MHD Simulations of Line-Driven Winds from Hot Stars

Asif ud-Doula & Stan Owocki

Bartol Research Institute, University of Delaware, Newark, DE

Hot-Star Winds

Over the course of their lifetimes, hot, luminous, massive (OB-type) stars lose large amount of mass in nearly continous outflow called a stellar wind.

These winds are driven by scattering of the star s continuum radiaton in a large ensemble of spectral lines (Castor, Abbott & Klein 1975; CAK)

There is extensive evidence for variability and structure on both small and large scales.

Our simulations show that magnetic fields may explain some of the large scale variability in wind flow, UV and X-ray emissions from hot stars.

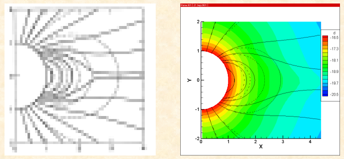
There have been some positive detection of magnetic fields in hot stars, e.g, Donati et al. (2001) report a tilted dipole field of B_{pole}~300 G in Beta Ceph.

Magnetic Effects on Solar Coronal Expansion

At sunspot minimum, Sun has a global dipole magnetic field of about 1 Gauss.
Left panel: soft X-ray image of the sun; note dense, static closed loops.
Middle panel: solar corona; note coronal streamers where the wind opens field toward radial.
Right panel: solar wind outflow speed at 1 AU as a function of latitude.
Magnetic fields can modulate stellar winds.

Pneuman and Kopp Model of Solar Corona

MHD model for base dipole with B_o=1 G   Our Simulation

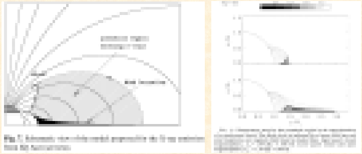


First dynamical model of coronal streamers: Pneuman and Kopp (1971) using iterative scheme (left panel).
Dynamical MHD reproduction of this model using time explicit magnetohydrodynamic code (ZEUS-3D).

Magnetically Confined Wind-Shocks (MCWS)

Babel & Montmerle 1997a,b

Magnetic A_p-B_p stars θ^1 Ori C (O7 V)



Effect of magnetic fields in hot stars: non-linear radiative force + MHDfi no simple analytical solutions.
Past attempts: **fixed-field** model of Babel and Montmerle (1997) to explain X-ray emission; flow computed along fixed magnetic flux tubes fi open-field outflow not modelled in detail.

Wind Magnetic Confinement

Ratio of magnetic to kinetic energy density:

$$\eta(r) \equiv \frac{B^2/8\pi}{\rho v^2/2} = \frac{B^2 r^2}{\dot{M} v} = \left[\frac{B_{eq}^2 R_*^2}{\dot{M} v_\infty}\right]\left[\frac{(r/R_*)^{(2-2q)}}{(1-(R_*/r))^\beta}\right]$$

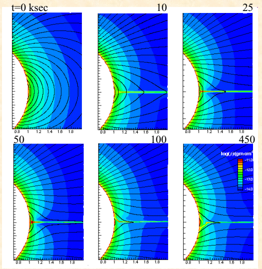
$$\boxed{\eta_* \ldots \frac{B_{eq}^2 R_*^2}{\dot{M} v_\times} = 1.6 \leftrightarrow \frac{B_{100}^2 R_{12}^2}{\dot{M}_{-6} v_8}}$$

for solar wind, η_*~ 45 ...
but for O-stars, to get η_*~ 1,
need:

B_{pole} ~ 150 G for Θ^1 Ori C
~ 300 G for ZPup

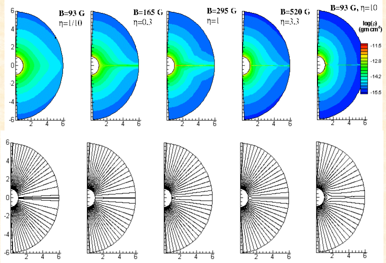
This dimensionless parameter, η_* is the governing parameter for our **dynamical** and **self-consistent** simulations.
Assumptions: isothermal, non-rotating star.
Standard model: ς Pup (R=1.3 10^{12} cm, M=50 M_{Sun}, L=1.0 10^6 L_{Sun}, Mass loss=2.6 10^{-6} M_{Sun}/yr, V_{inf}=2300 km/s.

Relaxation of Wind to a Dipole Field



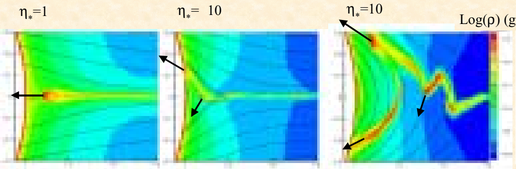
Snapshots of density and magnetic field lines at the labeled time intervals starting from the initial condition of a dipole field superimposed upon a spherically symmetric outflow for η_* = sqrt(10) (B_{pole}=520G).

