WINDS IN LATE-TYPE STARS: MECHANISMS OF MASS OUTFLOW

Jeffrey L. Linsky[1]
Joint Institute for Laboratory Astrophysics
National Bureau of Standards and University of Colorado
Boulder, Colorado 80309 USA

ABSTRACT

Four basic mechanisms have been proposed to explain the acceleration of winds in late-type stars -- thermal pressure gradients, radiation pressure on circumstellar dust grains, momentum addition by Alfvén waves, and momentum addition by periodic shock waves. In this review I describe recent work in applying these mechanisms to stars, and consider whether these mechanisms can work even in principle and whether they are consistent with recent ultraviolet and X-ray data from the IUE and Einstein spacecraft. Thermally-driven winds are likely important for late-type dwarfs, where the mass loss rates are small, and perhaps also in G giants and supergiants, but they cannot operate alone in the K and M giants and supergiants. Radiatively-driven winds are probably unimportant for all cool stars, even the M supergiants with dusty circumstellar envelopes. In principle, Alfvén waves can accelerate winds to high speeds provided the field lines are initially open or forced open by some mechanism, but detailed calculations are needed. Magnetic reconnection is an interesting suggestion for an acceleration mechanism when the field lines are initially closed. For the Miras and semiregular variable supergiants, periodic shock waves provide a simple way of producing rapid mass loss. Thus we are making some progress in understanding mass loss mechanisms for the cool half of the H-R diagram.

I. INTRODUCTORY REMARKS

The twin goals of this Colloquium are to understand stellar mass loss and its effects on stellar evolution. In this paper I will try to review and summarize our present understanding of the mechanisms

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[1] Staff Member, Quantum Physics Division, National Bureau of Standards.

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responsible for mass loss in the late-type stars. This is a difficult task because in all honesty we understand very little about why mass loss occurs in these stars. Many mechanisms are possible and four have been developed in some detail as I will describe shortly. The determination of which mechanisms in fact drive stellar mass loss in different regions of the H-R diagram can only be decided empirically; and, except for the M supergiants, we have only begun to obtain critical data from spacecraft like IUE and the Einstein Observatory. While IUE and Einstein are important, they will likely be unable to provide crucial information on geometry, inhomogeneity, magnetic fields, and small-scale phenomena. Thus theory is being developed with only fragmentary observational guidance.

While the solar wind may be a useful prototype for understanding winds in late-type dwarfs, it may not be a useful detailed guide for winds in the more luminous stars. I say this because the giants and supergiants have gravities 2-5 orders of magnitude lower than the Sun, so that the dynamics and energetics of the flow could be far different from that for the Sun. Also, the escape temperature and supersonic point temperature in Parker-type solutions in the low gravity stars are far lower than for the Sun, so that radiative instabilities may be important. Despite these differences, results from detailed studies of the solar wind may provide some suggestions as to processes and mechanisms that could be important throughout the cool half of the H-R diagram. These include: (1) magnetic fields can play a role in inhibiting mass loss and thermal conduction when the field lines are closed, (2) the wind may originate only over small portions of the stellar surface where the magnetic field lines are open (coronal holes), (3) there may be an anticorrelation between radiative losses and mass loss, (4) individual transient events like eruptive prominences can be important contributors to mass loss, (5) acoustic wave heating is unimportant (e.g. Linsky 1980a), and (6) the ionization equilibrium in the wind can be frozen in close to the star and the electron and proton temperatures can diverge. These phenomena, well known for the solar wind (cf. reviews by Withbroe and Noyes 1977 and by Vaiana and Rosner 1978), cast doubt on most models now in the literature which assume that stellar winds are homogeneous, steady-state, spherically symmetric, and do not have magnetic fields.

