COOL STAR WINDS - RECENT OBSERVATIONS AND THEORETICAL IMPLICATIONS

L. Hartmann
Harvard-Smithsonian Center for Astrophysics
60 Garden Street
Cambridge, MA 02138, U.S.A.

1. Introduction

Much of our knowledge of winds from late-type stars comes from the detection of ejected material, called circumstellar shells, as observed in absorption lines of low-excitation species such as Mg II, Ca II, Na I, and K I (cf. Reimers 1977). Observations of CS shells are difficult to translate into quantitative mass loss rates, a limitation which has not helped to test various mass loss mechanisms. The data clearly demonstrate one very important fact: shell velocities are very low. In fact, they are so much lower than surface escape velocities that it was not clear that material is actually being lost until Deutsch (1956) detected the existence of the CS absorption shells ejected from α Her and α Sco in the spectra of distant companion stars. Today it is possible to demonstrate the expansion of shells out to several thousand stellar radii in K I scattering (Honeycutt et al. 1980).

The information obtained from studies of CS absorption is limited, because the shells represent asymptotic states of stellar winds. Recent observations have begun to focus on the physical conditions in the inner wind, where acceleration is taking place. These data are leading us to a new picture of stellar winds which differs quite dramatically from the common views of a few years ago.

I have attempted to address two general problems in the following brief survey of recent observational results. The first question is whether mass loss from low-gravity stars is related to solar-type activity. This is an important question to answer, for one may be able to draw on a great deal of detailed solar physics in attempting to explain stellar behavior. The second problem is the description of energy balance in the accelerating, near-wind region, and what clues the energetics provide toward understanding the origin of the flow.

Richard M. West (ed.), Highlights of Astronomy, Vol. 6, 549–563.

2. Low-Temperature Winds and Solar-Type Activity

The launch of the International Ultraviolet Explorer (IUE) satellite made possible the direct detection of gas in the temperature regime 10^4K - 2 x 10^5K in a large sample of stars for the first time. Similarly, observations with the HEAO-2 (Einstein) satellite indicated the presence of x-ray emission from many late-type stars. The combined space observations have given us a much clearer picture of the temperature structure of cool star envelopes.

The IUE observations show that low-gravity stars do not exhibit emission from regions at 10^5K, and that CS shells are strongly anticorrelated with C IV emission (Linsky and Haisch 1979; Dupree and Hartmann 1980). Emission characteristic of the solar transition-region is almost entirely confined to the region below the CS shell boundary in the HR diagram (*cf.* Simon, Linsky, and Stencel 1982); this is also true of the X-rays which are the presumed signature of coronal emission (Vaiana *et al.* 1981). These observations rule out the possibility of thermally-driven winds. At first sight, the disappearance of high-temperature, solar-type atmospheres for stars with CS shells might suggest the sudden onset of a new mechanism of mass loss unrelated to solar activity. Closer examination of the data indicates that this mass loss transition is in fact somewhat gradual. The "hybrid atmosphere" stars (Hartmann, Dupree, and Raymond 1980, 1981) exhibit both CS shells and 10^5K emission regions. Positioned near the CS shell boundary in the HR diagram (Figure 1), the hybrid stars appear to provide a link between solar activity and cool winds.

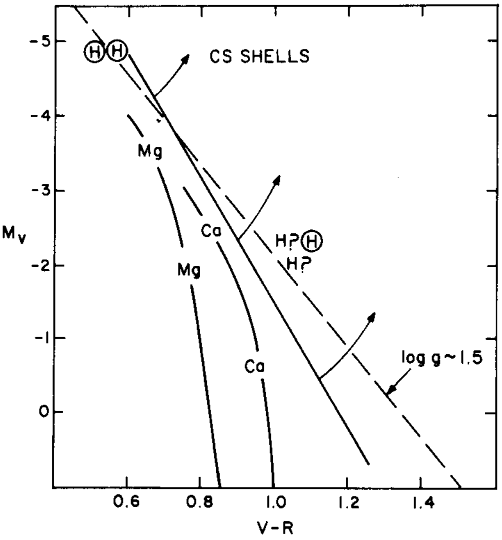


Figure 1. Positions of hybrid stars and CS shell stars in the HR diagram. Stars to the right of the Mg II and Ca II lines tend to exhibit asymmetries in these lines suggestive of mass loss.

It is difficult to tell how ubiquitous hybrid stars are, because detection of the high-temperature emission requires very long exposures with IUE. Recent work indicates that they may not be very uncommon (Reimers 1982), although this point is still debated (Simon, Linsky, and Stencel 1982).

