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LYMAN ALPHA INITIATED WINDS IN LATE-TYPE STARS

B. M. Haisch,\* J. L. Linsky\*† and K. A. van der Hucht

Joint Institute for Laboratory Astrophysics, University of Colorado and National Bureau of Standards, Boulder, Colorado 80309

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Abstract

One of the first major results of the IUE survey of late-type stars was the discovery of a sharp division in the HR diagram between stars with solar type spectra (chromosphere and transition region lines) and those with non-solar type spectra (only chromosphere lines). This result is especially interesting in view of observational evidence for mass loss from G and K giants and supergiants discussed recently by both Reimers and Stencel. We have calculated models of both hot coronae and cool wind flows using stellar model chromospheres as starting points for stellar wind calculations in order to investigate the possibility of having a "supersonic transition locus" in the HR diagram dividing hot coronae from cool winds. We conclude from these models that the  $L\alpha$  flux may play an important role in determining the location of a stellar wind critical point. We investigate in detail the interaction of  $L\alpha$  radiation pressure with Alfvén waves in producing strong, low temperature stellar winds in the star Arcturus.

I. INTRODUCTION

An important result of the first survey of late-type stars by the International Ultraviolet Explorer (IUE) was the discovery by Linsky and Haisch (1979) of a sharp division in the HR diagram between stars which do or do not have outer atmospheres similar to the Sun. The short wavelength (1175-2000 Å) spectra of the solar type group contain chromospheric emission lines ( $L\alpha$ , C I, O I, Si II) indicative of 5000-10,000 K plasma and emission lines of He II, C II-IV, Si III-IV, N V indicative of 20,000-250,000 K plasma analogous to the solar transition region. The non-solar type group has spectra containing the chromospheric lines, but none of the hotter lines.

\* Guest Observer with the International Ultraviolet Explorer satellite.

† Staff Member, Quantum Physics Division, National Bureau of Standards.

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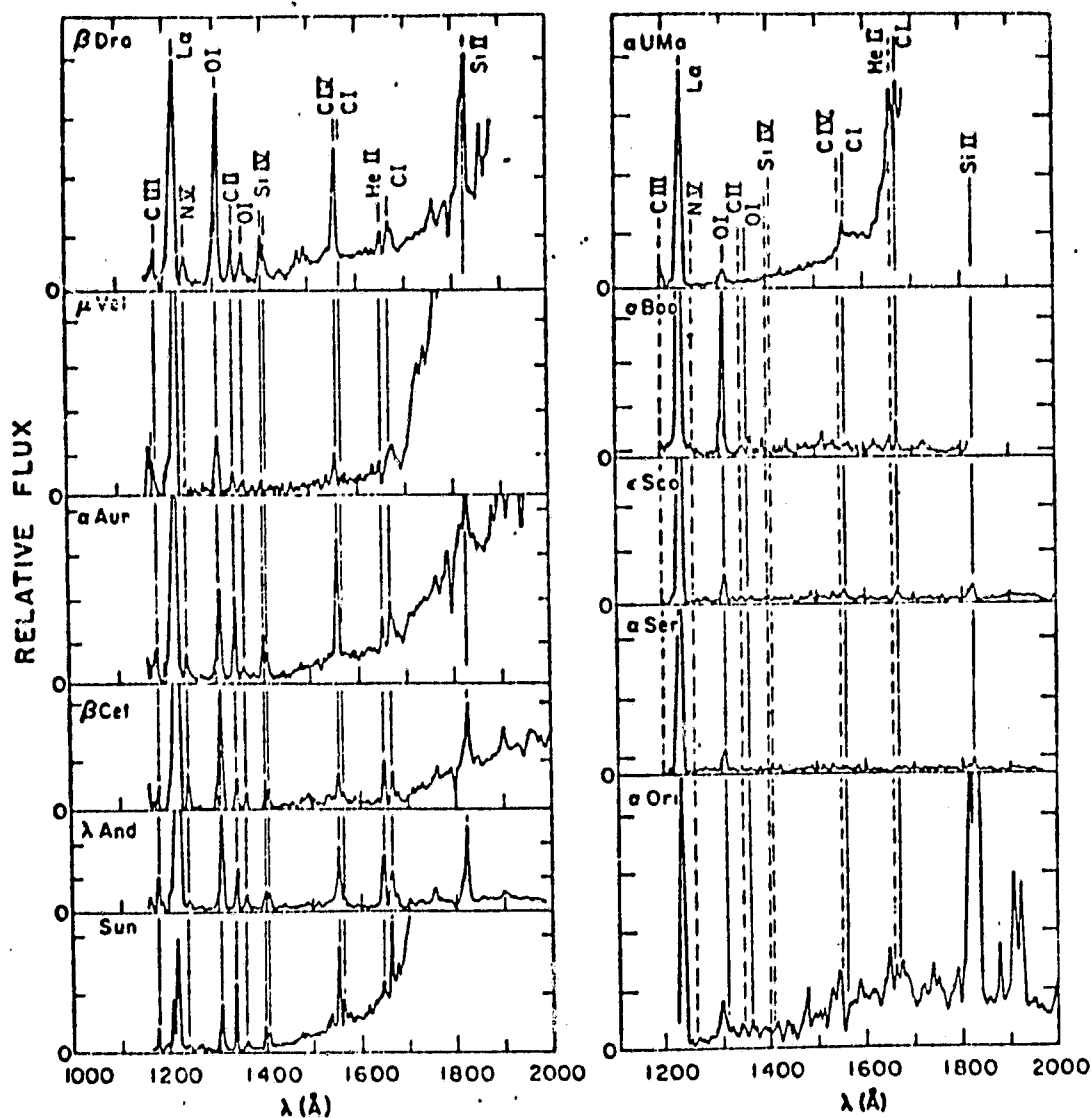
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The spectra of these two groups are shown in figure 1. This discovery is especially interesting in light of observational evidence in the visible spectrum for extensive mass loss from G and K giants and supergiants presented by Reimers (1977) and by Stencel (1978). Their results also indicate a division into two fairly distinct groups in about the same place in the HR diagram, a division characterized by the onset of large stellar winds.

