Steady-State Analysis

Townsend et al. (2007) developed a Rigid-Field Hydrodynamics (RFHD) approach to simulate magnetospheres in the limit of strong magnetic confinement in which the 3-D stellar outflow is approximated as many one-dimensional flows along individual field lines subject to external driving by radiative and gravitocentrifugal forces. We have since extended the RFHD technique to incorporate completely arbitrary magnetic configurations (arbitrary RFHD; Bard et al. in prep), though the analysis presented in this poster focuses on the simplest case of a rotation-aligned dipole field.

From the ARFHD equations, we derive the steady-state equation of motion:

\[ \rho \left( \frac{1}{2} \dot{v}^2 - g_{\text{grav}} v - g_{\text{cent}} \dot{\psi} - g_{\text{rad}} \dot{\psi} \right) = 0 \]

where \( \rho \) is the mass density, \( \dot{v} \) is the velocity, \( g_{\text{grav}} \) is the gravitational acceleration, \( g_{\text{cent}} \) is the centripetal acceleration, and \( g_{\text{rad}} \) is the radial acceleration. The right-hand side is given by the optically-thin-corrected version of the CAK line force (Owocki et al. 1988):

\[ g_{\text{rad}} = \frac{\kappa \rho \dot{\psi}}{4 \pi c} \frac{1 + q_{\text{rad}}}{1 - q_{\text{rad}}} \]

where \( \kappa \) is the CAK alpha, \( T_{\text{eff}} \) is the effective temperature, \( q_{\text{rad}} \) is the radial line-strength parameter introduced by Gayley (1995). The centrifugal acceleration is related to the stellar rotation through the critical rotation fraction, \( \alpha \), and the distance to the rotation axis, \( r_{\text{sub}} \):

\[ g_{\text{cent}} = \frac{8 G M_{\odot} \omega^2}{c^2 r_{\text{sub}}^3} \]

where \( \omega \) is the critical rotation and \( r_{\text{sub}} \) is the Sobolev optical depth, and \( Q_{\text{bar}} \) is the dimensionless line-strength parameter introduced by Gayley (1995).

For each star, we generate a grid of 500 dipole field lines with footprints covering the northern half of the star (co-latitudes: \( 0 < \theta < \pi/2 \)) and calculate the critical locations and values for each line. This is repeated for several critical rotation fractions (\( \alpha = 0.0, 0.2, 0.35, 0.5, 0.65, 0.8 \)).

Surface Mass-Flux Scalings

From the model calculations, we derive a simple surface wind mass-flux scaling as a function of surface co-latitude and stellar rotation rate:

\[ \dot{M} \propto \frac{T_{\text{eff}}}{R_{\odot}} \sum_{\text{rad}} \alpha^{1-1/\alpha} \dot{M}_{\text{CAK}} \]

with \( \alpha \) the critical radius. The correction terms are:

\[ N = 1 - \left( \frac{8 G \omega^2}{c^2 r_{\text{sub}}} \right)^{1/\alpha} \left( \frac{\rho q_{\text{rad}}}{\kappa} \right) \]

with an "optically-thin correction level parameter" (larger means correction is more important): \( \chi_{\text{opt}} = (1 - \Gamma_{\text{opt}}) / (\Gamma_{\text{opt}} Q) \)

Integrated Mass Loss

Table 2: Mass-loss rates (in units 10^{-6} M_{\odot}/yr) for our B-star type, as calculated from integrating the surface mass-flux scaling relationship over the stellar surface. "No B" indicates a CAK-type mass-loss rate calculated from a radial line with spherical divergence. The other mass-loss rates were calculated from a dipole magnetosphere with the given rotation fraction \( \omega \). "Optically-Thick" indicates the mass-loss from using the optically thick limit of the radiative acceleration (i.e. the CAK form); the rest use the optically-thin-corrected version of Owocki et al. (1988). "Open" is the mass-loss into open field lines. "Disk" is the mass-loss into a centrifugally-supported disk. "Effective" is the total mass-loss rate of plasma which does not fall back to the star. Numbers in parentheses next to a mass-loss rate are the ratio of that rate to the "General" mass-loss rate at that particular rotation fraction. The stellar magnetic field was used to estimate both the size of the magnetosphere and centrifugally-supported disk using MHD-derived scaling relations for the Kepler and Alven radii (ud-Doula+Owocki 2002).

References

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