*Circumstellar Dynamics at High Resolution*
*ASP Conference Series, Vol. 464*
*A. C. Carciofi and Th. Rivinius, eds.*


# Circumstellar Disk Models: Unraveling the Mysteries of Be Star Disks

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**Abstract.** Continuing improvements in observational technologies are providing a wealth of new observations of disk structures that surround B-emission (Be) stars. For example, high-resolution interferometry in the optical and the infrared now routinely provides information at sub-milliarcsecond scales advancing our understanding of the structure and the physical conditions in the circumstellar regions. However, reconstructing images directly from observational data is not possible since the $(u, v)$ plane coverage is unfortunately still quite exiguous. There remain key unanswered questions such as what is the mechanism that launches the material off the star and why do some B-type stars form a disk and later lose it while other disk systems remain stable for decades? Detailed theoretical models tightly constrained by observations are required to make progress on these longstanding questions.

## 1. Introduction

Stellar accretion, mass-loss, and rotation are important processes that lack sufficient understanding. These phenomena affect the evolution of massive stars and, in turn, these stars govern the evolution of their parent galaxies. Circumstellar disks offer unique laboratories for studying these key phenomena. An important subset of massive stars associated with disk-like distributions of gas are the classical Be stars. Their characteristic emission is due to radiatve processes within the disk. Rapid rotation of the central star is a common feature among these stars suggesting that rotation must play a significant role in the formation of a disk. However, it is unclear if rotation alone is sufficient to build and maintain a disk in all systems (Townsend et al. 2004). The Be stars are generally believed to be on the main sequence or slightly evolved. Nonetheless, the evolutionary status of Be stars and the possible connection to other types of stars is not clear. Uncertainty in Be star rotation rates and how rotation and evolution interplay compounds the difficulty in understanding these systems. The Be stars represent ~ 20% of B-type stars (Zorec & Briot 1997) and therefore they represent a significant fraction of stars where our knowledge is lacking. Through the study of Be stars key information about other astrophysical processes involving disks may also be revealed.

Mounting evidence supports the suggestion that disks surrounding classical Be stars are geometrically thin (see, e.g., Quirrenbach et al. 1997) with material orbiting in a Keplerian fashion or with minor departures (see, e.g. Meilland et al. 2007; Stee 2011; Kraus et al. 2012). Stars are generally thought to rotate below the critical value but exactly how close to critical they are remains a contentious issue (Townsend et al. 2004).

The precise role of other factors such as the effect of binary systems (Mennickent et al. 2012; Okazaki et al. 2001), magnetic fields (Oksala et al. 2012), and how variability (McDavid et al. 2000; Wisniewski et al. 2007) including pulsation (Rivinius et al. 2003) come into play are not completely clear. The more fundamental questions such as, why do some B stars form a disk and later lose it while other disk systems remain stable for decades (for example, see, Wisniewski et al. 2010) also remain.

This review begins with a discussion of current disk models in Sect. 2 with an emphasis on the thermal structure and effect of gravity darkening. Sect. 3 presents preliminary work on the early Be star, $\delta$ Sco, and its binary disk system. A summary is provided in Sect. 4.

## 2. Disk Models

Struve (1931) first proposed that Be star disks are formed due to rapid rotation of the central star and that the observed variety in spectral line shape is due to different viewing angles. Although this simple model does reproduce the bulk properties of these disks, it is clear that more sophisticated models are required to explain properties such as variability, x-ray flares, why some normal B stars enter a Be phase while other lose their disks, and so on. Since Struve's time, many other models have been proposed to explain the multitude of observational features associated with this group of stars.