The observations of Reimers (1977) and Stencel (1978) were used by Mullan (1978) to derive a "supersonic transition locus" (STL) in



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Fig. 1. Calibrated IUE spectra of the solar-type stars  $\beta$  Dra (G2 II),  $\mu$  Vel (G5 III),  $\alpha$  Aur (G5 III+G0 III),  $\beta$  Cet (K1 III), and  $\lambda$  And (G8 III-IV). Also included for reference is the quiet Sun spectrum of Rottman (1978), which is degraded to the IUE spectral resolution. Important spectral features are noted. (b) Calibrated IUE spectra of the non-solar type stars  $\alpha$  Ori (M2 Iab),  $\alpha$  UMa (K0 II-III),  $\alpha$  Boo (K2 III),  $\epsilon$  Sco (K2 III-IV), and  $\alpha$  Ser (K2 III). Dashed lines, spectral lines absent in the data.

the HR diagram. In Mullan's picture, stellar wind flows are expected to become supersonic at the base of the corona along a locus of points in the HR diagram corresponding to the observed mass-loss division.

Mullan's STL is also in rough agreement with the dividing line between solar type and non-solar type spectra in the HR diagram drawn by Linsky and Haisch (1979). A plausible physical connection between these two ideas is that when a strong wind develops it dominates the energy balance such that the major portion of the available nonradiative heating above the chromosphere goes into driving the mass flow rather than into heating a corona. Thus late-type stars either have a chromosphere and a hot corona, or they have a chromosphere and a large wind. Although this simple picture is appealing, there are some serious problems. The minimum flux corona theory that forms the basis of Mullan's arguments incorporates various simplifications and approximations which may not be valid, especially in the limiting case used by Mullan (see Antiokos and Underwood 1978 and Vaiana and Rosner 1978 for discussions of the pros and cons of the minimum flux corona theory debate). Another serious difficulty is that one cannot simply push material through a critical point. A proper matching of densities, temperatures, and velocities is required to get through the "throat of the nozzle" (see Brandt 1970, pp. 72-75), and the addition of new material into the existing steady-state flow would change the nature of the temperature and velocity structure and upset the balance that defines the critical point in the first place.