Another indication of a gradual increase in mass loss rates near the CS boundary has come from the statistical surveys of Ca II and Mg II profiles by Stencel and Mullan (1980). This work showed that, for stars of decreasing surface gravity, the Mg II and Ca II lines increasingly tend to exhibit asymmetries, in the sense that the short wavelength peak is weaker than the long-wavelength emission peak. Although the asymmetries cannot be uniquely interpreted, one simple explanation is differential expansion due to mass loss. It is suggestive that the asymmetries appear near the CS boundary in the HR diagram (Figure 1).

As one proceeds toward the upper right-hand corner of the HR diagram, stars statistically first exhibit Mg II asymmetry in the sense of mass loss, followed by Ca II asymmetry, and finally CS shells. This progression is exactly what one would expect from a gradual increase in mass loss, with the wind expansion becoming observable in successively weaker lines.

The tentative inference from these data is that mass loss does not turn on instantaneously, although the temperature structure of the outer atmosphere undergoes a rapid change. Consider a star just below the CS boundary, which has UV and X-ray emission at levels comparable to the Sun. This suggests that surface conditions are similar to those of the solar atmosphere. It is not obvious why the patterns of convection and magnetic field activity should vary dramatically as the star evolves the small amount necessary to place it on the other side of the CS boundary, resulting in a cool rather than a hot envelope. This suggests that it is a change in the response of the atmosphere, rather than changes in momentum and energy input, which reduces wind temperatures (Hartmann 1981).

3. Energy and Momentum Balance in Stellar Envelopes

Optical observations of eclipsing systems have provided evidence for large turbulent motions in supergiant atmospheres (Wright 1980). Ultraviolet observations now permit the study of motions in high-excitation ions. In a high-dispersion IUE study of the K4II hybrid star α TrA, Hartmann, Dupree, and Raymond (1981) found that the transition-region lines were extremely wide, with some optically thin lines indicating large non-thermal motions $\sim 100 \text{ km s}^{-1}$. Subsequently, Ayres et al. (1982) observed this phenomenon in a wider variety of stars, showing that the broadening is most prominent in low-gravity stars, or in objects with large mechanical energy fluxes such as RS

CVn variables.

The interpretation of these motions is open to debate. Hartmann, Dupree, and Raymond (1981) suggested that the line broadening in α TrA is due to a combination of wind expansion and wave turbulence. On the other hand, Ayres et al. (1982) pointed out that stars without CS shells can have comparable line widths. These authors feel that the absence of CS shells rules out wind expansion, and instead postulate complicated upflows and downflows. In any event, it is clear that transition regions of these stars are not in hydrostatic equilibrium, and that important dynamical processes are occurring which must be taken into account.

Similarly, evidence is accumulating that the low-temperature atmospheres of stars with CS shells are neither in hydrostatic nor radiative equilibrium. This evidence is provided from studies of what have been termed "extended chromospheres", i.e. envelopes at chromospheric ($\sim 10^4$ K) temperatures which have scale heights of the order of the stellar radius. For example, Goldberg (1979) showed that the infrared triplet of Ca II and Hα in the M supergiant α Ori exhibit blue-shifted absorption, as if they are being formed at least in part in the accelerating wind region. Population of these excited levels appears to require some mechanical heating. The absorption does not seem to take part in the slow, irregular pulsation of the photosphere, suggesting that the chromosphere is physically extended from the surface of the star.

This picture seems to be borne out by occultation measurements and speckle interferometry. White, Kreidl, and Goldberg (1982) and Goldberg et al. (1982) have presented evidence for spatially extended Hα emission surrounding M supergiants from occultation measurements and speckle interferometry. In addition, optically thick free-free emission from α Ori has been detected at a variety of radio frequencies (Altenhoff, Oster, and Wendker 1979; Bowers and Kundu 1979; Newell and Hjellming 1982). The data appear to require fractional ionizations $\sim 1\%$, and temperatures of 5000 - 10^4 K, ranging over several stellar radii (Wischnewski and Wendker 1981).

Ultraviolet observations have enabled new density diagnostics to be used for stellar envelopes. Stencel et al. (1981) have shown that observations of the C II λ2325 line with IUE appear to require envelopes with electron densities $\sim 10^8$ cm^{-3} and scale heights $\sim 1\ R_*$ for several red giants.

Radiative equilibrium cannot explain the ionization and/or temperatures of the envelopes surrounding these cool stars. In Figure 2 I show an estimate for the total radiative cooling from an extended chromosphere in comparison with other stars with high-temperature atmospheres. The extended chromosphere estimate is very crude, because the cooling rate depends very sensitively on the exact chromospheric temperatures, which are poorly known. However, it is clear that the radiative losses from extended chromospheres may represent a significant energy loss, comparable to what is being deposited in the outer atmosphere of the Sun. Further observational study at a variety of wavelengths should enable us to empirically determine the total energy radiated by the extended chromosphere.

