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# MASS EJECTION FROM OLD AND YOUNG STARS AND THE SUN

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RESUMEN. Para poder explicar: 1) la enorme cantidad de pérdida de masa y la baja velocidad asintótica de las estrellas gigantes de tipo tardío, y 2) los flujos de masa observados en protoestrellas, se sugiere un modelo para la pérdida de masa, en donde se usa un flujo de ondas de Alfvén como un mecanismo de aceleración para los vientos de estrellas de tipo tardío y vientos en protoestrellas. Se estudian los mecanismos de disipación de las ondas de Alfvén: los amortiguamientos no lineal, de superficie resonante y turbulento. En nuestro modelo se usa una geometría divergente $A(r) = A(R_o)\ (r/r_o)^S$ (donde $A(r)$ es el área a una distancia radial $r$, y $(A(r)/r^2)_{max}/(A(r_o)/r_o{}^2 = 10)$. También se sugiere un modelo para una geometría de hoyo coronal en el Sol. Se muestra que para satisfacer los datos observacionales en el Sol, tomando en cuenta la deposición del momento de las ondas de Alfvén sobre el viento, se necesita: (a) una divergencia lenta en un hoyo coronal hasta una altura de 0.01 - 0.1 $R_\odot$; seguido de (b) una divergencia rápida de hasta una altura aproximada de 1 $R_\odot$.

ABSTRACT: In order to explain (1) a large mass-loss rate and a small asymptotic flow speed of late-type giant stars and (2) the observed protostellar mass outflows, we suggest a model for mass loss, where we use a flux of Alfvén waves as a mechanism of acceleration for late-type giant star winds and protostellar winds. We study the Alfvén wave dissipation mechanisms: nonlinear damping, resonant surface damping, and turbulent damping. In our model we use a diverging geometry $A(r) = A(r_o)\ (r\ /\ r_o)^S$ (where $A(r)$ is the cross sectional area of the geometry at a radial distance $r$, and $(A(r)\ /\ r^2)_{max}/(A(r_o)/r_o{}^2) = 10)$. We also suggest a model for a coronal hole geometry in the sun. We show that in order to satisfy the observational data of the sun, taking into account Alfvén wave momentum deposition in the wind, we need: (a) a slow divergence in a coronal hole up to a height of 0.01 - 0.1 $R_\odot$; followed by (b) a rapid divergence up to a height of approximately 1 $R_\odot$.

*Key words*: HYDROMAGNETICS — STARS-LATE TYPE — STARS-MASS LOSS

## INTRODUCTION

Stellar mass loss has been systematically derived from observations and is present in almost all regions of the HR diagram.

In the spectra of late-type giant and supergiant stars, the blueshifted circumstellar absorption lines are interpreted as indicating the presence of cool and massive winds with: (i) a mean temperature $T \leq 10^4$ (K); (ii) terminal velocities inferred: $u_\infty \sim 50$ (kms/s), lower than the surface escape velocity ($v_{eo}$) (Deutsch, 1956, 1960; Weymann, 1962); and (iii) the mass loss rate $\dot{M} \sim 10^{-6} - 10^{-7}$ ($M_\odot$/yr).

On the other hand, observations concerning outflows from young stellar objects suggest that all stars pass through an outflow stage as a fundamental part of the star formation process (Lada, 1985; Snell, 1986). The outflows are highly energetic with kinetic energies of up to $10^{47}$ erg and exhibit a wide variety of observable phenomena. Some level of collimation usually exists for the outflows, the most notable examples being massive flows of cold molecular gas (e.g. Mundt and Fried, 1983). In general, these molecular outflows have: (1) a mean temperature $\overline{T} \sim 10 - 50$ (K); (2) $u_\infty \sim 10 - 50$ (kms/s) ($< v_{eo}$); and (3) mass loss rate $\dot{M} \sim 10^{-3} - 10^{-4}$ ($M_\odot$/yr). Also highly collimated optical jets have been observed in $H_\alpha$ images (Mundt and Fried, 1983). In addition,a disklike structure perpendicular to the directions of the outflows was found in redor of the central object (Kaifu et al., 1984).