In the pioneering work by Poeckert & Marlborough (1978) an ad hoc steady-state model for the star $\gamma$ Cas was created that successfully reproduces the observed emission spectra of prominent emission lines including H$\alpha$, and H$\beta$, continuum polarization, and the spectral energy distribution. This model was quite remarkable for its time given it successfully reproduced a wide range of observables. However, a large number of free parameters were required. An additional assumption employed by Poeckert & Marlborough (1978) and many other early models is that the disk thermal structure is isothermal at some fraction of the effective temperature of the central star. More recently, it has been shown that the disk thermal structure varies strongly as a function of radial distance from the central star and with vertical distance from the equatorial plane (Millar & Marlborough 1998; Sigut & Jones 2007; Carciofi & Bjorkman 2006). These models demonstrate that for moderately dense disks, a cool region forms near the star in the equatorial plane where the disk density (and therefore opacity) is large. The disk temperature directly affects the state of the gas, the level populations, and ultimately the observational features that are predicted. For example, Silij et al. (2010) demonstrated that the H$\alpha$ line profile can be doubly-peaked or singly-peaked at a given inclination by changing the disk density alone when a self-consistent thermal structure is adopted.

The characteristic rapid rotation of Be stars causes two significant effects, distortion of the central star and changes in surface temperature, commonly called gravity darkening. The surface temperature of the star becomes hottest at the poles with a gradual decrease towards the equator as a function of increased rotation. The distortion of the star also affects the energy supplied to the disk. In a recent study of this effect, McGill et al. (2011) find that the cool region within the disk near the star and in the equatorial plane (see above) generally increases in size with increased rotation. For rotation rates less than ~ 80% of critical, this effect can be adequately approximated with a spherical star with a variation in surface temperature, but, as rotation rates increase, the distortion of the central star must be taken into account to correctly account for the energy budget within the disk. A self-consistent thermal structure is also important for dynamic models that follow disk structure over time (see below).

The review by Porter & Rivinius (2003) discusses disk formation mechanisms such as radiatively driven winds, wind compressed disks, magnetically compressed disks and viscous disks. Currently, mounting evidence puts the viscous disk model as the leading contender. Originally proposed by Lee et al. (1991) and later examined by Okazaki (2001), this model is successfully being used to explain Be disk systems in remarkable detail (see the recent review by Carciofi 2011). Basically this model uses standard $\alpha$-disk theory commonly employed in accretion disks, except in Be disk systems the material is slowly out-flowing as viscosity carries material outward as it gains angular momentum. The beauty of this model is the fact that near-Keplerian rotation is predicted with relatively slow outflow. Viscous disks may become unstable to density perturbations allowing the formation of under- and over-dense volumes of gas that could give rise to the characteristic variability of $V/R$ (violet to red) emission peaks. These models have also successfully predicted the observed IR excess characteristic of all Be disk systems. How the material becomes launched from the central star remains unknown, and most models simply assume a mass loss rate as one of the model input parameters (see, e.g., Carciofi et al. 2006).

The early investigations of the viscous model, such as Lee et al. (1991) and Okazaki (2001), analogous to many of the early ad hoc time-independent models, assumed that the disk thermal structure is isothermal. More recent studies have included a self-consistent thermal structure for the gas dynamics including the ionization state and level populations (Jones et al. 2008; Carciofi & Bjorkman 2006; Carciofi et al. 2009). In a recent study of the Be star 28 CMa Carciofi et al. (2012) were able to determine the value of $\alpha$ by modeling the reduction of V-band excess as the disk dissipates. They find an $\alpha = 1.0 \pm 0.2$, which is at the upper limit of the expected range of 0.1 to 1.0 (Lee et al. 1991; Okazaki 2001). This may imply that the origin of the turbulent viscosity results from an instability modulated by shocks (Carciofi et al. 2012).

## 3. $\delta$ Sco

$\delta$ Sco (HD 143275) is an early type (B0.2 IVe) Be star with a binary companion on an eccentric orbit with a period of about 11 years (Tango et al. 2009; Tycner et al. 2011). Due to the recent periastron passage in 2011, this system generated much interest and it was the focus of many observational campaigns. We obtained $V$ and $B$ band photometry for the 2009, 2010, 2011 and partial 2012 observing seasons with the T3 0.4 m automatic photoelectric telescope (APT) located at Fairborn Observatory in southern Arizona. The telescope is owned and operated by Tennessee State University (TSU). These observations are plotted in Fig. 1. Note the large $\Delta V$ of ~ 0.2 magnitudes in 2009 and also that the periodic behavior of ~ 70 days is present in all three seasons despite obvious differences in the magnitude of variation. These fluctuations could be due to changes in the size (see Table 1 below) and density of the disk. This periodic behavior on the same scale was observed much earlier by Gandet et al. (2002) so these variations have persisted for about a decade. The contribution to the $V$-band from the disk is primarily due to gas emission and absorption of stellar radiation and originates in a small volume of gas near the star (see the Appendix in Carciofi & Bjorkman 2006 and Fig. 1 in Carciofi 2011). We are currently investigating what changes in disk density and/or disk geometry could account for this variation of $V$-band photometry with this particular period.