We have investigated in detail various possible stellar wind models for one of the IUE non-solar type stars, Arcturus ( $\alpha$  Boo, K2IIIp), which has been observed to have a variable chromospheric outflow (Chiu et al. 1977; van der Hucht et al. 1979) and which has a chromospheric model (Ayres and Linsky 1975; Haisch et al. 1977) that can be used as a starting point for stellar wind calculations. Our first models attempted to take into account the energy balance of mass flux, conductive flux, radiative cooling, and various forms of mechanical energy dissipation, but these models were found to have high temperature coronae ( $T > 3 \times 10^6$  K). Other models having various pre-specified temperature distributions with  $T_{\max} < 20,000$  K yielded analytical solutions for the mass flow based on the mass and momentum conservation equations alone which resulted in very low wind velocities near the stellar surface and very low mass loss rates. Models including divergence of the wind flow also failed by several orders

of magnitude to account for the outflow rates sometimes seen in Arcturus by Chiu et al. (1977) of near sonic velocities in the upper chromosphere. We conclude, therefore, that cool stellar winds which become supersonic in or near the chromosphere require a source of momentum input to the mass flow.

Radiation pressure on dust grains has been suggested as a possible source of momentum input in M-type supergiants (Jennings 1973; Kwok 1975; Hagan 1978), but K-type giants and supergiants do not usually exhibit infrared excesses or polarization indicative of dusty circumstellar envelopes. We decided to look elsewhere for an adequate source of radiation pressure on the gas, and were surprised to discover that the scattering of  $\text{L}\alpha$  photons in an optically thin envelope could provide a large force locally comparable to gravity. A closer examination of a detailed chromospheric model for the  $\text{L}\alpha$  flux indicates that the radiation pressure gradient exceeds gravity by as much as a factor of 4 in the upper chromosphere, and provides a significant "push" at line center optical depths greater than  $\tau = 200$ . Although locally large, the force due to the  $\text{L}\alpha$  flux is only significant over a limited region in the upper chromosphere, and thus by itself could not provide sufficient momentum to drive a wind. The nature of any stellar wind, however, must be strongly affected by the presence of the steep radiative pressure gradient, and the interaction of this effect with other sources of momentum input, such as Alfvén waves or acoustic waves, may bring about a multiple critical point topology possibly involving a stationary shock front. Thus the presence of a strong  $\text{L}\alpha$  force, although insufficient by itself to bring about a large mass loss, could be viewed as a necessary condition for a stellar wind driven primarily by some other mechanism or mechanisms, since even a small outflow at some point in the atmosphere by continuity requires an outflow everywhere. This in turn may be possible only in conjunction with a much larger stellar wind. We examine the  $\text{L}\alpha$  flux radiation pressure, Alfvén wave pressure, and the formation of a stationary shock in a possible cool wind model for Arcturus. Our results should be viewed as an exploratory attempt to delimit some of the constraints on cool wind flows. Lastly, we extrapolate conditions in Arcturus to other G, K and M stars to delineate in which region of the HR diagram cool winds may be important.

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## II. THE WIND MODELS

We chose Arcturus as our prototype model for cool stellar winds in late-type stars for several reasons: the star lies just to the right of the Linsky-Haisch division in the HR diagram, it has been observed to have a variable chromospheric outflow on the order of  $10\text{--}20 \text{ km s}^{-1}$ , and it has a well-modeled chromosphere. It is much easier to evaluate the importance of various terms in the flow equations when the stellar parameters are well specified, and only a detailed model atmosphere can provide the  $L_\alpha$  fluxes needed for an examination of the radiative force in the upper chromosphere.

We assume a maximum temperature  $T_{\text{max}} \approx 20,000 \text{ K}$  in the chromosphere or extended wind region, and we take as fundamental parameters  $R_\star = 1.9 \times 10^{12} \text{ cm}$  ( $27.3 R_\odot$ ) and  $g = 50 \text{ cm/s}^2$  (Ayres and Linsky 1975). We extend the Ayres-Linsky model chromosphere to include a  $20,000 \text{ K}$  plateau. In this model  $R(T=20,000 \text{ K}) = 2.017 \times 10^{12} \text{ cm}$  ( $1.06 R_\star$ ) and  $n(T=20,000 \text{ K}) = 2 \times 10^8 \text{ cm}^{-3}$ . More than 98% of the hydrogen is ionized at this point, and thus  $n_p \approx n_e \approx n$ . We assume a mean particle weight  $\mu = 0.7$ , and for simplicity of notation we let  $2 \mu m_H = m = 2.33 \times 10^{-24} \text{ g}$ , i.e.  $\rho = nm$ .

