Using Spectropolarimetry to Determine Envelope Geometry and Test Variability Models for Hot Star Circumstellar Envelopes

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Abstract. A survey and monitoring of the spectropolarimetric characteristics of hot stars over the entire visible wavelength range has been carried out over the past 8 years using the HPOL instrument at the Pine Bluff Observatory. Data from these projects is being used to derive physical characteristics of circumstellar envelopes. Quantitative modeling of the polarization, in combination with optical interferometry, has shown that the circumstellar disks of classical Be stars are geometrically thin, consistent with either the wind-compressed disk model or with hydrostatically supported Keplerian disks. Furthermore, spectropolarimetric variability, which is significant in a large fraction of the hot stars observed, provides information about changes occuring in the circumstellar envelope. For example, polarimetric changes provide a critical test of the one-armed density wave models proposed to explain observed V/R variations.

1 Introduction

One of the difficult aspects of trying to study the nature of stellar winds and circumstellar envelopes is that the radiation from the star itself dominates the observed spectrum. Furthermore, the circumstellar environment is rarely directly resolvable with current instruments and techniques. However, polarimetry, and particularly spectropolarimetry, provides a means of probing the disk directly. The polarization in hot stars is produced primarily by electron scattering in the circumstellar environment. This polarized flux is affected by passage through the circumstellar material, via pre- and post-scattering attenuation of the flux. The measured polarization is the ratio of the polarized flux to the total flux (which is dominated by the direct starlight). Because of this, in the ratio the wavelength dependence of the stellar spectrum cancels out. Thus, any residual wavelength dependence of the polarization level is determined by the opacity within the circumstellar envelope. So observations of the polarization (as opposed to the total flux) give insights into the physical conditions of the circumstellar material. Furthermore, the combination of spectropolarimetric observations with other techniques, such as high-dispersion spectroscopy, optical interferometry, and infrared photometry, can provide strong constraints on models of the circumstellar environment.

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2 Spectropolarimetric Observations

We are continuing an optical spectropolarimetric survey and monitoring program for several types of early-type stars (as well as other kinds of objects). The data have been obtained using the Halfwave Polarimeter (HPOL) system (designed by K. Nordsieck) on the 1-m telescope at the University of Wisconsin's Pine Bluff Observatory (PBO) and on the 3.5-m WIYN telescope at Kitt Peak National Observatory. Types of hot stars included in the program include Oe/Be stars, Herbig Ae/Be stars, Wolf-Rayet stars, LBV's, and OB supergiants. An atlas of the Be star observations from 1989-94 is in preparation (Bjorkman, Meade & Babler 1997), and the 1995-98 observations will be published in a follow-up paper. Using these data, we are now developing techniques to analyze the nature of the circumstellar envelopes of these types of stars. In our analysis we also include ultraviolet spectropolarimetry from the Wisconsin Ultraviolet Photo-Polarimeter Experiment (WUPPE), flown on Astro-1 (1990) and Astro-2 (1995). Polarimetric observations of hot stars are also discussed in other papers in these proceedings (c.f. contributions by Rodrigues, Magalhães, and Schulte-Ladbeck et al.)

3 Diagnostics of Circumstellar Disks

Recently we have used spectropolarimetry to diagnose the physical geometry and density of circumstellar disks around classical Be stars (Wood, Bjorkman, & Bjorkman 1997; Quirrenbach et al. 1997). As discussed by Wood et al. (1997), we find that measurement of the peak polarization level observed, together with the size of the polarimetric Balmer jump, provides a diagnostic of both the geometrical thickness of the disk (the opening angle) and the optical depth in the disk, which indicates the density of material. For the case of ζ Tau, our results indicate a very thin disk with an opening angle of only 2.5°, which agrees with predictions of either the wind-compressed disk model (Bjorkman & Cassinelli 1993) or a hydrostatically-supported Keplerian disk. Evidence for the thin nature of the disk is confirmed by a combination of optical interferometry and spectropolarimetry (Quirrenbach et al. 1997), and the good agreement between these two different techniques demonstrates the power of spectropolarimetry to diagnose disks even in cases that cannot be resolved at all.

4 Variability Issues

Combining contemporaneous spectropolarimetric observations with more traditional types of observation, such as spectroscopy, can also place much stronger constraints on proposed models for variability and asymmetries in hot star envelopes. For example, in collaboration with D. McDavid, we have just begun looking at the question of whether the combined Hα spectroscopic

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and polarimetric variations observed in Be stars can be adequately explained by the proposed "one-armed density wave" model (c.f. Okazaki 1997). While this model has been successful as a potential explanation for some cases of observed V/R variations of the Hα line profile, our preliminary analysis indicates that the polarimetric observations are 90° out of phase compared to theoretical predictions based on the one-armed density wave model. This work is still quite preliminary, and we are currently investigating whether a spiral geometry can remove the discrepancy. Other models make definite predictions of polarimetric variability as well, so this type of analysis demonstrates how polarimetric observations can provide a complementary and somewhat independent test of model predictions.

5 Future Work

We intend to continue our development of techniques for using spectropolarimetry as a diagnostic of the nature of the physical nature of circumstellar envelopes. Ultraviolet spectropolarimetric observations, which show pronounced polarization decreases in regions of strong line-blanketing (Bjorkman et al. 1991; 1993), can provide information about the temperature of the disk material. We are pursuing this possibility by developing temperature diagnostics based on reproducing this depolarization effects. We are also continuing to investigate specific models for circumstellar disks by combining spectropolarimetry with other kinds of data. These techniques are applicable to a number of different types of hot stars.