Table 1 gives the preliminary sizes of $\delta$ Sco H$\alpha$ disk for the observing seasons 2009, 2010, and 2011 via interferometric observations acquired using the Navy Prototype Optical Interferometer (NPOI). The NPOI is described in detail in Armstrong et al. (1998) and the technique used to extract interferometric observables from the spectral channel containing the H$\alpha$ emission line has been discussed by Tycner et al. (2003). Note that the preliminary disk size estimates vary substantially for the three seasons.

The size of the H$\alpha$ emitting region should be roughly equivalent to the size of the disk (Miroshnichenko et al. 2003) with the optical fading anti-correlated with H$\alpha$ line strength (see Miroshnichenko 2011; Carciofi et al. 2006). However, as discussed above, the $V$-band contribution will originate in a volume of gas very close to the star not over the full extent of the H$\alpha$ emitting region.

We produced dynamic models of the $\delta$ Sco system and recent periastron passage following the approach by Holman & Wiegert (1999). These models rely on gravity to follow the particles orbiting in a Keplerian fashion within the disk; gas dynamics are not included. We adopt the star/disk system and orbital parameters from Carciofi et al. (2006) and Tycner et al. (2011), respectively. The total mass of the disk for our simulation of $6 \times 10^{-8}\,\mathrm{M}_\odot$ was calculated from the base density, $\rho_0 = 4.5 \times 10^{-10}\,\mathrm{g\,cm^{-}3}$ (Carciofi et al. 2006) with an average power-law density fall off of 3.5 for a disk truncated at $7\,R_\star$. While the mass of $\delta$ Sco's disk certainly changes over time, and perhaps substantially near the inner disk during mass ejection, this is a reasonable estimate of the total disk mass for our preliminary modeling. Fig. 2 shows the system 3.4 years after perihelion passage. For this particular simulation we assume that the disk, equatorial plane of the star and the secondary all lie in the same plane. Although the secondary does not directly impact the disk, material is pulled away from the disk, forming a tidal tail that extends out to 5 AU at the time of the snapshot. Assuming a distance of 135 pc (Tycner et al. 2011), the tail size is equivalent to ~ 40 milliarcseconds. Over time the tail will continue to expand. Despite the fact that the secondary does not impact the disk, it does change the geometry of the disk system and these changes could poten-

Table 1. Preliminary H$\alpha$ disk size (FWHM) for $\delta$ Sco obtained via H$\alpha$ interferometry for 2009, 2010, and 2010.

| Observing Season | Size [mas] |
|---|---|
| 2009 | 4.32 ± 0.93 |
| 2010 | 2.63 ± 0.42 |
| 2011 | 2.39 ± 0.21 |