We now ask the question, "How much radial wind flow can be generated by the thermal energy of the gas alone, with and without possible temperature gradients?" The equations of mass and momentum conservation are

$$nvr^2 = n_0 v_0 r_0^2 \quad , \quad (1)$$

$$v \frac{dv}{dr} = \left( \frac{4kT(r)}{r} - \frac{GMm}{r^2} - 2k \frac{dT}{dr} \right) / \left( m - \frac{2kT(r)}{v^2} \right) \quad . \quad (2)$$

We have used the perfect gas law,  $P = 2nkT$ , to replace the pressure gradient, and for simplicity bypass energy balance considerations by specifying a priori a temperature structure.

We have analyzed solutions of (2) for four possible models

- a)  $T = 20,000 \text{ K}$  for all  $r > R_\star$ .
- b)  $r_c$  (critical point)  $= R_\star$ ,  $T(r_c) = 20,000 \text{ K}$ ,  $dT/dr < 0$  for  $r > r_c$ .
- c)  $T = 20,000 \text{ K}$  for  $R_\star < r < r_c$ ,  $dT/dr < 0$  for  $r > r_c$ ,  $v(r) = v_c$  for  $r > r_c$ ,  $T(r) \rightarrow 0$  at  $\infty$ .
- d)  $T = 20,000 \text{ K}$  for  $R_\star < r < r_c$ ,  $dT/dr < 0$  for  $r > r_c$ ,  $v(r) = v_c$  for  $r > r_c$ ,  $T(r) \rightarrow 0$  at  $R$ , where  $R$  is determined by interstellar pressure conditions.

For all of these models the mass loss rates are extremely small,  $< 10^{-17} M_{\odot}/\text{yr.}$  Clearly a spherically symmetric evaporative wind model is not feasible for temperatures less than 20,000 K.

It is probable that Arcturus, like the Sun, has an inhomogeneous chromosphere such that mass loss involves inhomogeneous flows. The possible existence of giant convective cells has been discussed by Schwarzschild (1975) and by Chiu *et al.* (1977) in connection with their observations that the Ca II K line profiles are variable. An excellent discussion of the effects of diverging geometries on solar and stellar winds is given by Holzer (1977). Assuming as before various given temperature structures with the constraint that  $T_{\text{max}} < 20,000$  K, we investigate the effect of divergence in the flow by assuming the mass and momentum conservation equations may be written as

$$nvA = n_0 v_0 A_0 \quad (3)$$

$$v \frac{dv}{dr} = \left[ \frac{2kT(r)}{A(r)} \frac{dA}{dr} - \frac{GM_m}{r^2} - 2k \frac{dT}{dr} \right] / \left[ m - \frac{2kT}{v^2} \right] \quad (4)$$

The flow takes the form of diverging cones in this first order approximation. We parametrize the cross section  $A(r)$  of the flow as

$$A(r) = r^2 w(r) \quad (5)$$

where the expansion factor  $w(r)$  is allowed to have various assumed functional forms, and  $w(r_0) = 1$ , thus normalizing the flow to a rate per steradian.

We again analyze solutions of the equation of motion (1) for several possible configurations allowing for divergence of the flow. No reasonable combination of expansion factors  $w(r)$  or temperature gradients will produce a stellar wind involving large mass loss.

A crude calculation of the effects of  $L\alpha$  resonance scattering in an optically thin envelope showed that a substantial radiative force could result. We therefore chose a model chromosphere based on the Ayres and Linsky (1975) modeling of the Ca II H and K lines, and ran a five-level ionization equilibrium-non-LTE radiative transfer program for hydrogen to calculate  $L\alpha$  fluxes in the upper chromosphere. The model is shown in figure 2. We found that at optical depths as high as  $\tau \approx 200$ , the radiative force exceeds gravity. For a spherically symmetric outflow the equation of momentum conservation, including the effect of radiation pressure, is

