TOWARD MAPPING THE DETAILED DENSITY STRUCTURE OF CLASSICAL Be CIRCUMSTELLAR DISKS

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ABSTRACT

The first results from a near-contemporaneous optical and infrared spectroscopic observing program designed to probe the detailed density structure of classical Be circumstellar disks are presented. We report the discovery of asymmetrical infrared emission lines of He I, O I, Fe II, and the Brackett, Paschen, and Pfund series lines of H I that exhibit an opposite V/R orientation (V > R) to that observed for the optical Balmer Hα line (V < R) in the classical Be star τ Tauri. We interpret these data as evidence that the density wave that characterizes τ Tauri’s disk has a significantly different average azimuthal morphology in the inner disk region as compared to the outer disk region. A follow-up multiwavelength observational campaign to trace the temporal evolution of these line profile morphologies, along with detailed theoretical modeling, is suggested to test this hypothesis.

Subject headings: circumstellar matter — stars: emission-line, Be — stars: individual (48 Librae, τ Tauri)

1. INTRODUCTION

Both observational and theoretical evidence indicates that classical Be stars are near-main-sequence B-type stars with gaseous circumstellar disks (e.g., see review by Porter & Rivinius 2003); however, the mechanism(s) responsible for creating these disks are not well understood. Optical spectroscopic studies have uncovered a myriad of different line profile morphologies commonly observed in classical Be stars (Hanuschik et al. 1996), including double-peaked asymmetrical emission lines (McLaughlin 1961; Dachs et al. 1992; Hanuschik et al. 1995). The ratio of the violet (V) to red (R) flux within individual lines, hereafter referred to as a V/R ratio, is observed to vary on quasi-periodic timescales of several to 10 years, as documented for a large set of Be stars by Okazaki (1997). While numerous theories have been proposed to explain this observed phenomenon, as summarized within Hanuschik et al. (1995) these features are most commonly interpreted as evidence of one-armed density waves within these circumstellar disks (Okazaki 1991, 1997; Hanuschik et al. 1995). Note however that the presence of phase lags between polarimetric and Hα observations has led McDavitt et al. (2000) to suggest these waves might be more spiral-like than previously thought. Interferometric studies (Vakili et al. 1998; Berio et al. 1999) have also provided evidence that Be disks deviate from axisymmetry; namely, they have provided evidence of prograde one-armed oscillations in several disks.

It is not uncommon to observe multiple emission lines in a spectrum of a classical Be star that exhibit a V/R asymmetry, and with a few exceptions the same orientation of this asymmetry is observed in all lines. Baade (1985) summarizes several of these exceptions, in which a phase lag appears to be present between optical hydrogen and Fe II lines (Slettebak 1982) and between different lines in the hydrogen Balmer series (Kogure & Suzuki 1984). Baade (1985) also suggested that a phase lag exists between the Hα and hydrogen Pa 15–18 lines of γ Cas presented by Chalalae & Maillard (1983); however, we believe this suggestion is rather dubious given the poor resolution of these data and clear evidence of contamination from nearby lines.

Few moderate-resolution infrared (IR) spectroscopic studies of classical Be stars have been performed to date. Clark & Steele (2000) and Steele & Clark (2001) have investigated a large set of Be stars in the H and K bands at sufficient resolution to begin to search for detailed line profile effects. The first tentative evidence of IR V/R reversals, analogous to the optical V/R phase lags summarized by Baade (1985), was presented in Clark & Steele (2000), who noted that the Brackett γ and He I 2.058 μm lines had opposite orientations in one of their targets.

In this Letter, we present the initial results from a near-contemporaneous, optical and IR spectroscopic observing campaign designed to provide insight into the detailed density structure of classical Be circumstellar disks, and hence diagnose the mechanisms responsible for creating these disks. Detailed modeling of these data, as well as follow-up observations, will be presented in subsequent papers. In § 2 we outline the observational data to be discussed in this work. An analysis and discussion of these data are presented in § 3. Finally, a summary of our main results and suggested follow-up work is presented in § 4.

