The Lives and Death-Throes of Massive Stars
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Effect of a Dipole Magnetic Field on Stellar Mass-Loss

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Abstract. Massive star winds greatly influence the evolution of both their host star and local environment though their mass-loss rates, but current radiative line-driven wind models do not incorporate any magnetic effects. Recent surveys of O and B stars have found that about ten percent have large-scale, organized magnetic fields. These massive-star magnetic fields, which are thousands of times stronger than the Sun's, affect the inherent properties of their own winds by changing the mass-loss rate. To quantify this, we present a simple surface mass-flux scaling over the stellar surface which can be easily integrated to get an estimate of the mass-loss rate for a magnetic massive star. The overall mass-loss rate is found to decrease by factors of 2-5 relative to the non-magnetic CAK mass-loss rate.

Keywords. stars: magnetic fields; stars: winds, outflows; stars: mass-loss; stars: early-type

1. Introduction

Recent surveys of magnetic massive stars have found that 5-10% of OB stars have detectable magnetic fields (Wade *et al.* 2014; Morel *et al.* 2015). These magnetic fields have significant effects on their host star. In order to quantify how these fields affect the stellar wind, Bard & Townsend (2016) undertook a steady-state analysis of a Castor *et al.* (1975) (hereafter CAK) line-driven wind flowing along dipole magnetic field lines for both the optically-thick formulation of the radiative acceleration (a la CAK) and the more general limit (Owocki *et al.* 1988). For this simplest case, a point source of radiation was assumed such that the line acceleration was solely radial. This assumption of "radially-streaming" photons can be relaxed by treating the star as a finite disk. The transformation between these two cases is provided by the so-called "finite-disk correction factor" (fdcf). Numerical solutions of a CAK wind modified with the fdcf (so-called "mCAK" models) (Friend & Abbott 1986; Pauldrach *et al.* 1986) found that the fdcf had a large effect on the stellar mass-loss rate, reducing it by roughly half.

In this proceeding, we will focus on the effects of a dipole field on the finite-disk corrected CAK wind and present a simple scaling relation for the surface mass-flux of a magnetic massive star. We will leave the full mathematical details of this derivation to a forthcoming paper, though they can currently be found in Bard (2016).

2. Surface Mass-Flux Scaling

We provide here a simple scaling which roughly reproduces the more detailed model of Bard (2016) to within an $\approx (25\%, 15\%, 7\%, 3\%, 0\%)$ underestimate for critical rotation

Table 1. Stellar and wind parameters used in this proceeding to represent a typical magnetic B–type star with a centrifugal magnetosphere and an O-type star with a dynamical magnetosphere. Values are identical to those used in Bard & Townsend (2016).

Type	M_*	R_p	$T_{\rm eff}$	α	$\Gamma_{\rm el}$	$\bar{Q}$	B_p	η_*
B	9.0 $M_\odot$	4.5 $R_\odot$	21000 K	0.56	9.27×10^{-3}	1025.14	11 kG	4.29×10^5
O	50 $M_\odot$	19 $R_\odot$	41860 K	0.6	0.5	500	3.715 kG	100

fractions $\omega = (0.65, 0.5, 0.35, 0.2, 0.0)$. This scaling assumes an aligned dipole magnetic field and a general CAK line force:

$$\dot{m}_*(\theta) \approx \mu_B^{1+1/\alpha} f^{1/\alpha} \Sigma_f \aleph^{1-1/\alpha} \dot{m}_{\rm CAK}, \tag{2.1}$$

with θ the surface co-latitude, α the CAK power-law index and f is the finite-disk correction factor evaluated at the pole ($\theta = 0$). This scaling relation does require the calculation of the polar f for each star, but $f \approx 0.6 - 0.7$ can be used in a pinch.

With R_p the polar radius of the star, the CAK surface mass-flux is

$$\dot{m}_{\rm CAK} = \frac{\dot{M}_{\rm CAK}}{4\pi R_p^2} = \frac{L_*}{4\pi R_p^2 c^2} \frac{\alpha}{1-\alpha} \left(\frac{\bar{Q}\Gamma_{\rm el}}{1-\Gamma_{\rm el}} \right)^{(1-\alpha)/\alpha}, \tag{2.2}$$

with $\bar{Q}$ the Gayley (1995) Q-parameter and $\Gamma_{\rm el} \equiv \kappa_e L_*/(4\pi c G M_*)$ is the Eddington parameter. μ_B is the surface tilt of the magnetic field with respect to the stellar surface normal,

$$\mu_B = \frac{2\cos\theta - \sin\theta (R'_*/R_*)}{\sqrt{(1+3\cos^2\theta)(1+(R'_*/R_*)^2)}} . \tag{2.3}$$

The stellar radius of a rotating star is given by

$$\frac{R_*}{R_p} = \frac{3}{\omega \sin\theta} \cos\left[\frac{\pi + \arccos(\omega\sin\theta)}{3} \right] , \tag{2.4}$$

with its derivative $R'_* = dR_*/d\theta$ defined as

$$\frac{1}{R_p}\frac{dR_*}{d\theta} = \frac{\cot\theta \sin\{\frac{1}{3}\left[\pi + \arccos(\omega\sin\theta)\right]\}}{1-\omega^2\sin^2\theta} - \frac{3\cot\theta\csc\theta\cos\{\frac{1}{3}\left[\pi + \arccos(\omega\sin\theta)\right]\}}{\omega} . \tag{2.5}$$