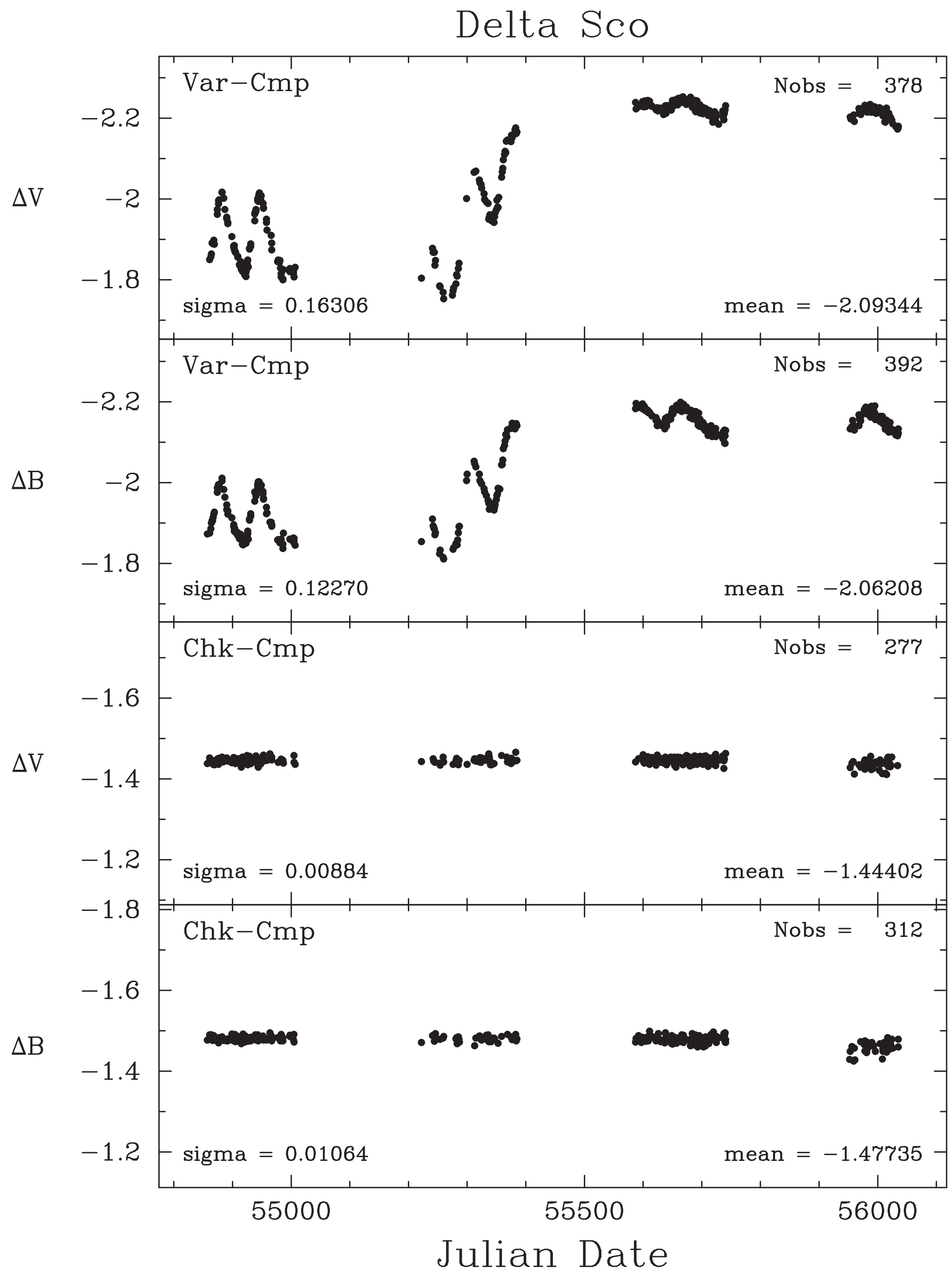


Figure 1. Photometry in $V$ and $B$ bands for $\delta$ Sco for the complete observing seasons of 2009, 2010, 2011 and the partial season for 2012. The total number of observations is given in the upper right of each panel and the mean $\Delta V$ or $\Delta B$ in the lower right. The standard deviation, $\sigma$, is given in the lower left of each panel.