2. OBSERVATIONS

The IR spectroscopic data presented in this paper were obtained at the 3 m NASA Infrared Telescope Facility (IRTF), using the SpeX medium-resolution spectrograph (Rayner et al. 2003). We used a 0.3′′ × 15′′ slit to provide wavelength coverage from 0.8 to 2.4 μm at R ∼ 2000. Observations of A0 V stars were obtained at ∼15 minute intervals throughout our run, at a similar hour angle and air mass to our science targets, to serve as telluric standards. Further details regarding the telluric correction method commonly applied to SpeX data are presented in Vacca et al. (2003). All observations were reduced using SpeXtool (Cushing et al. 2004). These data were taken during a period of extremely poor weather conditions on Mauna Kea, and thus we have not attempted to perform a rigorous flux calibration. While these observing conditions did introduce small artifacts in wavelength regimes outside of those presented here (see Wisniewski 2005), we are fully confident that the line...
profile morphologies and line-to-continuum ratios of the data presented in this paper are not influenced by the presence of any residual telluric features.

The optical spectroscopic data presented here were obtained at the 1 m telescope of the Ritter Observatory, using its fiber-fed echelle spectrograph. Nine non-overlapping orders, each of width 70 Å, were obtained over the wavelength range 5300–6600 Å at R ~ 26,000. Standard IRAF* techniques were used to reduce these data, including procedures to apply bias, flatfield, and wavelength calibration corrections to all data. Further details regarding the reduction of Ritter data can be found in Morrison et al. (1997). A summary of the optical and IR data to be discussed in this paper is presented in Table 1. Note that we have not corrected any of our optical or IR spectral line data for underlying photospheric absorption components.

3. RESULTS AND DISCUSSION

As demonstrated by our near-contemporaneous optical and IR observations of 48 Librae (see Fig. 1), double-peaked asymmetrical profiles in Be spectra often exhibit the same V/R orientation for all observed transitions. Slettebak (1982) reported phase lags between optical Fe II hydrogen lines in several of his observations of Be stars; we found evidence of a similar phenomenon in our IR observation of the suggested classical Be star NGC 2439 WBBe 1 (see Wisniewski 2005; Wisniewski & Bjorkman 2006).

We obtained two Hα spectra of the well-studied classical Be star ζ Tau (see Fig. 2) 1 month before and 1 month after our IR observations, and note that both Hα profiles exhibit triple-peaked profiles characterized by an overall V < R asymmetry. The V/R period is often several years, so the line profiles are generally stable on timescales of several months (Okazaki 1997). We are confident that ζ Tau exhibited a Hα profile similar to that shown in Figure 2 at the time of our IR observation, and was not in the midst of a cycle of irregular fluctuations of the type described by Guo et al. (1995), based on our long baseline of previous observations of the star. At the resolution of SpeX, ζ Tau’s IR spectrum shows many emission lines characterized by a range of morphologies, including single-peaked profiles, asymmetrical double-peaked profiles, and asymmetrical double-peaked shell profiles. As shown in Figure 2, hydrogen Brackett transitions in these data exhibit shell-like profiles, which are asymmetrical with V < R. Other IR emission lines that have asymmetrical profiles with a V/R orientation similar to the H i Brackett series include O i 0.8446, 1.129, 1.317 μm; Fe ii 1.086, 1.113 μm; He i 1.083 μm; H i Paschen γ and β; and the H i Pfund lines at 2.382, 2.392, 2.403 μm. These data exhibit a fundamentally different V/R morphology than our near-contemporaneous Hα profile.

