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# Centrifugal Breakout of Magnetically Confined Line-Driven Stellar Winds

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**Abstract.** We present 2D MHD simulations of radiatively driven winds from a hot star having a dipole magnetic field aligned with the star's rotation axis. We focus in particular on a model with a moderately rapid rotation (about half the critical value), and also a strong magnetic confinement parameter, $\eta_* \equiv B_{\rm eq}^2 R_*^2/\dot{M} v_\infty = 600$. The magnetic field channels and torques the wind outflow into an equatorial, rigidly rotating disk extending from near the Keplerian co-rotation radius outwards. The strong centrifugal force on material in the outer edge of this disk stretches the magnetic loops, leading to episodic breakout of mass when the field reconnects. The associated dissipation of magnetic energy heats material to temperatures of nearly $10^8$ K, high enough to emit hard (several keV) X-rays. Such *centrifugal mass ejection* represents a novel mechanism for explaining X-ray flares recently observed in the magnetic Bp star $\sigma$ Ori E.

## 1. Introduction

A topic of much discussion at this workshop is the possible role of hot-star magnetic fields in channeling a radiatively driven outflow into a circumstellar disk. A phenomenological *Magnetically Torqued Disk* (MTD) analysis summarized in the contribution by Brown envisions that the torquing of a surface field can spin outflowing material up just enough to deposit it into an orbiting, Keplerian disk. MHD simulations summarized by Owocki show, however, that such magnetically channeled flow tends either to fall back to the star or escape altogether, depending on whether its equatorial intersection occurs above or below the Keplerian co-rotation radius. Nonetheless, as discussed in the contribution by Townsend, Owocki, & Groote (2004), very strong fields can both spin up material to above Keplerian rotation *and* hold it down against the net outward centrifugal-gravitational force; this leads to accumulation of a *Rigidly Rotating Magnetosphere* (RRM) which, in the case of field-aligned rotation, corresponds to an azimuthally symmetric, *rigid-body* disk at the common rotation and magnetic equator. For such a relatively strong field case, the present paper presents MHD simulations that show episodic, centrifugal break out of confined material once the accumulated density becomes too high; a key finding is that the resulting stressing and reconnection of the magnetic field can heat material to temperatures high enough to emit quite hard (several keV) X-rays.

## 2. Numerical Simulations and Results

As discussed by ud-Doula & Owocki (2002), the relative effectiveness of magnetic fields in confining and/or channeling a wind outflow depends on the ratio of energy densities in the field vs. flow, as characterized by the dimensionless magnetic confinement parameter $\eta_* \equiv B_{\rm eq}^2 R_*^2/\dot{M} v_\infty$ (where $B_{\rm eq}$ is the equatorial field strength at the stellar surface radius $R_*$, and $\dot{M}$ and $v_\infty$ are the mass loss rate and flow terminal speed). For $\eta_* \ll 1$, the magnetic field has very little effect on the wind, while for $\eta_* \gg 1$, the magnetic field is strong enough to confine the wind to large radii, thereby resulting in a rigidly rotating magnetosphere.

Here, we present 2D MHD simulations of the wind from a star rotating at half the critical rate, with a rotation-aligned dipole field of magnetic confinement parameter $\eta_* = 600$. For such a strong magnetic confinement, the magnetic field torques the wind outflow into an equatorial, rigidly rotating disk; but as material builds up in the disk the net outward centrifugal force stretches the field lines until they break open, releasing discrete mass ejections.

We study the fully self-consistent dynamical competition between field and wind by evolving a MHD simulations from an initial condition at time $t = 0$, when a dipole magnetic field is suddenly introduced into a previously relaxed, 1D spherically symmetric, line-driven wind for the assumed magnetic confinement parameter $\eta_* = 600$. We assume that the star is rigidly rotating with a constant angular speed corresponding to half the critical value; the oblateness and gravity darkening of the stellar surface at this rotation rate are small, and are therefore neglected in the simulations. We perform our calculations using publicly available Zeus-3D MHD code (see Stone et al. 1992) and use MacDonald & Bailey (1981) radiative cooling function in solving the energy equation.

Our simulations show that magnetic field channels gas from higher latitudes towards the equatorial plane, where it undergoes wind-wind collision shocks. The cooled post-shock material is maintained in strict corotation by the strong field; beyond the Keplerian radius, the centrifugal force associated with this corotation supports the equatorial material at the tops of closed magnetic loops, where it steadily accumulates over time. However, the magnetospheric material eventually reaches densities where the centrifugal force rips open the overly-stressed magnetic loops, allowing the material to break out. The immediate post-breakout reconnection of the field heats the ejected plasma to nearly 108 K, hot enough to emit hard X-rays (several keV).

Figure 1 shows the logarithm of density (top panel) and temperature (bottom panel) for a series of time snapshots to illustrate such a breakout event. Such hot and dense cloud breakout can represent a novel mechanism for explaining the observed x-ray flares in $\sigma$ Ori E (Groote & Schmitt 2004; Mullan 2004).