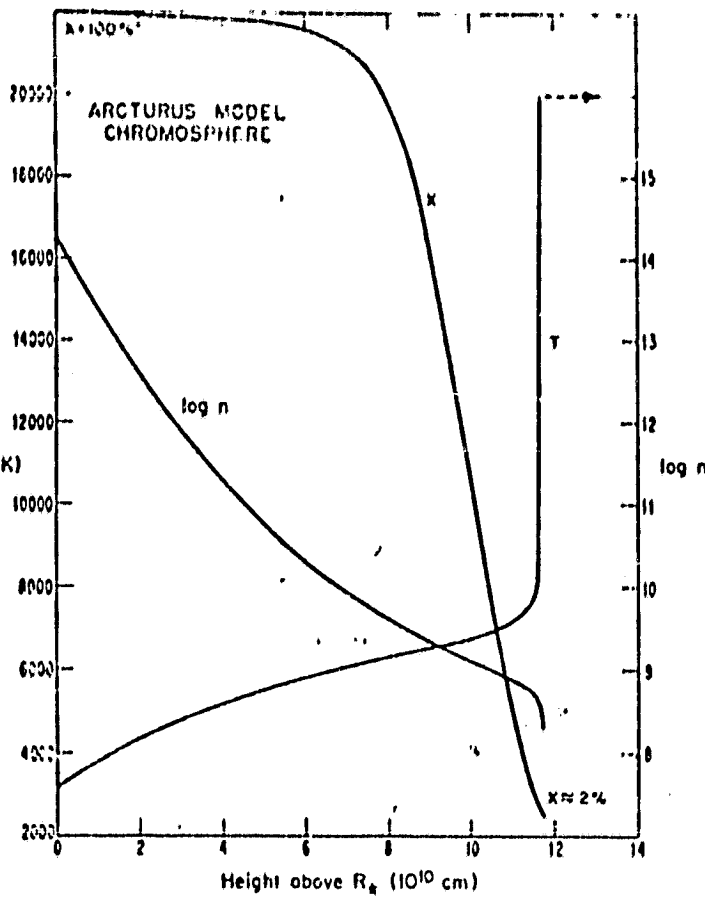


Fig. 2. Distributions of total density, temperature, and fractional neutral hydrogen (x) in the 20,000 K plateau model chromosphere for Arcturus. The scale for x is linear with 100% at the top and 0% at the bottom.

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$$v \frac{dv}{dr} = \left[ \frac{4kT(r)}{r} - \frac{GMm}{r^2} - 2k \frac{dT}{dr} - \frac{1}{n(r)} \frac{dP_R}{dr} \right] / \left[ m - \frac{2kT(r)}{v^2} \right] \quad (6)$$

where

$$-\frac{1}{n(r)} \frac{dP_R}{dr} = x(r) \frac{\pi}{c} (0.011) \bar{F}_v(r) \quad (7)$$

$\bar{F}_v$  is the mean  $L\alpha$  flux near line center, and x the fraction of neutral hydrogen. The numerator of (6) goes through zero at the top of the chromosphere due to the sudden onset of the radiative force. We call this the critical point,  $r_c$ , and choose  $v(r_c)$  so that the denominator also goes through zero. (6) may be solved for  $v(r < r_c)$  throughout the model chromosphere using the known temperature-density structure. This results in  $v(r)$  consistent with the prespecified  $n(r)$ , i.e.  $nvr^2 \approx \text{constant}$  for a mass loss rate of  $\sim 10^{-9} M_\odot/\text{yr}^{-1}$ .

Above  $r_c$ , however, the radiative force soon diminishes, and the wind finds itself with a supersonic velocity, but no means of maintaining that velocity. The multiple critical point topologies of Holzer (1977) allow for a wind flow passing through an innermost critical point close to a star's surface, around a second critical point, and out through an outermost critical point presumably at a large distance from the star. Such a topology may involve a shock discontinuity. We therefore let our wind model shock above  $r_c$ ,



evaluate the Rankine-Hugoniot relations for the post-shock conditions, and examine the wind flow in the regime of the second and third critical points. We find that the thermal energy of the gas is insufficient to maintain the flow.