As ζ Tau is known to experience cyclical V/R variations, likely due to the presence of a density wave in its disk (Okazaki 1997), we suggest that the observed opposite V/R orientation of the IR lines and Hα can be explained by the presence of a density wave in the disk that has a significantly different average azimuthal morphology (e.g., a spiral wave), combined with different loci for line formation. This idea is illustrated in Figure 3, where we show schematically the disk of ζ Tau with a one-armed spiral density perturbation: note that lighter shading denotes regions of density enhancement while darker shading denotes density decrements. The H i IR lines are much more optically thin than the optical lines and hence they form within the inner disk, while the optical H i lines originate from a much larger area. As a result of the different azimuthal properties of the disk with respect to the distance from the star, in certain phases of the V/R cycle the net density enhancement

![Image](https://example.com/fig1.png)

**Fig. 1.** Left: Hα spectrum of 48 Lib observed on 2004 March 11 exhibits an asymmetrical profile characterized by V > R. Right: A near-contemporaneous infrared spectrum obtained on 2004 March 6 also exhibits hydrogen Brackett lines having asymmetrical profiles with V > R. The agreement between the orientation of these line profile morphologies is the standard scenario expected in observations of classical Be stars.

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### Table 1

| Object | Observatory | Date       | Exposure Times |
|--------|-------------|------------|----------------|
| ζ Tau  | I           | 2004 Mar 5 | 60             |
|        | R           | 2004 Feb 28| 1200           |
| 48 Lib | I           | 2004 Mar 6 | 150            |
|        | R           | 2004 Mar 11| 3600           |

**Notes:** Some properties of our observational data are summarized. The observational abbreviation "I" corresponds to IRTF data and "R" corresponds to Ritter data. For our infrared observations, the listed exposure times are the total effective integration times of the science targets and do not represent the individual exposure times at each of the telescope nod positions described in the text.

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of the inner disk may occur in an opposite side (with respect to the line of sight) to the net density enhancement of the entire disk, thus producing line profiles with opposite V/R ratios. For instance, in Figure 3 the V > R morphology of Br-12 is produced by a net density enhancement in the inner disk region that is moving toward the observer, and the V < R morphology of Hα is produced by a net density enhancement in the outer disk region that is moving away from the observer.

Carciofi & Bjorkman (2006) and Carciofi et al. (2006, 2007) outline a new Monte Carlo code for solving the radiative transfer in the circumstellar disks of Be stars. This fully three-dimensional non-LTE Monte Carlo code produces a self-consistent determination of the hydrogen level populations, electron temperature, and gas density of a circumstellar disk, given a prescription of the central star and assuming a static, nearly-Keplerian disk with a given mass loss rate, truncation radius, and a prescription for the gas viscosity. In Carciofi et al. (2005) the authors used this code to study the circumstellar disk of ζ Tau. Following Wood et al. (1997) they adopted a luminosity class of IV and a spectral type of , which B2.9/H115060.4 corresponds to an effective temperature of 19,000 K and a stellar radius of 5.6R⊙. Assuming an outer disk radius of 100R⊙ and a mass-loss rate of 12.510−11M⊙yr−1 the authors were able to fit the observed SED from visible to mid-IR wavelengths, and optical (3200–10500 Å) spectropolarimetry. Using this model, we calculated intensity maps of Hα and Br-12 for ζ Tau which, as seen in Figure 4, illustrate that Br-12 is formed in the inner disk ( ) whereas Hα is produced over a much more extended region, thereby confirming our previous assertion that our optical versus IR Hα data probe distinctly different disk regions. Future iterations of the model will incorporate complex density profiles, such as one-armed waves, which will enable us to test our exploratory discussion in a more quantitative manner.

We note that reversals have been predicted by at least one other theory in the refereed literature. Waters & Marlborough (1992) predicted instances in which a ratio of in Hα line would reverse to a ratio in IR lines, due to line self-absorption in the inner region of edge-on disks. However, the presence of this reversal depends critically on the existence of a large expansion component in the disk velocity at the location where the lines form, an unlikely scenario given the very small radial velocities now believed to characterize inner disk regions (Rivinius et al. 1999; Hanuschik 2000; Porter & Rivinius 2003).