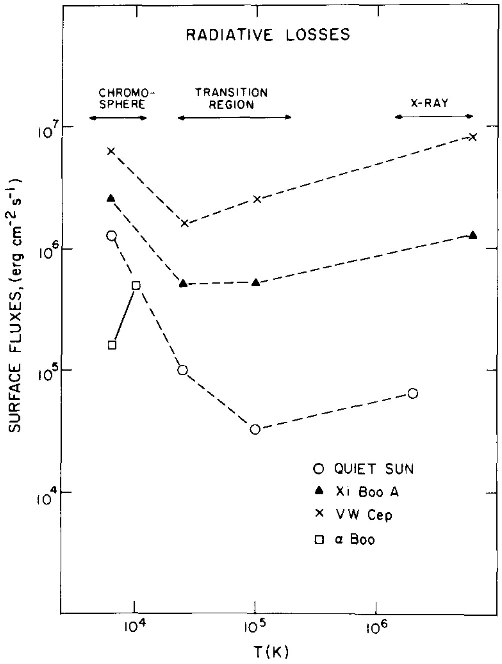


Figure 2. Radiative losses in different temperature regimes. The second chromospheric point for α Boo refers to the extended component.

In some cases we have velocity information which clearly shows that the extended chromosphere is not in hydrostatic equilibrium. However, in all cases the expected scale height due to thermal pressure alone is a tiny fraction of the stellar radius. The spatial extension required clearly shows that some mechanism of momentum deposition is controlling the chromospheric structure.

4. Wave-Driven Wind Theory

The first theoretical studies of mass loss processes in late-type stars understandably concentrated on the coolest and most luminous stars, which have the most massive winds. Mechanisms peculiar to these stars, such as pulsation and radiation pressure on dust, were proposed to account for the observed flows, and these forces may be very important in some objects. However, as shown in Fig. 1, CS shells are observed over a rather wide range in the HR diagram, and can be detected in stars for which neither dust emission or pulsation are present. There is a general tendency for wind speeds to decrease and mass loss rates to increase with decreasing stellar gravity, but there is no discernable qualitative difference between the winds of low and high gravity stars. One is led to seek mechanisms of more general applicability.

The considerations presented in the previous section indicate that one might investigate a mass loss mechanism which is a manifestation of solar-type activity. Following the discovery of Alfven waves in the solar wind (Belcher and Davis 1971), it was suggested by a number of authors that such waves may add significantly to the momentum and energy of the flow (Belcher 1971; Hollweg 1973; Jacques 1978). The possibility that such waves can drive mass loss in stars was considered by Belcher and Olbert (1975) and by Haisch, Linsky and Basri (1980), but Hartmann and MacGregor (1980) first made detailed wind solutions applied to the particular problem of low velocity winds.

The main reason for selecting Alfven waves rather than other possible modes is that they are non-compressive in first order. This means that they can carry relatively large energy fluxes, with supersonic wave amplitudes, without excessive damping. Acoustic waves, on the other hand, appear to dissipate too rapidly to be effective in driving mass loss for plausible wave periods (Hartmann and MacGregor 1980).

The general properties of wave-driven winds can be sketched in the following way. With the assumption of a purely radial magnetic field, the steady-state equation of motion takes the simple form

$$v \frac{dv}{dr} + \frac{1}{\rho} \frac{d}{dr} \left(P + \frac{<\delta B^2>}{8\pi} \right) = - \frac{GM}{r^2} , \qquad (1)$$

where v, ρ, and P are the gas velocity, density, and thermal pressure, respectively, and $<\delta B^2>$ is the mean square turbulent magnetic field. This equation shows that turbulent pressure takes over the role of gas pressure in the ordinary thermally-driven wind. The analogy can be extended even further to understand the nature of the critical point(s) of the momentum equation,

$$dv/dr = N/D \quad , \qquad (2)$$

where N and D simultaneously vanish. For the isothermal Parker wind, N=0 requires $P{=}GM\rho/2r$, and D=0 results in $\rho v^2{=}P$. The analogous conditions for the wave driven wind are $\delta B^2/16\pi \sim GM\rho/2r$ and $\rho v^2 \sim \delta B^2/32\pi$.

The critical point conditions, together with the radial evolution of the wave energy $F = \delta B^2 A/8\pi$, where A is the Alfven speed, permit the mass loss rate to be calculated. It can be shown that the critical points of the solutions are typically at r = 1.5 - 1.8R, and that within this region F varies roughly as r^{-2}. Using these constraints and the critical point conditions, one can derive the scaling of the mass loss rate,

$$\dot{M} \sim 10^{-25} M^{-1.5} R^{3.5} (F_5/B_o)^2 M_\odot \, yr^{-1} \quad , \tag{3}$$

where F_5 is the wave energy flux in units of 10^5 erg cm^{-2} s^{-1} and B_o is the magnetic field in gauss.