To satisfy a clear need for an additional source of momentum input, we choose among several potential sources the pressure due to outwardly propagating Alfvén waves. Alfvén waves have been identified in the solar wind and are observed to be associated with, and are perhaps responsible for, solar active regions (Hollweg 1973). We incorporate an Alfvén wave pressure gradient term into the equation of motion while limiting ourselves to regimes where heating is negligible,

$$\left(m - \frac{2kT}{v^2}\right) \frac{dv}{dr} = \frac{1}{v} \left[ \frac{4kT(r)}{r} - \frac{GMm'}{r^2} - 2k \frac{dT}{dr} - \frac{1}{n(r)} \frac{d}{dr} \left\langle \delta B^2(r) \right\rangle \right], \quad (8)$$

where  $\langle \delta B^2 \rangle$  is the fluctuating part of the magnetic field. If we make certain simplifying assumptions, such as a radial magnetic field,  $\langle \delta B^2 \rangle \ll B^2$ , and Alfvén velocities  $v_A \gg v_{\text{flow}}$ , (8) may be solved for various magnetic field strengths. We re-examine the wind flow in our model chromosphere at the critical point due to the  $L\alpha$  force (which involves adding the term  $-[1/n(r)](dP_R/dr)$  to (8) in the upper chromosphere), and in a shock and post-shock regime. One such solution is shown schematically in figure 3.

At present we do not have a completely consistent solution for such a wind flow. Somewhat higher magnetic field strengths are required to maintain the mass flow in the outer regimes of the Holzer multiple critical point topologies than are consistent with mass flux conservation in the model chromosphere. However we feel that the interaction of a strong  $L\alpha$  force with other sources of momentum input will point to some significant new configurations for stellar wind models in late type stars.

#### VII. IMPLICATIONS FOR OTHER LATE-TYPE STARS

The role of the  $L\alpha$  flux is to define a condition which in turn can only be satisfied by the existence of a certain stellar wind. If we accept that the  $L\alpha$  force exceeds gravity somewhere in a stellar chromosphere, then mass loss and a transition through a singular point in the momentum equation both must occur. If we also require that the maximum temperature not exceed a certain value determined observationally, then the constraints on possible wind models

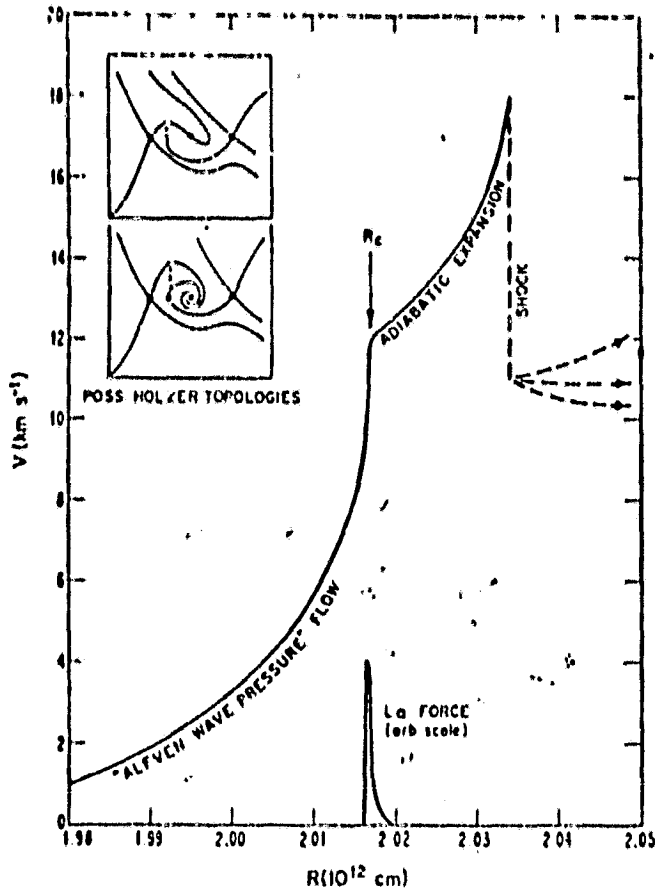


Fig. 3. A schematic representation of a wind model for  $\langle \delta B^2 \rangle \approx 0.01$  near the critical point showing the acceleration to the critical point, adiabatic expansion and a shock transition.  $R_c$  is the critical point and possible Holzer topologies are indicated.