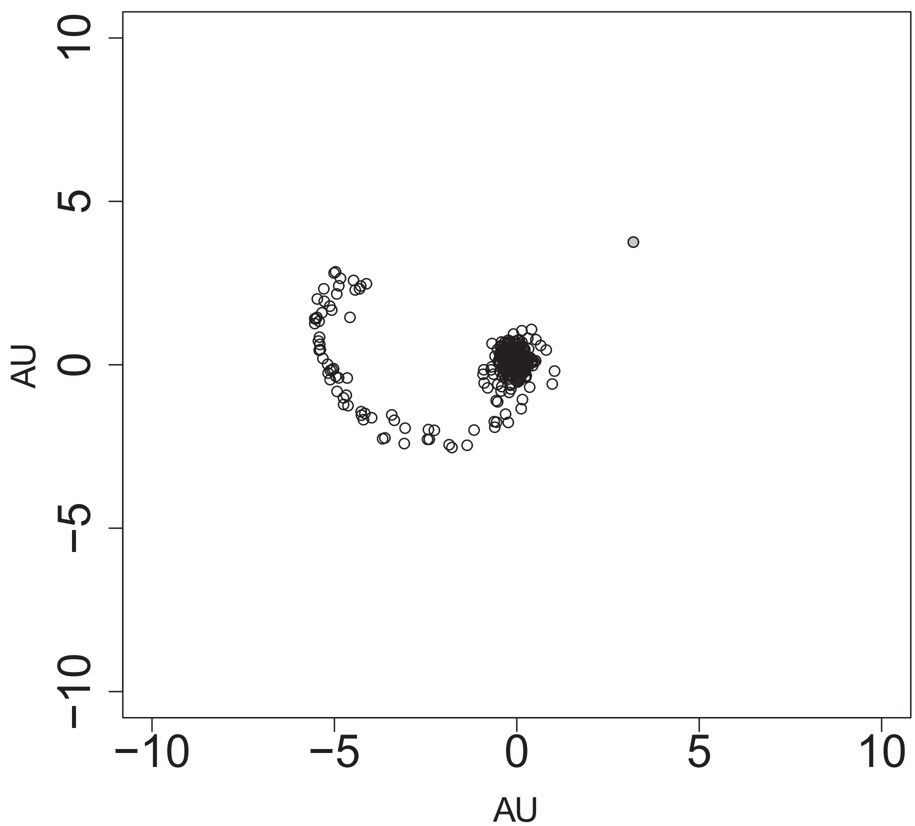


Figure 2. Disk particles (open circles) after the passage of the secondary (shown by the grey dot in the upper right) past periastron. In this case, the disk is $7\,R_\star$ in radius and so the secondary does not impact the disk nor does it capture any material from the system but a dramatic tidal tail is produced.

tially block parts of the primary star and disk from the field of view. However, since the orbital time scale for the secondary passage is of order of a decade, there must be some other process that is responsible for the ~ 70 day period.

Figure 3 shows a snapshot of a simulation that has a ~ 70 day orbital period of a tertiary companion of $1\,M_\odot$ orbiting at a distance of $14\,R_\star$ outside the disk. The disk and the third orbiting companion are initially inclined 5° from the equatorial plane of the primary. To date, we note that this third component has not been directly detected, but such a companion could, in principle, cause a precession with the observed period.