Previous work has concentrated on the M supergiants because these stars have massive cool winds that can be readily observed by circumstellar absorption components and P Cygni line profiles in the visible and infrared, by infrared excesses, by radio emission, and even by direct imaging in the case of α Orionis (cf. Honeycutt et al. 1980, Goldberg 1979). While these stars are interesting, the mass loss mechanisms that work for these stars may not be applicable to other stars. The G and K giants and supergiants are also interesting and mass loss from these stars is likely important for stellar evolution, but they show few signatures of mass loss in the visible and infrared. As discussed here and in the previous paper by Dupree (1980), IUE and Einstein are presenting important data on the winds of these stars.

Before proceeding, I encourage the reader to study the excellent reviews by Cassinelli (1979), Holzer (1980), and Castor (1981). I am indebted to their thoughtful discussions and have used their presentations as a guide. As will become clear, we are only beginning to apply different mass loss mechanisms to late-type stars and a great deal of work needs to be done. I believe that these theoretical problems are at least as challenging as those for the hot stars, and I encourage people to enter the uncrowded field of cool star mass loss theory.

II. THERMALLY-DRIVEN WINDS

a) General Considerations

In this paper I consider the four broad classes of mechanisms that have been developed in some detail to explain mass loss in late-type stars. Conceptually, they may be distinguished by the relative importance of different terms in the momentum equation for steady-state radial flows,

$$u \frac{du}{dr} + \frac{GM}{r^2} + g_T + g_R + g_W = 0 \quad , \qquad (1)$$

where u is the mean flow spread, G is the gravitational constant, M is the stellar mass, and r the radial distance. The term $g_T = (1/\rho)dP/dr$ represents thermal pressure acceleration, g_R is the radiative acceleration, and g_W is the wave pressure acceleration. We distinguish three regimes:

(1) When $g_T > g_R, g_W$, the wind is thermally-driven. This is the mechanism first proposed by Parker (1958) and commonly thought responsible for the solar wind, but as discussed by Holzer (1979) this mechanism may not be responsible for all of the solar wind acceleration.

(2) When $g_R > g_T, g_W$, the wind is radiatively-driven. In hot stars radiation pressure on resonance and subordinate lines of abundant ions in the ultraviolet generally has been assumed to be an important acceleration mechanism, but this theory may be inconsistent with the observed relation between mass loss and luminosity (e.g. Conti 1980). Hearn (1980) has reviewed the present status of this theory. Below we consider radiation pressure on grains as a mechanism for accelerating winds in M supergiants.

(3) When $g_W > g_T, g_R$, the wind is wave-driven. Below we describe two variants of this mechanism, acceleration by Alfvén waves and by periodic shock waves.

It is important to point out that this classification says nothing directly about the energy equation, the temperature distribution, the geometry, or the heating mechanism. These aspects of the stellar wind problem implicitly determine the magnitudes of g_T, g_R, and g_W, and are important in determining the asymptotic flow speed and mass loss rate. They also provide all of the complexity and subtlety to the stellar mass loss problem.

Parker (1958) first presented the solution to the momentum equation for an isothermal, steady-state, radial flow that satisfies boundary conditions. In this solution the flow goes through a critical point between subsonic flow ($r < r_{crit}$) and supersonic flow ($r > r_{crit}$). At the critical point, the temperature, T_{crit}, is

$$T_{crit} = 8 \times 10^6 \text{ K} \left(\frac{M}{M_{sun}}\right)\left(\frac{r_{sun}}{r_{crit}}\right) \quad . \qquad (2)$$

It is important to recognize the <u>inverse relationship</u> between T_{crit} and r_{crit}. The mass loss rate is

$$\dot{M} = 4\pi r^2 \rho v \quad , \qquad (3)$$

and when hydrostatic equilibrium is valid

$$\rho(r) = \rho_o e^{-r/H} \quad , \qquad (4)$$

$$H = \frac{kT_{cor}}{\mu g} \quad . \qquad (5)$$

For the Sun, empirically $T_{cor} \approx 2\times10^6$ K, so that the scale height $H \approx 0.15 r_o$ and $r_{crit} \approx 4 r_{sun}$. Thus for the Sun

$$\dot{M} = 4\pi(4 r_{sun})^2 \rho_o e^{-25} v \quad ,$$

which is a very small number ($\approx 10^{-14} M_{sun} yr^{-1}$).