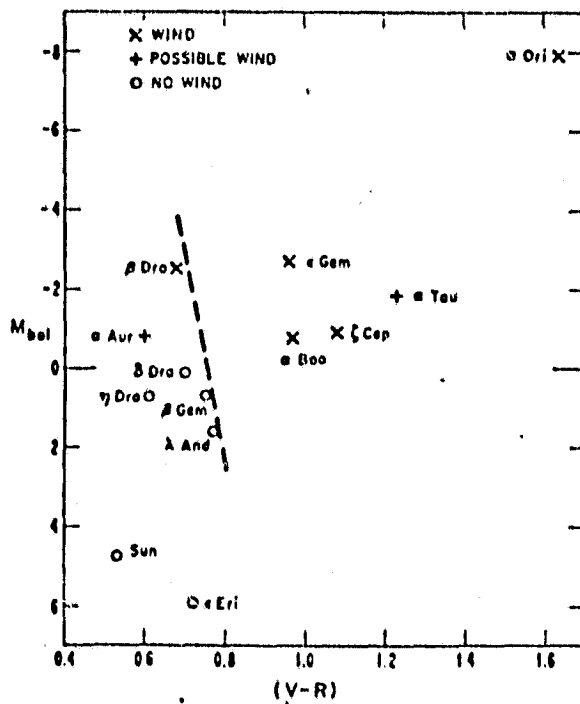


Fig. 4. An HR diagram with our predictions of which stars have  $L_\alpha$  initiated cool winds. The dashed line indicates the Linsky-Haisch empirical division between stars with hot coronae (to the left) and stars with no evidence of material hotter than 20,000 K (to the right).

Fulfilling these conditions are quite severe. We have here presented only one schematic wind model; one that relies on a combination of several different regimes in which one or the other type of mechanism dominates the solution. Other models must certainly be possible, for example, with acoustic wave pressure instead of Alfvén wave pressure (see Ulmschneider 1979).

We extrapolate our results to other late-type stars by assuming similar ionization and temperature conditions, and derive a  $\text{L}\alpha$  "supersonic transition locus" by comparing  $\text{L}\alpha$  fluxes and stellar gravities. Figure 4 shows an HR diagram with our predictions of large cool winds based on a comparison of  $\text{L}\alpha$  fluxes to stellar gravities for some representative G, K and M stars. The dashed line is the division between stars with hot coronae (to the left) and those with cool winds (to the right) determined observationally by Linsky and Haisch (1979). We suggest that the onset of  $\text{L}\alpha$  initiated winds is responsible for this division by providing a large sink for the nonradiative heating which would otherwise produce a hot corona.

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#### REFERENCES

- Antiokos, S. K. and Underwood, J. H. 1978, Astr. Ap., 68, L19.  
Ayres, T. R. and Linsky, J. L. 1975, Ap. J., 200, 660.  
Brandt, J. C. 1970, Introduction to the Solar Wind (San Francisco: Freeman).  
Chiu, H.-Y., Adams, P. J., Linsky, J. L., Basri, G. S., Maran, S. P. and Hobbs, R. W. 1977, Ap. J., 211, 453.  
Hagan, W. 1978, Ap. J. Suppl., 38, 1.  
Haisch, B. M., Linsky, J. L., Weinstein, A. and Shine, R. A. 1977, Ap. J., 214, 785.  
Hollweg, J. V. 1973, Ap. J., 181, 547.  
Holzer, T. E. 1977, J. Geophys. Res., 82, 23.  
v. d. Hucht, K., Stencel, R. E., Haisch, B. M. and Kondo, Y. 1979, Astr. Ap. Suppl., in press.  
Jennings, M. C. 1973, Ap. J., 185, 197.  
Kwok, S. 1975, Ap. J., 220, 962.  
Linsky, J. L. and Haisch, B. M. 1979, Ap. J. (Letters), 229, L27.  
Nullan, D. J. 1978, Ap. J., 226, 151.

Reimers, D. 1977, Astr. Ap., 57, 395.

\_\_\_\_\_. 1978, in The Interaction of Variable Stars with Their Environment, IAU Colloquium No. 42, eds. Kippenhahn, R., Rake, J. and Strohmeier, W. (Dordrecht: Reidel), p. 559.

Rottman, G. J. 1978, private communication.

Schwarzschild, M. 1975, Ap. J., 195, 137.

Stencel, R. E. 1978, Ap. J. (Letters), 223, L37.

Ulmschneider, P. 1979, Sp. Sci. Rev., submitted.

Vaiana, G. S. and Rosner, R. 1978, Ann. Rev. Astr. Ap., 16, 393.

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