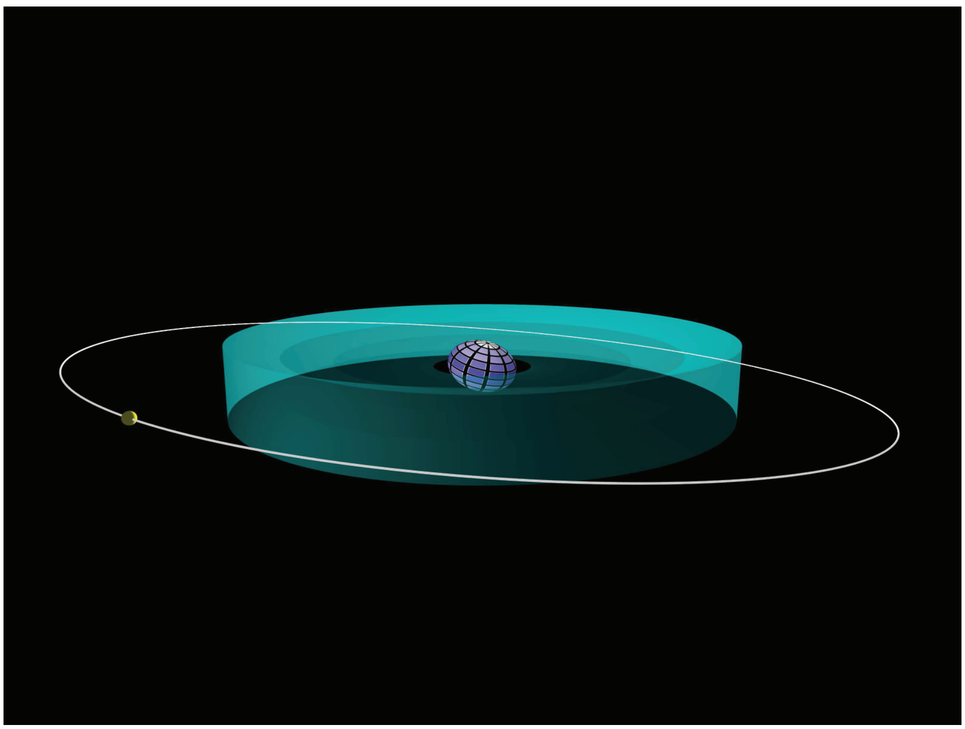

Figure 3. Cartoon showing the primary with a flared disk (with radius of $7\,R_{\star}$) in light blue, along with a $1\,M_{\odot}$ companion orbiting outside the disk with a 70 day period. The primary is shown slightly tilted at 5° to the disk, as is the companion.

## 4. Summary

Variations in disk density affect the thermal structure and level populations. In turn, the predicted observational signatures are affected. Therefore, to interpret observations correctly, it is essential to determine the state of the gas as consistently as possible. Realistic disk physical conditions will allow dynamic models that follow disk structure over time to be reliably tested. Be star circumstellar disks, are valuable laboratories to study disks and these disks may offer clues to understand other objects with disks. Key to continuing progress will be further development of theoretical models tightly constrained by high quality observations from the ground and space. It is paramount that theorists present their model results in a form that can be easily be compared to observations.

**Acknowledgments.** C.E.J. acknowledges research supported by NSERC, the Natural Sciences and Engineering Research Council of Canada and would also like to thank the workshop organizers for their kind invitation.

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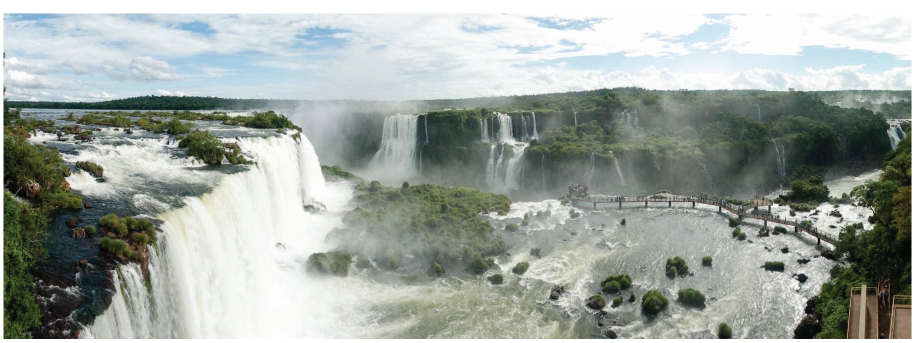
**Discussion**

*A. Okazaki*: I have a comment on your model with the proposed companion very close to the star. In addition to the companion clearing the inner regions where there is tidal torque, this torque also works on the gas between the companion and the star and extracts angular momentum of the gas. This pushes the gas back onto the star and would stop gas ejected from the star from moving outward and forming a disk.

*D. Baade*: Your model, too, shows the temperature minimum at a few stellar radii from the stars, where Jon Bjorkman surmised classical shell absorption lines may form. Is the local puffing up of the disk at about the same location a possible way to explain those rare Be to Be-shell transitions?

*C. Jones*: Detailed dynamical simulations that follow disk structure over time will be required to answer your question. Currently, we are working on some static models to try to decipher the disk density distribution to model a set of shell lines. The paper Silaj et al. 2012 in preparation may help to answer your question.



(Photo: TRi)