For $\omega = 0$, $R_* = R_p$ and $R'_* = 0$. The rotation effect parameter is

$$\aleph \equiv 1 - \frac{12\cos^3\left[\frac{1}{3}(\pi + \cos^{-1}(\omega\sin\theta))\right]}{\omega\sin\theta}, \tag{2.6}$$

and the so-called "optically-thin correction" parameter is defined as

$$\Sigma_f \equiv \frac{\left| 1 - \alpha - \left[\frac{1-\left(\frac{\chi_0 \aleph}{\mu_B f}\right)^{1/\alpha - 1}}{1-\left(\frac{\chi_0 \aleph}{\mu_B f}\right)^{1/\alpha}} \right] \right|}{\alpha}. \tag{2.7}$$

Finally, we have

$$\chi_0 = (1-\Gamma_{\rm el})/(\Gamma_{\rm el}\bar{Q}). \tag{2.8}$$

For O-stars with high mass-loss rates, the "optically-thick" version of the CAK

Table 2. Mass-loss rates (in units of $10^{-9}\ M_{\odot}/\ \mathrm{yr}$) for our example B-type star ($\eta_* = 4.28\times10^5$). "No B" indicates a mCAK-type mass-loss rate calculated from a non-rotating radial flow with spherical divergence. The other mass-loss rates are calculated from a dipole magnetosphere with the given rotation fraction ω. "Optically-Thick" indicates the mass-loss calculated from using the optically-thick CAK radiative acceleration; the rest use the general version. "Open" is the mass-loss into open field lines ($L > R_c$). "Disk" is the mass-loss into field lines with a centrifugally supported disk ($R_K < L < R_c$). Numbers in parentheses next to a mass-loss rate represent the ratio of that particular rate to the "General" mass-loss at its rotation fraction ω.

	No B	$\omega = 0.0$	0.2	0.35	0.5	0.65	0.8
Optically-Thick	0.89	0.373	0.373	0.372	0.371	0.365	0.349
General	0.605	0.253	0.253	0.252	0.252	0.248	0.236
Open	...	0.021(0.08)	0.020(0.08)	0.020(0.08)	0.019(0.075)	0.017(0.07)	0.015(0.06)
Disk	...	...	0.090(0.36)	0.138 (0.54)	0.178(0.7)	0.208(0.84)	0.221(0.93)
Effective	...	0.021(0.08)	0.11(0.44)	0.157(0.62)	0.196(0.77)	0.225(0.91)	0.236(0.999)

line-acceleration can be used instead of the general version. In this case, Σ_f can be set to 1 and the remaining terms of the above scaling relation are unchanged.

3. Magnetic Effects on Mass-Loss Rate

The estimated stellar mass-loss rate is found by integrating the mass-flux scaling over the stellar surface:

$$\dot{M}_{\mathrm{global}} = \int \dot{m}_r\ dA = 2\pi \int R_*^2\ \mu_B\ \dot{m}_* d\mu\ , \tag{3.1}$$

with $\mu = \cos\theta$. Following Bard & Townsend (2016), we define "open", "disk", and "effective" mass-loss rates based on the behavior of the wind after it flows away from the stellar surface. The "effective" mass-loss is simply the mass lost to wind flowing along open field lines out of the magnetosphere ("open") or into a centrifugally-supported disk ("disk"). Plasma which does not escape the magnetosphere nor settles into a disk eventually falls back to the stellar surface, so it is never "lost". We define open field lines as having dipole shell radii (L) larger than the closure radii (R_C) as derived from MHD simulations:

$$R_C \approx R_p + 0.7[R_p(0.3 + \eta_*^{1/4}) - R_p], \tag{3.2}$$

with the usual "wind magnetic confinement parameter"

$$\eta_* \equiv \frac{B_{\mathrm{eq}}^2 R_*^2}{\dot{M}_{B=0} v_{\infty,B=0}} \tag{3.3}$$

(ud-Doula & Owocki 2002). Lines with a centrifugally-supported disk are defined with $L > R_K$, where the Kepler radius

$$R_K = \frac{GM_*}{v_\phi^2} = \omega^{-2/3} R_p, \tag{3.4}$$

demarcates the beginning of the centrifugally-supported disk.

To illustrate the effect of a magnetic field on stellar mass-loss rates, we integrate the full finite-disk-corrected mass-flux model from Bard (2016) for two prototypical magnetic massive stars (Table 1). One star represents a B-star with a centrifugal magnetosphere,

Table 3. Same as Table 2, except for an O-type star with $\eta_* = 100$. All mass-loss rates are given in 10^{-6} $M_\odot$/yr. Numbers in parentheses next to a mass-loss rate represent the ratio of that particular rate to the "General" mass-loss with the same rotation fraction.

	No B	$\omega = 0.0$	0.2	0.35	0.5	0.65	0.8
Optically-Thick	3.34	1.50	1.50	1.50	1.49	1.46	1.39
General	3.26	1.46	1.46	1.46	1.45	1.42	1.35
Open	...	0.40(0.27)	0.36(0.25)	0.37(0.25)	0.34(0.24)	0.34(0.24)	0.32(0.24)
Disk	...	...	0.25(0.17)	0.51 (0.35)	0.76 (0.52)	0.94 (0.66)	1.03 (0.76)
Effective	...	0.40(0.27)	0.62(0.42)	0.88(0.60)	1.10(0.76)	1.28(0.9)	1.35 (0.999)

and the other represents an O-star with a dynamical magnetosphere. The results are presented in Tables 2 and 3. We find that the overall effect of a dipole magnetic field is to reduce the "effective" mass-loss rate by roughly a factor of 2 (at $\omega = 0.8$) to 5 (at $\omega = 0.2$) compared to the CAK-estimated mass-loss rates for non-magnetic, non-rotating stars. This result implies that magnetic massive stars will both evolve differently and have a disparate impact on their interstellar environments compared their non-magnetic counterparts. Models of magnetospheric emission will also be affected, though the results here are more applicable to centrifugal magnetospheres with stronger fields than to dynamical magnetospheres with weaker fields.

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