Ideally, one would test the theory from measurements of wave fluxes, magnetic field strengths, and mass loss rates. Unfortunately, we don't have magnetic field measurements, and observational mass loss rates are only order of magnitude estimates. However, it is suggestive that the observed mass loss rates can be obtained with wave fluxes ($\sim 10^5$ erg cm^{-2} s^{-1}) and magnetic field strengths ($\sim$ gauss) typical of the Sun.

The presence of waves predicts that lines should be broadened. Force balance at the critical point requires $\delta B_c^2/8\pi\rho_c \sim GM/r_c$. Using the Alfven-wave relation $\delta B/B = \delta v/A$, this condition becomes $\delta v_c^2 \sim GM/r_c$, that is, the wave amplitude is of the order of escape velocity at the critical point. This means that line broadening will be significantly affected by wave motions.

Although the Alfvenic mode is attractive in that it does not damp too rapidly, there are severe difficulties if the waves do not dissipate rapidly enough. Hartmann and MacGregor (1980) showed that, if undamped, Alfven waves tend to drive mass loss at unacceptably high velocities. By parameterizing the dissipation, they were able to show that the waves must damp on a scale length of the order of the stellar radius if this mechanism is to account for cool, low-velocity winds.

Many effects could contribute to wave damping, depending upon details, wave energy generation, periods, magnetic field geometry, etc. At the moment, there is no clear theoretical reason why the dissipation should behave in this manner. However, the parameterized models are able to make important predictions. As shown previously, one can obtain reasonable mass loss rates for solar wave fluxes and magnetic fields. This energy flux must be damped over a scale length L comparable to a stellar radius in order to obtain low terminal velocities. Thus a heating rate F_w/L is predicted. It can be shown that in the inner wind region, energy losses are dominated by radiation following collisional excitation (Hartmann, MacGregor, and Avrett 1982). If the radiative cooling rate $\Lambda(T)$ is known, the inner wind temperature structure can be calculated from

$$F_w/L \cong \Lambda(T) \, N_H \, N_e \quad . \tag{4}$$

Coupled with the equation of motion (1), one can solve for the temperature, density, and velocity structure.

Sophisticated radiative transfer calculations (Hartmann, MacGregor, and Avrett 1982) yield a relatively simple form for the radiative cooling law which is not strongly dependent on optical depth. The temperature dependence is very steep at low temperatures, flattening out at ∿ 10^5K. Because of this dependence, one can see that a wide variety of heating rates can result in temperatures ∿ 10^4K, while small perturbations in the heating per particle can change the temperature enormously near ∿ 10^5K. This suggests that, given a variety of surface conditions, we should expect most cool wind material to be observed at ∿ 10^4K, as long as the energy equation is of the form (4). It has been claimed that winds must be "unstable" above 10^4K (Simon, Linsky, and Stencel 1982). This is not true, particularly if conduction is taken into account. Wind models for late-type stars with temperature of a few x 10^5K may exist, but have not yet been calculated due to the difficulties in combining an energy equation including conduction with the solution of the momentum equation.

5. Comparison of Wind Theory and Observation

The typical temperature structure resulting from such wave-driven wind models is shown in Figure 3. The inner wind temperature structure is dominated by the static energy equation (4); adiabatic cooling

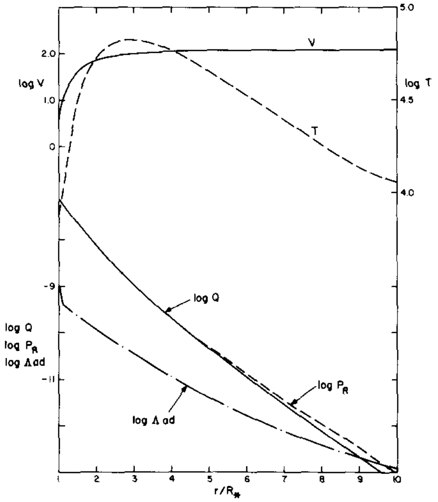


Figure 3. Velocity and temperature structure for a model wind, and the resulting wave heating rate (Q), radiative cooling losses (P_R), and adiabatic cooling (Λad), in erg cm^{-3} s^{-1}.

becomes dominant only at large radii. Most of the wave energy is radiated away, preventing the increase in streaming energy at infinity which would result in high terminal velocities. The low wind temperatures are not due to lack of heating; energy fluxes comparable to those needed to maintain the solar corona are being dissipated in these model flows. Rather, the large volumes of high-density gas being heated result in efficient radiative cooling to low temperatures.