This very simple calculation is instructive because it highlights the roles played by T_{cor}/T_{crit} and by the hydrostatic equilibrium assumption. When T_{cor}/T_{crit} approaches unity, r_{crit} approaches the photosphere where the densities are large and the mass loss rate becomes large. Conversely, for stars with $T_{cor}/T_{crit} << 1$, the mass loss rate is negligible due to the exponential decrease in density out to the distant critical point. However, if one can greatly increase the density at the critical point either by dynamical events, turbulent motions, or by the input of momentum by waves, then the mass loss rate will increase proportional to this density increase. The large photospheric line widths in α Ori (cf. Goldberg 1979) do imply that scale heights in M supergiants can be far larger than thermal. We now need to look at the data in order to estimate T_{cor}/T_{crit} for different types of stars.

b) <u>Empirical Estimates of Coronal Temperatures</u>

The outer atmosphere of the Sun consists of three distinct non-radiatively heated layers: the chromosphere, transition region, and corona. Linsky (1980b) has proposed working definitions for these three layers in terms of the dominant loss terms in the energy balance and geometrical thickness of these layers. The empirical evidence for the existence of these layers in late-type stars has been reviewed recently by Linsky (1980b,c, 1981), Vaiana (1980), and Dupree (1980). This is a rapidly advancing field due to observations by IUE and Einstein, and we should expect important changes in our understanding as a result of these new data. In view of these review papers I will only summarize quickly what we can now say concerning the hottest temperatures reached in the outer atmospheres of late-type stars.

(1) By far the most sensitive way of detecting stellar coronae hotter than say 5×10^5 K is by detecting their soft X-ray flux. Most of what we now know about stellar coronae has come from the imaging focal plane instruments on the Einstein Observatory - the Imaging Proportional Counter (IPC) and the High Resolution Imager (HRI) (see Giaconni et al. 1979). Table 1 summarizes the results of the first stellar survey being published by Vaiana et al. (1980) and the subsequent survey of cool stars by Ayres et al. (1981). Table 1 gives the observed range and mean values of the total X-ray luminosity (L_X), the ratio of X-ray to bolometric flux (L_X/L_{BOL}), and the estimated X-ray fluxes per unit area of the star (F_X = surface flux). Several important points should be made concerning the late-type dwarf stars. First, there is a factor of 10^2-10^3 range in L_X/L_{BOL} for stars of similar spectral type, implying that there are one or more stellar parameters other than effective temperature and gravity that control coronal heating and other coronal properties. The large range in L_X/L_{BOL} at each spectral type and the absence of a large systematic decrease in this range towards the M dwarfs have been used by Rosner and Vaiana (1979), Vaiana et al. (1980), and Linsky (1980a) to argue that purely acoustic modes are not responsible for coronal heating. Instead, they argue that direct conversion of magnetic fields into heat must be responsible (see also Vaiana and Rosner 1978; Rosner 1980). Stein (1981) and Ulmschneider (1980) find that magnetoacoustic waves appear to match many of the observed properties of solar and late-type stellar chromospheres and coronae.

(2) Among the more luminous stars, Vaiana et al. (1980) and Ayres et al. (1981) find that G III and G II stars are reasonably bright sources (log L_X = 28-30), but that early K giants like α Ser (K2 III) and ε Sco (K0 III-IV) are weak sources (log L_X = 28). The values of log L_X/L_{BOL} = -7 for these stars are comparable to solar coronal holes. Cooler K giants like α Boo (K2 III) and α Tau (K5 III) are not detected (log $L_X/L_{BOL} < -8.5$), as are G supergiants like β Aqr (G0 Ib), α Aqr (G2 Ib), and ε Gem (G8 Ib) at log $(L_X/L_{BOL}) < -7$, and M supergiants like α Ori (M2 Iab) and α Sco (M1 Ib) at log $(L_X/L_{BOL}) < -8.5$. The upper limits on X-ray surface fluxes for these M supergiants are 10^{-3} times that of a solar coronal hole.

