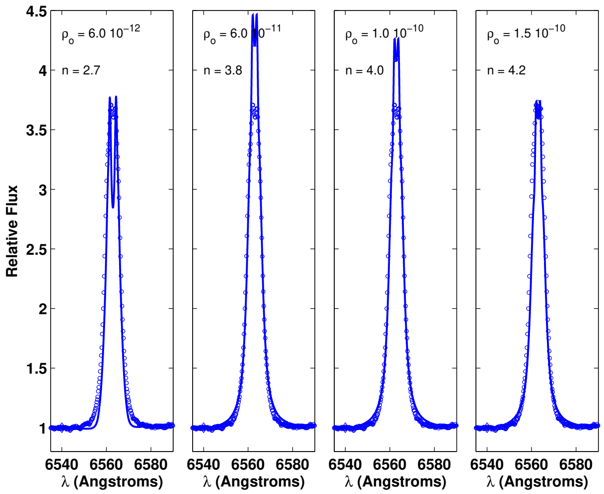

Fig. 2. The observed Hα line for κ Dra compared with predicted lines for the 4 models that correspond to the best fit from both interferometry and spectroscopy. The reduced χ^2 from interferometry for these models are 1.18, 1.29, 1.18, and 1.18, from left to right.

for the Be stars, χ Oph and κ Dra, was necessarily different. For χ Oph a comparison of interferometric observations with models allowed a best fit to be determined and that this best fit model matches other observables. On the other hand, it was necessary to use *both* Hα interferometry and spectroscopy for κ Dra in order to remove the degeneracy and find a preferred model.

In future, we plan to extend the work by including more sophisticated forms of the disk density distribution eventually expanding our analyzes to include dynamical models.

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DISCUSSION

Oliver Chesneau: *You have presented the χ^2 valley as a function of ρ_o and n, and the valleys are similar for the Hα and the interferometric data. The fit of the SED's even though the sources are variable, should be considerable help the fitting process. The determination of the n factor is potentially important for constraining the dynamics of the material.* — Yes, I agree the value of n is an important diagnostic. The average value of n could potentially be used to either support or refute particular dynamic models.

Douglas Gies: *I am impressed by the location of the cooler gas in your models: close to the equatorial plane and relatively near to the star. Do you think that this cooler gas might be the source of the shell lines that are observed in spectra of stars with inclinations close to 90°? These lines often correspond to the spectrum of a star cooler than the Be star.* — Yes, the deep absorption troughs at the line centres of shell spectra likely originate from this cooler gas along the line of sight.

D. Baade *I would not worry too much about simultaneaously fitting the wings of the Hα emission and its' overall shape. The former are quite variable and probably signal phases of enhavend star-to-disk mass transfer. But a strong emission line (disk) often shows little or no response to this at later times. Therefore, wings and overall shape of the Hα emission lines may not merit simultaneous modeling.*

Chris Tycner *The Hα emssion was very stable (at the few percent level) during the NPOI interferometric observations. No variations in the wings were detected.*

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