In Figure 4 calculations of winds for surface parameters $B_o = 3$ gauss, $F_W \sim 3 \times 10^5$ erg cm^{-2} s^{-1} are shown for a variety of stellar masses and radii (Hartmann, MacGregor, and Avrett 1982). It is clear that the approximate location of the observed boundary of CS lines can be reproduced in this way. The key prediction of wave-driven wind theory is the existence of extended chromospheres. The model wind results indicated in Fig. 5 are compatible with the IUE density diagnostics for C II (Stencel et al. 1981).

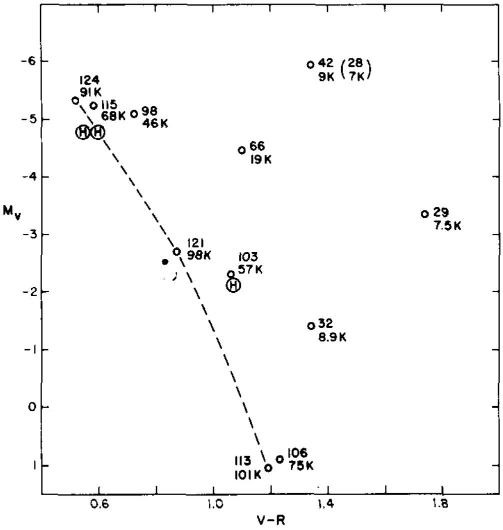


Figure 4. Results of wind model calculations. The upper number is the terminal velocity in km s^{-1}; the lower value is the maximum wind temperature in units of 10^3K.

As noted previously, the waves should broaden spectral lines appreciably. For example, with B = 3G, $F_W = 3 \times 10^5$ erg cm^{-2} s^{-1}, and a density $\sim 10^8$ cm^{-3} characteristic of extended chromospheres (Stencel <u>et al</u>. 1981), random projection of wave amplitudes results in an average line-of-sight turbulent velocity ~ 25 km s^{-1}. In many cases, inferred turbulent motions are of this order or even larger (Wilson and Abt 1954; Hartmann, Dupree and Raymond 1981; Ayres et al. 1982). This could mean that the field strength necessary is much smaller than assumed. I think it is more likely that only a fraction of the turbulent motions are being converted into far-propagating wave motions, much in the same way that mass flows near the solar surface are dominated by spicular motions which are not directly related to the solar wind.

More detailed comparisons can be made between theory and observation by comparing specific objects or classes of stars. For example, by adjusting the Alfven wave-driven wind theory parameters for α Ori, one can generate a mass loss rate $\sim 10^{-6}$ $M_{\odot}$ yr^{-1} and a wind speed ~ 20 km s^{-1} (Hartmann, MacGregor and Avrett 1982). This model predicts a maximum wind temprature $\sim$6000K, which is relatively insensitive to parameter changes. Detailed radiative transfer calculations show that this extended chromosphere has an ionization fraction $\sim 10^{-2}$. This is large enough to account for the observed excess free-free radio emission.

The wind temperature is sufficiently high that Hα will have an appreciable optical depth. Figure 5 shows that this wind model predicts considerable Hα emission in an extended halo around the star, in qualitative agreement with occultations and speckle measurements (White, Kreidl, and Goldberg 1982; Goldberg et al. 1982).

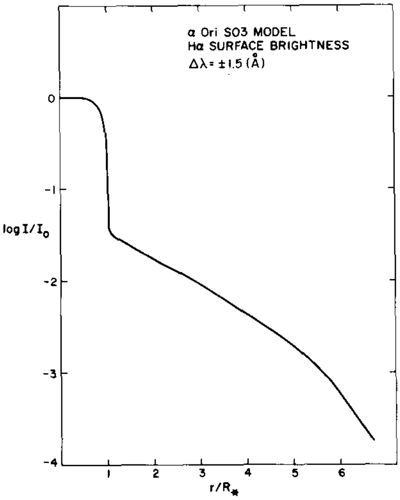
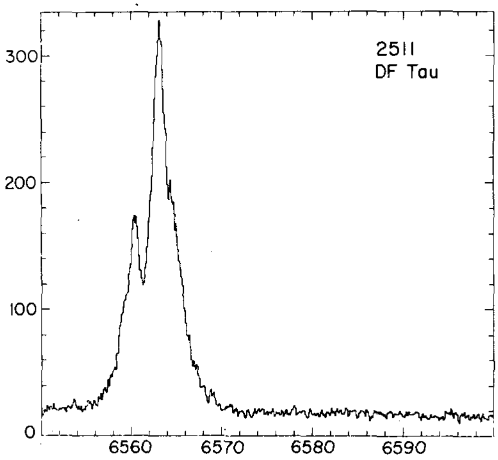


Figure 5. Predicted surface brightness of α Ori in a 3A bandpass centered on Hα.