## 3. Discussion

The rigid-body corotation makes the equatorial disk in our simulations quite distinct from the Keplerian disk envisioned in the MTD scenario promoted by Cassinelli et al. (2002). We find no evidence of an extended region of Keplerian rotation. Instead the results correspond more closely to those derived in the Rigidly Rotating Magnetosphere (RRM) analysis of Townsend & Owocki

(2004), although the confinement parameter we consider is near the lower end of range of validity for the basic RRM approach. For example, as discussed in the contribution by Townsend et al., a prime candidate for application of this RRM model is the magnetic Bp star $\sigma$ Ori E, which has confinement parameter of order $10^7$. Unfortunately, it is impractical to model such strong wind confinement cases numerically, because high Alfvén speeds require a very small Courant time step, making the computation prohibitively expensive.

Given that we used moderately large magnetic confinement parameter, the similarity between our numerical models and the semi-analytical RRM treatment is nonetheless quite encouraging. To further reconcile these approaches, in the future we plan to explore full 3D simulations with the rotation axis tilted to the magnetic field axis.

## References


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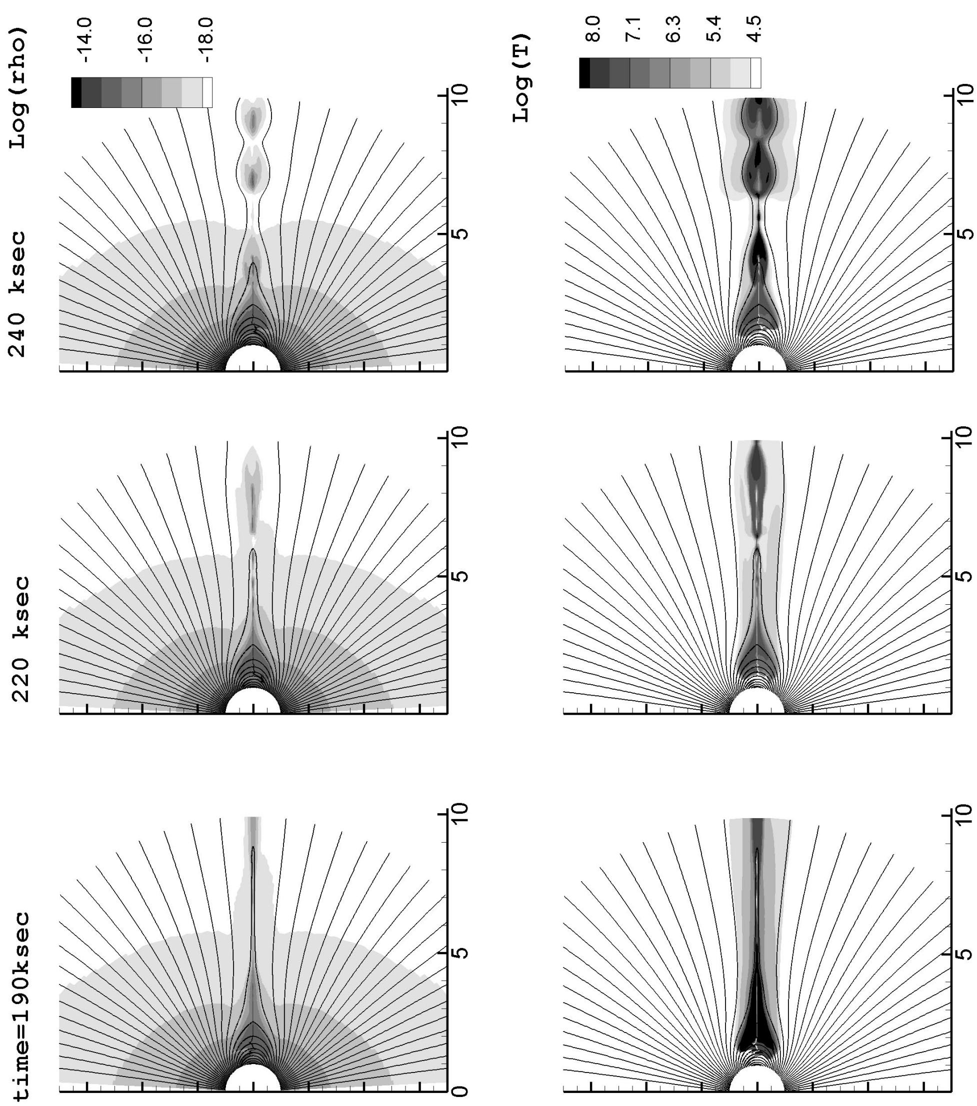


Figure 1. MHD simulation results for a radiatively driven stellar wind from a star rotating at half the critical rate, with a rotation-aligned dipole field that has a magnetic confinement parameter $\eta_* = 600$. The grayscales show the logarithm of density (top panels) and temperature (bottom panels) at three sample time snapshots, chosen to show the centrifugal ejection of material accumulated in an equatorial disk. The associated stretching and eventual reconnection of the field lines heats material to temperatures of order $10^8$ K, hot enough to emit hard (few keV) X-rays.