Massive Stars Near and Far
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Obliquely Rotating Massive Star Magnetospheres

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Abstract. We present results from 3D MHD simulations of the magnetospheres from massive stars with a dipole magnetic axis that has an arbitrary obliquity angle (β) to the stars rotation axis. As an initial direct application, we examine the global structure of co-rotating disks for tilt angles $\beta = 0$, 45 and 90 degrees using ζ Pup stellar parameters as a prototype. We find that for models with rapid stellar rotation ($\sim$ 0.5 critical rotation), accumulation surfaces closely resemble the form predicted by the analytic Rigidly Rotating Magnetosphere (RRM) model, but with a mass distribution and outer disk termination set by centrifugal breakout processes. However, some significant differences are found including warping resulting from the dynamic nature of the MHD models in contrast to static RRM models. These MHD models can be used to synthesize rotational modulation of photometric absorption and H-alpha emission for a direct comparison with observations.

Keywords. massive stars, magnetohydrodynamics, magnetic fields, rotation

Hot, luminous, massive (OB-type) stars lose large amount of mass through radiatively-driven stellar wind (Castor et al. 1975, CAK). In general, winds of these objects are spherically symmetric, but some fraction of them exhibit variability and structure on both small and large scales which can be caused by global magnetic field. Babel & Montmerle (1997) have shown that in Bp stars magnetic field is so strong that it acts like rigid rods that guide material towards the magnetic equator wherein they collide leading to magnetically confined wind shocks (MCWS). Once the material cools, the dense material is a source of strong Hα emission. However, this MCWS was a phenomenological model and did not make any specific predictions about how much material would accumulate within magnetosphere or provide a mechanism for emptying it.

A vast improvement upon MCWS model was made by Townsend et al. (2005) who developed rigidly rotating magnetosphere (RRM) model for Bp star using σ Ori E as a prototype. RRM model predicts the accumulation of circumstellar plasma situated in magnetohydrostatic equilibrium at the intersections between the magnetic and rotational equators. Amount of accumulated material depends on mass feeding rate at the base of rigid field lines. The model also predicts large scale emptying of the magnetosphere via centrifugal breakout (CBO) and has been successfully used to reproduce the periodic modulations observed in the light curve and Hα emission-line profile of σ Ori E.

Key advantage of the RRM model is that it is analytic and does not require expensive numerical computations. However, it lacks self-consistent interactions between magnetic field and the wind that is inherent in magnetohydrodynamic (MHD) simulations. As such, RRM model is unable to predict density structure within the magnetosphere, one of the main goals of this work here.

In an extensive series of papers (see ud-Doula & Owocki 2002; ud-Doula et al. 2006, 2008, 2009), we have applied MHD simulations to understand the dynamics of such magnetic wind channeling, the consequent hard X-ray emission and Hα emission. But

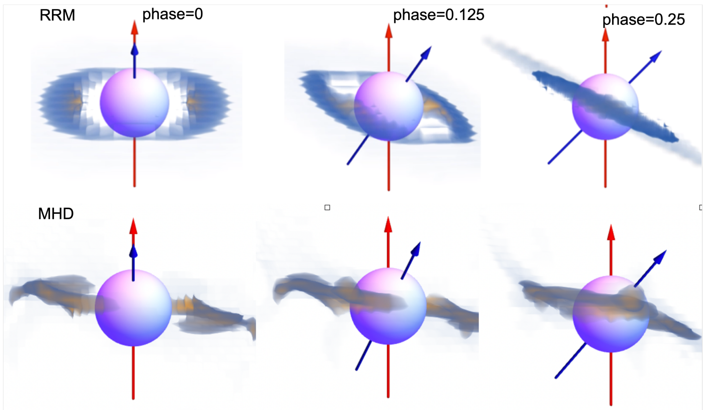

Figure 1. Comparison between analytic Rigidly Rotating Magnetosphere (RRM) vs our fully self-consistent 3D MHD models. They are quite similar but significant differences exist. MHD model shows the sense of rotation with denser part of the disk leading unlike in RRM model. Dragonfly wing-like structure exhibits warping which can have observational implications.

all these models were either 2D or simplified 3D models where magnetic axis is aligned with rotational axis.

In practice, magnetic massive stars are often oblique rotators, which naturally leads — especially when rotation is rapid — to lateral structures that cannot be modeled by axisymmetric 2-D models. But for rapid rotators with magnetic field tilted with respect to rotational axis, this is not option as axisymmetry is fully broken. Here we present a 3D MHD model where magnetic field is tilted by 45^o with respect to the rotational axis.

We use PLUTO code in spherical geometry. We follow the same basic formalism as in ud-Doula & Owocki (2002); ud-Doula et al. (2008). We evolve our model for over 1.5Ms, which allows the model to settle in quasi-steady state. As shown in Fig. 1, fully self consistent MHD model (bottom panel) and the RRM model (top panel) match relatively well. However, there are some notable differences. The MHD model shows the dynamic effects of rotation that leads to warping of the circumstellar structure, making it resemble a 'dragonfly wing'. The overall structure exhibits the sense of rotation with higher density material leading the way. Such MHD models also allow to extract density scaling information that can have observational consequences.

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