4. SUMMARY AND FUTURE WORK

We have presented the first results of near-contemporaneous optical and IR spectroscopic observations of classical Be stars. We report the discovery of asymmetrical infrared emission lines (He i, O i, Fe ii, and the H i Paschen, Brackett, and Pfund series) in ζ Tau that have oppositely oriented V/R ratios to that seen at Hα. We suggest these data indicate that the density...
Fig. 4.—Carciofi & Bjorkman (2006) model images of the \( \xi \) Tau disk at H\( \alpha \) (top) and H\( \text{I} \) Br-12 (bottom). The scale of these images is 40\( \text{R}_\odot \) (\( \sim 224 \text{R}_\odot \)). These images clearly demonstrate that H\( \alpha \) is produced over a much larger disk area, whereas H\( \text{I} \) Br-12 is produced from a more inner disk region.

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REFERENCES

Baade, D. 1985, A&A, 148, 59
Berio, P., et al. 1999, A&A, 345, 203
Carciofi, A. C., & Bjorkman, J. E. 2006, ApJ, 639, 1081
Carciofi, A. C., Bjorkman, J. E., & Bjorkman, K. S. 2005, in ASP Conf. Ser. 343, Astronomical Polarimetry: Current Status and Future Directions, ed. A. Adamson et al. (San Francisco: ASP), 417
Carciofi, A. C., Bjorkman, J. E., Miroshnichenko, A. S., Magalhães, A. M., & Bjorkman, K. S. 2007, in ASP Conf. Ser. 361, Active OB Stars: Laboratories for Stellar and Circumstellar Physics, ed. S. Owocki, S. Stefl, & A. Okazaki (San Francisco: ASP), in press
Carciofi, A. C., et al. 2006, ApJ, 652, 1617
Chalabaev, A., & Maillard, J. P. 1983, A&A, 127, 279
Clark, J. S., & Steele, I. A. 2000, A&AS, 141, 65
Cushing, M. C., Vacca, W. D., & Rayner, J. T. 2004, PASP, 116, 362
Dachs, J., Hummel, W., & Hanuschik, R. W. 1992, A&AS, 95, 437
Guo, Y., Huang, L., Hao, J., Cao, H., Guo, Z., & Guo, X. 1995, A&AS, 112, 201
Hanuschik, R. W. 2000, in IAU Colloq. 175, The Be Phenomenon in Early-Type Stars, ed. M. A. Smith, H. F. Henrichs, & J. Fabregat (ASP Conf. Ser. 214; San Francisco: ASP), 518
Hanuschik, R. W., Hummel, W., Sutorius, E., Dietle, O., & Thimm, G. 1996, A&AS, 116, 309
Kogure, T., & Suzuki, M. 1984, PASJ, 36, 191
McDavid, D., Bjorkman, K. S., Bjorkman, J. E., & Okazaki, A. T. 2000, in IAU Colloq. 175, The Be Phenomenon in Early-Type Stars, ed. M. A. Smith, H. F. Henrichs, & J. Fabregat (ASP Conf. Ser. 214; San Francisco: ASP), 460
McLaughlin, D. B. 1961, JRASC, 55, 73
Morrison, N. D., Knauth, D. C., Mulliss, C. L., & Lee, W. 1997, PASP, 109, 676
Okazaki, A. T. 1991, PASJ, 43, 75
———. 1997, A&A, 318, 548
Porter, J. M., & Rivinius, T. 2003, PASP, 115, 1153
Rayner, J. T., et al. 2003, PASP, 115, 362
Rivinius, Th., Stefl, S., & Baade, D. 1999, A&A, 348, 831
Slettebak, A. 1982, ApJS, 50, 55
Steele, I. A., & Clark, J. S. 2001, A&A, 371, 643
Vacca, W. D., Cushing, M. C., & Rayner, J. T. 2003, PASP, 115, 389
Vakili, F., et al. 1998, A&A, 335, 261
Waters, L. B. F. M., & Marlborough, J. M. 1992, A&A, 253, L25
Wisniewski, J. P. 2005, Ph.D. thesis, Univ. Toledo
Wisniewski, J. P., & Bjorkman, K. S. 2006, ApJ, 652, 458
Wood, K., Bjorkman, K. S., & Bjorkman, J. E. 1997, ApJ, 477, 926