Ayres et al. (1981) have plotted the ratio of soft X-ray flux to bolometric luminosity, f_X/ℓ_{bol}, for the 29 G-M giants and supergiants

Table 1. Summary of <u>Einstein</u> Observations of Late-Type Stars

Spectral Type or Specific Star	$\log L_x$ (range)	$\langle\log L_x\rangle$	$\log L_x/L_{BOL}$ (range)	$\langle\log L_x/L_{BOL}\rangle$	$\log F_x$
F Dwarfs	28-30	29	-7 to -4	-5.5	5 to 7.5
GK Dwarfs	26-30	28	-7.5 to -4.5	-6.	4.5 to 7
Solar Flare	31-33		-2 to -1		8.5
Solar Active Region		29.3		-4.3	6.5
Quiet Sun		27.7		-5.9	4.9
Solar Coronal Hole		26.7		-6.9	3.9
M Dwarfs (quiescent)[a]	26-30		-5 to -3	-4.	4.5-7.5
Flares	28-31				
G Giants	28-30		-7 to -5		4 to 6
Early K Giants		28	-7		
Late K Giants[b]					
α Boo (K2 III)		<27.3		<-8.5	<1.7
α Tau (K5 III)		<27.9		<-8.4	<1.6
G Supergiants[b]					
β Aqr (G0 Ib)				<-7.0	<3.7
α Aqr (G2 Ib)				<-7.0	<3.6
ε Gem (G8 Ib)				<-7.2	<3.0
M Supergiants[b]					
α Ori (M2 Iab)				<-8.5	<1.4
α Sco (M1 Ib+B)		<29.3		<-8.7	<1.2
RS CVn Systems	30.3-31.3		-5 to -2.5		

[a] dMe stars are much brighter than dM stars.

[b] No detections.

they observed on an H-R diagram. This plot (Fig. 1) clearly shows that stars in the upper right-hand portion of the H-R diagram typically have f_x/ℓ_{bol} upper limits 2-3 orders of magnitude smaller than for many G giants. They conclude that there is a boundary in the H-R diagram (line marked C in Fig. 1) separating a region in which stars do not show X-ray emission (down to low upper limits) from a region in which stars are commonly strong X-ray emitters. Thus to the right of this boundary either the maximum temperatures in the outer atmospheres of stars are <500,000 K or the emission measures of the hotter plasma must be very small.