Finally, the observational data on the sun put strong limits on possible flow geometries in coronal holes as (a) mass loss rate $\dot{M} \sim 2 \times 10^{-14}$ ($M_\odot$/yr); (b) temperature $T(r \sim 2\, r_o) \sim 10^6$ (K); (c) coronal base pressure $(nT)_o \sim 2 - 4 \times 10^{14}$ (cgs); (d) magnetic field $B_o \sim 10$ (G); (e) coronal hole area increasing by a factor $\sim 4 - 8$ in a height $\sim 1\, R_\odot$; (f) coronal holes occupying an area $A_e \sim 10 - 20\%$ of the solar surface; (g) solar wind velocity at 1AU ($u_\infty$) $\sim 500$ (kms/s).

## PREVIOUS STUDIES FOR LATE-TYPE AND PROTOSTARS

Several acceleration mechanisms have been proposed for driving these winds and one of the most promising involves the mass loss by an outward-directed flux of Alfvén waves (e.g. for late-type stars, Belcher and Olbert, 1975; Haisch et al., 1980; Hartmann and MacGregor, 1980) which have been observed and included in various solar wind models (Belcher and Davis, 1971); Alazraki and Couturier, 1971; Belcher, 1971; Hollweg, 1973; 1978; Jacques, 1977; Leer et al. 1982). In particular, Holzer, Fla and Leer (1983) proposed a model for mass loss using a collision damping length $L_{coll} \propto P^2$ (with P being the period of Alfvén waves) and concluded that such a wind can be only produced if $L_{coll} \sim 0.85 - 1.0 r_o$. This requires that the Alfvén wave period (P) must be fine tuned ($P \sim 1.77 \times 10^4$ s), which is unrealistic.

Also, many suggestions have been made in order to explain the observed bipolar molecular outflows, in particular, Pudritz and Norman (1986) proposed a model with trapped magnetic field lines in an accretion disk. It can be demonstrated, however, that there occurs a back reaction on the disk implying unrealistic mass accretion rates ($>10^{-2}$($M_\odot$/yr)) and mass of accretion disc ($>10^2$($M_\odot$)).

Alfvén waves are a good candidate for driving the observed galactic outflows. We have evidence for Alfvén waves in molecular clouds from the facts that (a) the velocity width of CO lines $\Delta V$ is approximately twice the gravitational energy, and (b) polarization maps indicate well-defined magnetic fields. These facts indicate that $\Delta V$ is wave-like and not eddy-like.

## PRESENT STUDY FOR LATE-TYPE STARS AND PROTOSTARS

In the present study, we suggest a model for mass ejection in old stars (Jatenco-Pereira and Opher, 1989a) and protostars (Jatenco-Pereira and Opher, 1989b), where we use a flux of Alfvén waves as a mechanism of wind acceleration. For long periods ($10^6$ s $> P > 2 \times 10^4$ s) collision absorption is small, and we assume that the dominant mechanism for the absorption of the Alfvén waves is:

1) Nonlinear damping - with the damping rate (e.g. Lagage and Cesarsky, 1983) being given by

$$\Gamma_{NL} \propto \omega \left( \frac{V_S}{V_A} \right) \frac{\rho < \delta v^2 >}{B^2/8\pi}$$

and the damping length $L_{NL} = V_A/\Gamma_{NL}$, where $V_S$ is the sound velocity, $V_A$ is the Alfvén velocity , $\rho < \delta v^2 >$ is the energy density of the Alfvén waves and $\omega$ is a characteristic Alfvén frequency.

2) Resonance surface damping - with the damping rate (e.g. Lee and Roberts, 1986) given by

$$\Gamma_{SW} \propto (ka) \frac{\omega_2^2 - \omega_1^2}{2\varpi}$$

and the damping length $L_{SW} = V_A/\Gamma_{SW}$, where inside of an inhomogeneity (e.g. a diverging open field geometry) we have an Alfvén wave frequency $\omega_2$ and on the outside a lower Alfvén wave frequency $\omega_1$; k is the wave number of the surface wave; a is the width of the inhomogeneity;and $\varpi^2 = (\omega_2^2 + \omega_1^2)/2$.

