Emission Line Profiles from Be Stars—A Test of the MTD Model

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Abstract. We examine the emission line profiles of Be stars predicted by the Magnetically Torqued Disk model of Cassinelli et al. (2002) and compare our results with the profile shapes expected for Keplerian and solid body disks. Our findings indicate that the MTD model produces profiles acceptably close to the observed profiles.

1. Introduction

Disks around Be stars have long been observed and yet, despite extensive study, their presence has never been unambiguously explained. The existence of these circumstellar disks is evidenced by the strong, double-peaked emission lines in Hα, the large IR continuum excesses and the intrinsic polarisations. The mechanism by which these disks become so dense and acquire angular momentum remains uncertain, as does the reason for their variability on a variety of timescales. The spatial structure of the disks is also unclear, although observational indications suggest that they are mainly moving azimuthally rather than outflowing.

Although Be stars are fast rotators, the equatorial surface rotation is less than 80% of the Keplerian limit, so rotational effects alone cannot centrifuge material off the equator. Be stars have strong winds but radiative line-driving forces are only effective for sufficiently optically thin wind material and require a velocity gradient steep enough for the absorbing lines to sweep through the stellar continuum. Be star disks are believed to be too dense and too slowly expanding to be supported against gravity entirely by line-driving.

The Wind Compressed Disk (WCD) model of Bjorkman & Cassinelli (1993) describes how stellar wind matter accelerating out from intermediate latitudes on a rotating star follows a trajectory that crosses the equatorial plane. Matter flows from opposite hemispheres collide in the equatorial plane and cause a shock bound disk to form. Some theoretical concerns have been raised regarding the WCD model (Owocki, Cranmer, & Gayley 1996) but perhaps the
most significant issue is that the predicted disks are outflowing rather than azimuthally-moving, Keplerian disks, as observations suggest.

A modified Wind Compressed Zone (WCZ) model in which no shocks occur was also developed (Ignace, Cassinelli, & Bjorkman 1996). This situation does not result in disk formation but causes a density enhancement in a broad zone around the equator.

2. The Magnetically Torqued Disk Model

The Magnetically Torqued Disk (MTD) model by Cassinelli et al. (2002) suggests that magnetic fields around Be stars could be responsible for the formation of the observed circumstellar disks. In the MTD model, the presence of a dipole-like magnetic field of sufficient strength results in the magnetic torquing and channeling of wind material from intermediate stellar latitudes into a shock compressed disk in the equatorial plane (see Fig. 1). A dense quasi-Keplerian disk, extending out to a distance of a few stellar radii, then forms. Beyond the Alfvén distance, however, a somewhat flattened WCD/WCZ (Wind Compressed Zone) region is predicted.

Estimates of the minimum field strength required to torque a detectable disk suggest that the range of spectral types for which a disk would be expected to form corresponds closely with observational evidence. Preliminary estimates of the disk luminosity and emission measure, in Hα, also produce plausible results. While these findings are encouraging, more detailed investigations must be performed, particularly regarding the properties of the emission line profiles, in order to test the properties and predictions of the MTD model.
3. Examination of the Expected Emission Line Profiles

We examine the behaviour of the expected emission line profiles from Be stars given key stellar parameters including stellar spin rate, $S_0$, and $\gamma$, a measure of the ratio of magnetic energy density to gravitational energy density. Our program calculates the predicted inner and outer disk boundaries, divides the disk into volume elements in $r$ and $\phi$ and plots a histogram of the emission measure versus wavelength shift, $\Delta \lambda$, calculated for each volume element. In particular, we study the situation where the velocity is described by the continuous parametric function used in the MTD model (with $x = r/R$);

$$\frac{v_\phi(x)}{v_\infty} = \frac{\alpha^2 + 1}{\alpha^2 x + x}.$$ 

This is not a monotonic function, so the maximum velocity will occur at some mid-point in the disk. For this reason it was decided to perform the integration as described above rather then to solve for the iso-velocity contours, although this is an area we hope to explore in the future. We assume also the MTD shock compressed disk density;

$$\rho_D(x) = \frac{\dot{M}v_\infty(x)}{4\pi R^2 c_s^2} x^{-b} = \frac{\dot{M}}{4\pi R^2 v_\infty} \left(\frac{v_\infty}{c_s}\right)^2 (1 - 1/x)^\beta x^{-b}.$$ 

We compare the expected emission line profiles for the MTD velocity and density laws with those predicted for solid body and Keplerian velocity laws. Our aim is to establish whether the MTD profiles are compatible with the observational evidence for Keplerian disks.

For recombination lines, the emissivity generally scales with the density squared (as for Balmer emission lines), however, we would prefer to model optically thin, faint emission lines as observed for Fe II transitions. In the Be star disk scenario, Fe II is the dominant state for iron and its density is proportional to electron density, and therefore to the total density in the case of an ionised plasma. We consider both of these cases, when emissivity is proportional to $n$ and to $n^2$.

3.1. Conclusions and Further Work

Our findings suggest that the emission line profile expected for a magnetically torqued disk around a Be-type star will appear almost identical to the profile of a Keplerian disk with the same disk density, given observational limitations (see Fig. 2). The MTD profiles have a greater width than the corresponding Keplerian profiles, however, the basic shape of the profile is the same in both cases. Work is in progress to establish the range of stellar parameters over which this holds true.

In addition to studying the implications of varying $S_0$ and $\gamma$, we are also investigating the effects of disk density and other parameters such as disk height, with the intent of establishing what information can be gathered from the line profile regarding, for example, the extent of the disk.

The calculation of shell line absorption profiles may prove to be a useful extension of the MTD line profile analysis and this is an area for future development. We wish also to explore the impact of gravity darkening on disk.
Figure 2. The top graph shows the expected emission line profile for a solid body disk, the second for a Keplerian disk and the third for a magnetically torqued disk. In all cases, the disk density inferred in the MTD model was assumed and the lower lines represent occultation effects. The emission measure was assumed to be proportional to $n^2$ and in the left-hand graphs and to $n$ in the right-hand graphs.

formation. When most of the matter is ejected from regions close to the poles it may be harder to form a disk and the outflow may instead contribute only to a WCZ or general stellar wind. Ultimately, our aim is to determine whether the MTD model of the dense inner disk and low density outer regions (where strong outflow occurs) produces overall line profiles consistent with observations. Comparing our findings with observations will be an important test of the MTD model.

References