The calculations displayed in Figure 4 predict a general increase in wind temperatures with increasing stellar gravity. This suggests that one should look for "warm" winds, i.e. winds with temperature ranges 3×10^4 K $\lesssim$ T $\lesssim 10^6$ K. Hartmann, Dupree and Raymond (1981) suggested that the hybrid atmosphere stars might be candidates for having such winds, although Ayres et al. (1982) comment that the evidence for this is not unique.

I think that at present the most direct evidence for warm winds comes from "double" CS absorption in Mg II and Ca II. As Reimers (1982) has pointed out, the presence of two distinct absorption components - one near the stellar rest velocity, the other blue-shifted - seems to be a good indicator of hybrid stars. The absence of intermediate-velocity absorption could possibly be explained by a rapid acceleration through this region; it may also be a transparent region due to ionization of Mg II and Ca II in a warm wind. The temperature must be in excess of 1-2 x 10^4 K in order to ionize Mg II and Ca II. On the other hand, upper limits to the X-ray flux for one hybrid star (Ayres et al. 1982) and the difficulty in having winds recombine at high temperatures (cf. Section IV) may indicate that $T_{wind} \lesssim 10^6$ K.

Wave-driven wind theory may also be applicable to pre-main sequence mass loss. De Campli (1981) first suggested that T Tauri stars have Alfven wave-driven winds. He found that mass loss rates greatly in excess of 10^{-8} $M_\odot$ yr^{-1} could not be sustained without invoking implausibly large wave fluxes (greater than the luminosity of the star). Although this mass loss limit is lower than many other estimated, De Campli pointed out that many emission line profiles observed in T Tauri stars are relatively symmetric (Figure 6a). If large-scale turbulence rather than expansion dominates the broadening of the Balmer lines, the required mass loss rates can be substantially reduced.



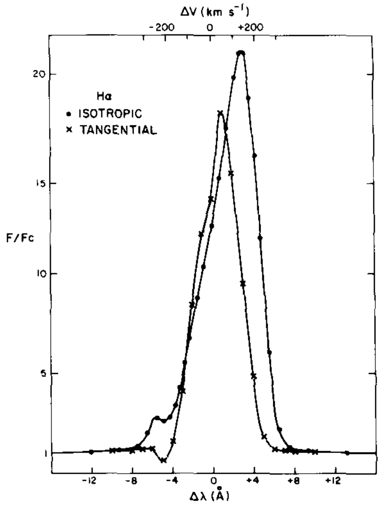


Figure 6a. Hα profile for DF Tauri.

Figure 6b. Model Calculation for T Tauri star wind, $\dot{M} = 7 \times 10^{-9}$ $M_\odot$ yr^{-1}.

Subsequently, Hartmann, Edwards and Avrett (1982) showed that the waves needed to drive such a flow have such large velocity amplitudes as to account for the required "turbulent" broadening. Assuming the same type of wave damping required to explain the low terminal velocities of the winds from giant stars, these authors found that they could reproduce the Balmer emission for mass loss rates below 10^{-8} $M_\odot$ yr^{-1} (Figure 6b). The theory shows that wind temperatures are expected to be low for such dense winds; again, radiative cooling is the dominant factor.

T Tauri stars emit strongly in both UV and X-ray regions in comparison with the Sun, but the enhancement is far greater in transition region lines than it is in coronal gas (Gahm 1980; Walter and Kuhi 1981). Although it has been suggested that X-ray emission reduced by the absorption of overlying cold wind material (Walter and Kuhi 1981), such absorption is likely to be significant only if $\dot{M}$ is substantially greater than 10^{-8} $M_{\odot}$ yr^{-1}. Upper limits on coronal lines visible in the optical region also argue against substantial X-ray absorption (Gahm, Lago and Penston 1981). In some T Tauri stars, N V appears anomalously weak relative to C IV, suggesting a decline in emission measures at high temperatures independently of any absorption (Cram, Imhoff and Giampapa 1981). From this evidence, and from the obvious indictions of ejection in Balmer lines, it appears that T Tauri variables certainly exhibit "warm" winds.

Although it appears that wave-driven winds can explain many features of T Tauri line emission, there are many examples of strange line profiles, inverse P Cygni profiles combined in the same line (cf. Krautter and Bastian 1980; Hartmann 1982). I think that any modest progress to be made in understanding the bizarre line shapes will require dedicated monitoring of line profile changes.