Global Structure



Comparison of density and magnetic field topology for different η_*, as noted.
Equatorial density enhancement for even η_* =1/10
Wind always wins: field lines extended radially at the outer boundary for all cases

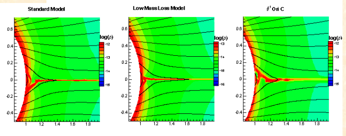
Inner Wind



Closed loops for η_* >1.
Magnetic flux tubes of opposite polarity guide wind outflow towards the magnetic equator fi wind collision fi heating of the gas (see below) fi X-ray.
Wind material stagnated after the shock: dense and slow fi radiative force inefficient fi gravity wins: infall of wind material in the form of dense knots onto the stellar surface.
Infall of dense knots: semi-regular, about every 200 ksec fi complex infall pattern.
Might explain red-shifted emission or absorption features (e.g., Smith et. al. 1991, ApJ 367, 302).

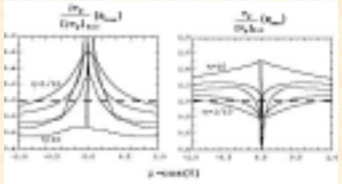
Fixed η_*(= 10), Different Stars

Log(ρ) (gm/cm^3)



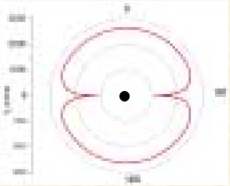
Log of density and magnetic fields for three MHD models with same magnetic confinement parameter, η_*, but for three different stars: standard ς Pup, factor-ten lower mass loss rate ς Pup, and Θ^1 Ori C.
Overall similarity: global configuration of field and flow depends mainly on the combination of stellar, wind, and magnetic properties that define η_*.

Mass Flux and Radial Outflow Velocity



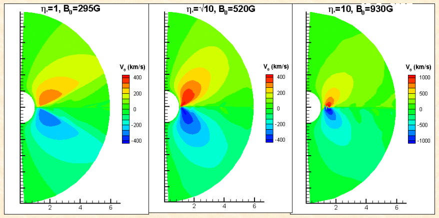
Radial mass flux density and radial flow speed at the outer boundary, r=6R_*, normalized by values of the corresponding non-magnetic model, for the final time snapshot (t=450 ksec).
The horizontal dashed lines mark the unit values for the non-magnetic case.
Note: decrease of mass loss rate for η_* >1

Velocity Modulation



Radial outflow velocity for the case η_* =1 plotted as a function of latitude.
Can magnetic fields shape Planetary Nebulae? See Dwarkadas, poster 135.09

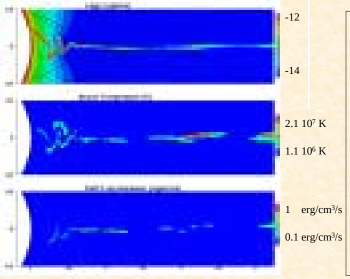
Latitudinal Velocity



Latitudinal velocities (V_θ) for η_* =1,sqrt(10),10 models.

Classically, these velocities determine the hardness of X-ray emission.
We find: oblique shocks are very important in X-ray emission as well. (see next figure)

X-ray Emission



For the strong magnetic confinement case (η_* =10), log of density superimposed with field lines, estimated shock temperature and X-ray emission above 0.1 keV (see preprint ud-Doula & Owocki 2002 for details).

Why is there a lot of hot gas outside the closed loops?
Slow radial speed within the disk fi high speed incoming material fully entrained with the disk fi big reduction of the speed fi high post-shock temperature.
See de Messieres et al., poster 135.12 for more on X-rays.

Conclusion

Overall properties of the wind depend on η_*.
For η_*<1, the wind extends the surface magnetic field into an open, nearly radial configuration.
For η_*>1, the field remains closed in loops near the equatorial surface. Wind outflows from opposite polarity footpoints channeled by fields into strong collision near the magnetic equator can lead to hard X-ray emission.
For all cases, the more rapid radial decline of magnetic vs. wind-kinetic-energy density implies the field is eventually dominated by the wind, and extended into radial configuration.
Stagnated post-shock wind material falls back onto the stellar surface in a complex pattern.
These simulations may be relevant in interpreting various observational signatures of wind variability, e.g. UV line Discrete Absorption Components , X-ray emission.