3) Turbulent damping - with the damping length (e.g. Hollweg, 1987) given by:

$$L_T \sim \frac{\rho<\delta^2>[u_{flow}+V_A]}{\rho<\delta v^2>^{3/2}/L_{cor}} \sim L_{cor}[u+V_A](<\delta v^2>)^{-1/2}$$

Hollweg (1986) assumes that $L_{cor} \propto B^{-1/2}$.

Our model is based on our knowledge of the magnetic structure of the Sun. At the surface, we observe coronal holes in which the opening solid angle ($\Omega_o$) changes to $\sim 7\Omega_o$ going from $r = R_\odot$($R_\odot$ = solar radius) to $r=3\ R_\odot$. Beyond 3 $R_\odot$ the edges of the coronal holes are radial and a net non-radial expansion factor of

$$F \equiv \frac{\Omega}{\Omega_o} = 7.26 \quad (r > 3R_\odot)$$

is found (Munro and Jackson, 1977). Thus, in our model we use a diverging geometry

$$A(r) = A(r_o)\left(\frac{r}{r_o}\right)^S$$

where A(r) is the cross-section of the geometry at a radial distance r, $r_o$ is the initial radius, and S is a parameter that determines the divergence of the geometry. In this study, at a given r, different values of S correspond to different values of $F = \Omega/\Omega_o$. At $r = fr_o$, for example, we have $F = \Omega/\Omega_o = [A(fr_o)/(fr_o)^2][A(r_o)/(r_o)^2]^{-1} = f^{(S-2)}$.

## RESULTS FOR LATE-TYPE STARS AND PROTOSTARS

From these two studies we found that:

- Large opening angles with $L_{NLO}$, $L_{SWO}$, and $L_{TO} \sim 0.1R_\odot$ produce $u_\infty < v_{eo}$ ; and
- Broad range of Alfvén waves periods [$10^6$ s $> P > 2x10^4$s].

The following parameters are predictions of the theory and can be observationally confirmed:

a) for late-type stars: 1) $(<\delta v^2>)_{max}^{1/2} \sim 30$(km/s) for $r \sim 2r_o$; and for $r = r_o$: 2) a magnetic field $B \sim 10$(G); 3) a flux of Alfvén waves $\phi \sim 3x10^6$ (ergs/cm$^2$-s); 4) a density $\rho \sim 10^{-13}$ g/cm$^3$; and , in general, 5) u(r) [e.g. $u(2r_o) \sim 30$ km/s $\rightarrow u(r_\infty) \sim 60$ km/s]

b) for protostars: 1) $(<\delta v^2>)_{max}^{1/2} \sim 20$ (km/s) for $r \sim 2r_o$; and for $r = r_o$: 2) a magnetic field $B \sim 40$(G); 3) a flux of Alfvén waves $\phi \sim 10^9$(ergs/cm$^2$-s); 4) a density $\rho \sim 10^{-8}$ g/cm$^3$; and, in general, 5) u(r) [e.g. $u(2r_o) \sim 20$ km/s $\rightarrow u(r_\infty) \sim 40$ km/s].

## PREVIOUS STUDIES FOR THE SOLAR WIND

Hollweg (1986), studying solar wind models produced by Alfvén waves, assumed classical thermal conductivity up to a radius $r \sim 10R_\odot$; anomalous thermal conductivity for $r > 10R_\odot$; and the divergent geometry of Munro and Jackson (1977). In the models of Hollweg (1986), parameters which yield correct base pressures have slow solar wind flow speeds. Hollweg (1986) was unable to find a set of parameters which simultaneously yield a high-speed solar wind flow and a reasonable base pressure.

## PRESENT STUDY FOR THE SOLAR WIND

We suggest a model for a coronal hole in the sun where in order to satisfy the bservational data of sun, we need: (a) a slow divergence in a coronal hole up to a height of .01-0.1$R_\odot$; followed by (b) a rapid divergence up to a height of approximately 1$R_\odot$ (Jatenco-ereira and Opher, 1989c).

## RESULTS FOR THE SOLAR WIND

Our results are consistent with observations of $\dot{M}$, T (r), $(nT)_o$, $B_o$, $\Omega_o \rightarrow 7\Omega_o$, $A_e$, u(r), the electron density as a function of temperature and the differential emission measure as a function of temperature.

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