6. New Directions

The new approaches to mass loss from late-type stars suggest a wide variety of problems for futher exploration. For example, the wave-driven wind theory predicts that the wave fluxes driving outflows are essentially equal to the radiative losses of extended chromospheres. These losses are not well known at present, in part because of the complications introduced by fluorescence (Wing and Carpenter 1979; Brown and Jordan 1980), but some progress should be made in the next few years on this topic.

Speckle interferometry should enable us to determine the spatial structure of the extended chromospheres of a few stars. Combining such data with radio measurements should yield a much clearer picture of electron densities and temperatures in the inner wind regions. Asymmetrical structure may also contain important clues to the mass loss process. There are indications from the continuum speckle observations of α Ori that the photospheric surface brightness is not uniform (Goldberg et al. 1982). Hayes (1980) has made intriguing observations which show that the polarization of α Ori varies on timescales of months. These data recall Schwarzschild's (1975) suggestion that the surfaces of supergiants may be irregular due to the presence of very large convective cells. This variation of the inner boundary condition may cause mass loss to be very time-dependent. It should be remembered that many stars pulsate, and such motions may have important effects in ejecting material (Willson and Hill 1979).

Another interesting question is whether double CS absorption indicates a warm wind. Studies of CS variability (Reimers 1977; Dupree and Baliunas 1979) may yield some insight into velocity structure of winds and better estimates of the location of the inner shell radius, which in turn indicates limits on warm-wind ionization (cf. Reimers 1974). "Turbulent" velocities of CS shells maybe dominated by large-scale changes in terminal velocity, so that observations of CS variability may help to estimate the broadening velocities required to turn equivalent widths into mass loss rates.

The new approaches also suggest many theoretical questions, for example concerning the survival of molecules and dust, which were unquestioned before the study of extended chromospheres. Infrared interferometry indicates that most of α Ori's dust radiation comes from regions of $r > 12\ R_*$ (Sutton et al. 1977), which makes it seem unlikely that radiation pressure can initiate the flow. Extended chromospheres may not be terribly inhospitable environments for already-formed grains; Draine (1981) shows that the radiation field will control dust temperatures more than local conditions. He suggests that grains are relatively "pure" in the inner wind region, accumulating impurities at large distances which enlarge the grain, efficiently absorb radiation, and thus enhance the infrared reradiation of energy.

Further refinement of mass loss rates will help constrain theories. Jura and Morris (1981) have devised a method which uses observations of spatially resolved K I shell of α Ori in conjunction with CO measurements. Since K I is not the dominant state of potassium, the ionization balance must be known in order to derive the total density; this is obtained from a knowledge of the CO abundance, as C is thought to be the major electron donor. Although this method holds great promise, the problem of the survival of CO passing through the extended chromosphere has not yet been considered and may substantially affect the result $\dot{M} \sim 10^{-5}\ M_\odot\ yr^{-1}$.

The theory of wave-driven winds is certainly not well-developed at this point. Alfven waves seem attractive, but we know so little about stellar magnetic fields that it is premature to focus completely on these modes to the neglect of other possibilities. Theories of the generation of wave fluxes and their associated periods are in a rudimentary state. Another open question is wave dissipation, which is such a crucial aspect of the whole theory. How does it occur? Are the waves non-linear?

The present Alfven wave-driven wind theory has difficulty in producing sufficiently low terminal velocities. Observations of the Hα and IR triplet in α Ori show that the core absorption is blueshifted by about one half of the wind terminal velocity (Goldberg 1979), whereas wind model calculations yield a much bigger shift (Hartmann, MacGregor, and Avrett 1982). This suggests that the actual wind accelerates more slowly with radial distance than in the present theory.

The slow acceleration is probably an important clue to the driving mechanism; if this leads to flow through a distant critical point, it would be much easier to understand why wind terminal velocities are so low.

REFERENCES

Altenhoff, W. J., Oster, L., and Wendker, H. J.: 1979, Astron. Astrophys., 73, L21.

Ayres, T. R., Linsky, J. L., Basri, G. S., Landsman, W., Henry, R. C., Moos, H. W., and Stencel, R. E.: 1982, Astrophys. J., 256, 550.

Belcher, J. W.: 1971, Astrophys. J., 168, 509.

Belcher, J. W., and Davis, R. L.: 1971, J. Geophys. Res., 76, 3534.

Belcher, J. W., and Olbert, S.: 1975, Astrophys. J., 200, 369.

Bowers, P. F., and Kundu, M. R.: 1979, Astron. J., 84, 791.

Brown, A., and Jordan, C.: 1980, Monthly Not. Roy. Astron. Soc., 191, 37p.

Cram, L. E., Giampapa, M. S., and Imhoff, C. L.: 1980, Astrophys. J., 238, 905.