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Discussion

H. Henrichs: Is optical interferometry essential to constrain the disk parameters?
K. Bjorkman: Not essential: one can actually use other types of data instead (such as spectroscopy or IR photometry, in conjunction with spectropolarimetry) to constrain the disk parameters. But interferometry is certainly

the best and most conclusive result to use. The combined interferometry-spectropolarimetry study gave us higher confidence in our ability to determine disk parameters from spectropolarimetric data and modelling. Even without the interferometry, the mid-IR data for ζ Tau also indicates that the thin disk solution is the preferred one.

A. Maeder: Can you get estimates of the disk mass from your observations?

K. Bjorkman: Yes, once we have the density parameters and opening angle, we can estimate the disk mass. For ζ Tau it was on the order of 10^{-9} or $10^{-10} M_{\odot}$.

G. Mathys: Your discussion dealt with the degree of polarisation. Can't you use the polarisation angle to enhance your diagnostics?

K. Bjorkman: Yes, and in fact we did use the position angle information in our analysis. We found that the polarisation position angle is exactly perpendicular to the disk as defined from interferometry. This had long been predicted, but this was the first test of the prediction from combined interferometry and spectropolarimetry. This held true for all four of the stars for which we were able to find an intrinsic position angle (see Quirrenbach et al. 1997), so this gives us confirmation that the polarisation position angle indeed does measure the intrinsic orientation of the disk on the sky for Be stars.

I. Appenzeller: What wavelength is most "helpful" in the case of polarimetry?

K. Bjorkman: For analyses such as the one that I have discussd here, the regions around the Balmer jump, Hα, and even the Paschen jump are most useful. However, higher resolution measurements (i.e., detailed spectropolarimetry) across Hα will also be useful; other groups are doing this sort of work.

M. Friedjung: Is the disk optically thick or thin in the continuum at optical wavelengths?

K. Bjorkman: It is optically thin, at least in the direction perpendicular to the disk. For a photon trying to travel radially outward within the disk, it would appear optically thick.

D. Baade: W. Hummel recently presented persuasive arguments that disks of Be stars may also be warped/tilted. Do you find supportive evidence in your polarimetry?

K. Bjorkman: Well, in some cases we do see a slight variability of the position angle about the intrinsic position angle of the disk. This might be interpreted as evidence for structure or warping in the disk. But the effects are very small and will require better S/N observations and more detailed analysis before we can say anything conclusive.

P. Stee: Are you able to fit the continuum energy flux with the very thin-disk model?

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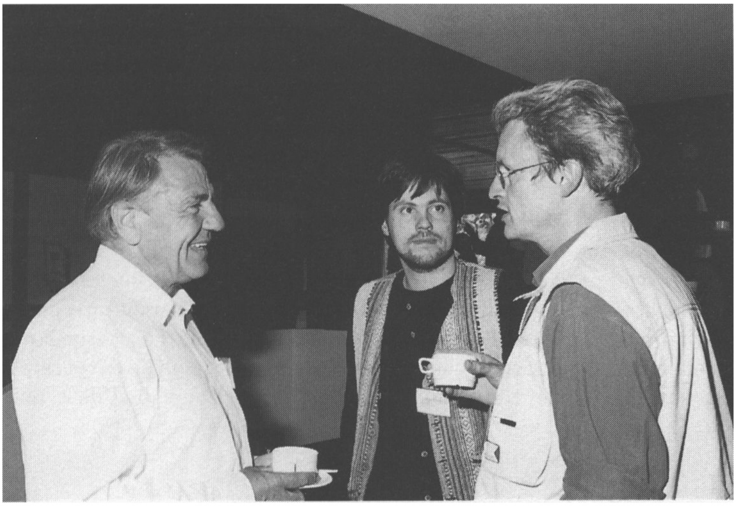
K. Bjorkman: Yes. In fact, in mid-IR the thin-disk solution fits the continuum flux slightly better than the thick-disk solution. Although I did not have time to discuss this here, the flux fitting is discussed in detail in our paper (Wood et al. 1997).



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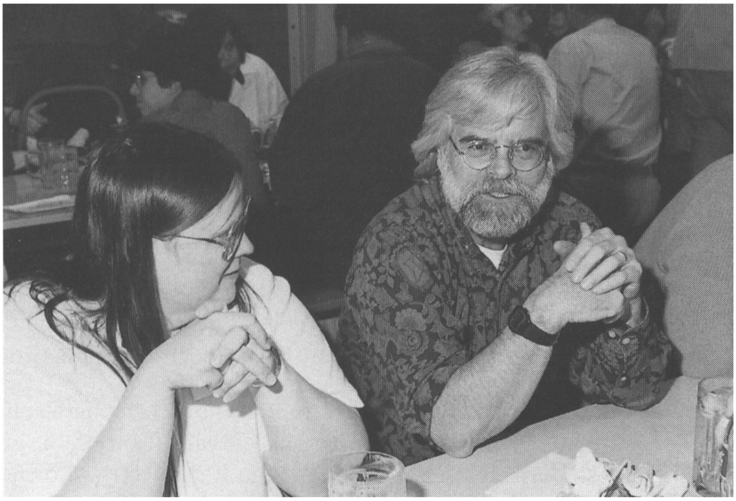

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