De Campli, W.: 1981, Astrophys. J., 244, 124.

Deutsch, A. J.: 1956, Astrophys. J., 123, 210.

Draine, B. T.: 1981, in Physical Processes in Red Giants, ed. I. Iben, Jr. and A. Renzini, Reidel, Dordrecht, p. 317.

Dupree, A. K., and Baliunas, S. L.: 1979, IAU Circular No. 3435.

Dupree, A. K., and Hartmann, L.: 1980, in IAU Colloq. 51, ed. D. F. Gray and J. L. Linsky, Springer, Heidelberg, p. 279.

Gahm, G. F.: 1980, Astrophys. J. (Letters), 242, L163.

Gahm, G. F., Lago, M. T. V. T., and Penston, M. V.: 1981, Monthly Not. Roy. Astron. Soc., 195, 59P.

Goldberg, L.: 1979, Quarterly Journ. Roy. Astron. Soc., 20, 361.

Goldberg, L., Hege, E. K., Hubbard, E. N., Strittmatter, P. A., and Cocke, W. J.: 1982, in Second Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun, ed. M. S. Giampapa and L. Golub, SAO Special Report 392, p. 131.

Haisch, B. M., Linsky, J. L., and Basri, G. S.: 1980, Astrophys. J., 235, 519.

Hartmann, L.: 1981, in Solar Phenomena in Stars and Stellar Systems, ed. R. M. Bonnet and A. K. Dupree, Reidel, Dordrecht, p. 331.

Hartmann, L.: 1982, Astrophys. J. Suppl., 48, 109.

Hartmann, L., Dupree, A. K., and Raymond, J. C.: 1980, Astrophys. J. (Letters):, 236, L143.

Hartmann, L., Dupree, A. K., and Raymond, J. C.: 1981, Astrophys. J., 246, 193.

Hartmann, L., Edwards, S., and Avrett, E. H.: 1982, Astrophys. J., in press.

Hartmann, L., and MacGregor, K. B.: 1980, Astrophys. J., 242, 260.

Hartmann, L., MacGregor, K. P., and Avrett, E. H.: 1982, in preparation.

Hayes, D. P.: 1980, Astrophys. J. (Letters), 241, L165.

Hollweg, J. V.: 1973, Astrophys. J., 181, 547.

Honeycutt, R. K., Bernat, A. P., Kephart, J. E., Gow, C. E., Sanford, M. T., and Lambert, D. L.: 1980, Astrophys. J., 239, 565.
Jacques, S. A.: 1978, Astrophys. J., 226, 632.
Jura, M., and Morris, M.: 1981, Astrophys. J., 251, 181.
Krautter, J., and Bastian, V.: 1980, Astron. Astrophys., 88, L6.
Linsky, J. L., and Haisch, B. M.: 1979, Astrophys. J. (Letters), 229, L27.
Newell, R. T., and Hjellming, R. M.: 1982, Astrophys. J. (Letters), in press.
Reimers, D.: 1974, Mem. Soc. Roy. Liege, 6e Serie, 8, p. 369.
Reimers, D.: 1977, Astron. Astrophys., 57, 395.
Reimers, D.: 1982, Astron. Astrophys., in press.
Schwarzschild, M.: 1974, Astrophys. J., 195, 137.
Simon, T., Linsky, J. L., and Stencel, R. E.: 1982, Astrophys., J., in press.
Stencel, R. E., and Mullan, D. J.: 1981, Astrophys. J., 238, 221.
Stencel, R. E., Linsky, J. L., Brown, A., Jordan, C., Carpenter, K. G., Wing, R. F., and Czyzak, S.: 1981, Monthly Not. Roy. Astron. Soc., 196, 47P.
Sutton, E. C., Storey, J. W. V., Betz, A. L., Townes, C. H., and Spears, D. L.: 1977, Astrophys. J. (Letters), 217, L97.
Vaiana, G. S. et al.: 1981, Astrophys. J., 245, 163.
Walter, F. M., and Kuhi, L. V.: Astrophys. J., 250, 254.
White, N. M., Kreidl, T. J., and Goldberg, L.: 1982, Astrophys. J., 254, 670.
Willson, L. A., and Hill, S. J.: 1979, Astrophys. J., 228, 854.
Wilson, O. C., and Abt, H. A.: 1954, Astrophys. J. Suppl., 1, 1.
Wing, R. F., and Carpenter, K. G.: 1979, Bull. AAS., 11, 419.
Wischniewski, E., and Wendker, H. J.: 1981, Astron. Astrophys., 96, 102.
Wright, K. O.: 1980, in Stellar Turbulence, IAU Colloq. 51, ed. D. F. Gray and J. L. Linsky, Springer, Heidelberg, p. 144.