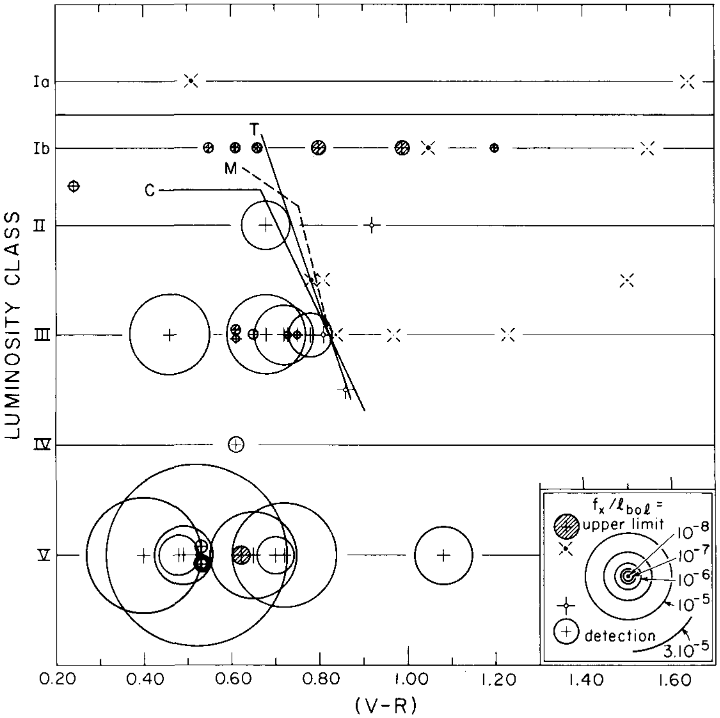

Fig. 1. An H-R diagram (cf. Ayres et al. 1981) in which soft X-ray detections (open circles) and upper limits (filled circles) are plotted as bubbles whose areas are proportional to the ratio of X-ray to bolometric flux, f_x/ℓ_{bol}. The line marked (C) roughly separates regions in which coronae are usually detected (to the left) from regions where coronae are usually not detected (above and to the right). The line marked (T) roughly separates the regions where transition regions are usually observed (to the left) and not observed (above and to the right) by emission in the C IV doublet. Also plotted is a boundary marked (M), which roughly separates stars having weak stellar winds (to the left) and strong winds (above and to the right) as determined by Mg II emission core asymmetries. Aside from the region of the early G supergiants, the three boundaries appear to coincide.

(3) To date we have very little information on the coronal temperatures of detected X-ray sources. In principle, the IPC on Einstein can measure rough temperatures for bright sources, but as yet the only published estimate of a coronal temperature of a late-type single dwarf is the rather uncertain value of 4×10^6 K for Proxima Cen (M5.5e V) at quiescent times (Haisch et al. 1980). Using the solid state spectrometer (SSS) on Einstein, Swank (1980) estimated $T_{cor} = 3.5-5.5 \times 10^6$ K for π^1 UMa (G0 V). Also using the SSS, Swank and White (1980) studied a number of binary systems of the RS CVn and Algol type. They found that the X-ray spectra of these systems can generally be matched by thermal emission from a two-component corona with temperatures $\sim 7 \times 10^6$ K and $\sim 50 \times 10^6$ K. Preliminary spectra from the Objective Grating Spectrometer (OGS) on Einstein (Mewe et al. 1980) for the widely separated Capella system (G6 III + F9 III) can be matched by thermal emission from an optically thin plasma at 7×10^6 K. Thus coronal temperatures for bright X-ray sources can be significantly larger than solar.

(4) When the maximum temperature reached in the outer atmosphere of a star is less than about 200,000 K, IUE should be able to measure it. In the ultraviolet accessible to IUE are emission lines emitted by ions and atoms that are abundant in the temperature range 3,000 K-200,000 K. Thus one should be able to measure T_{cor} by determining that emission lines are present for all ions abundant at temperatures up to this maximum and no emission lines are present for ions abundant at hotter temperatures. In their initial survey of 22 late-type stars with IUE, Linsky and Haisch (1979) found that the ultraviolet spectra of these stars fell into two distinct groups. All of the dwarf stars and the G giants showed spectra similar to the Sun in which all of the emission lines formed at cool temperatures (O I, Si II, H I, etc.) are present as well as the whole sequence of ions up to N V (200,000 K). Since the relative strengths of these emission lines are generally the same as is seen in the Sun, they concluded that these stars have chromospheres, geometrically thin transition regions, and presumably 10^6 K coronae like the Sun. On the other hand, the G-M supergiants and K giants in their sample all showed qualitatively different spectra in which only emission lines of ions formed at $T \lesssim 10^4$ K are visible and none of the higher temperature species. They concluded that the maximum temperature reached in the outer atmospheres of these stars is $\simeq 10^4$ K. They also proposed a dividing line in the H-R diagram (see line T in Fig. 1) separating stars with and without transition regions.

The important point in the Linsky-Haisch paper for our purposes is that they found no intermediate cases for which IUE spectra indicate a maximum (coronal) temperature in the range 10^4 K $< T_{cor} <$ 2×10^5 K. A large number of late-type stars have been observed subsequently by IUE, and a group of hybrid stars have been discovered by Hartmann, Dupree, and Raymond (1980) (cf. Dupree 1980) that violate the proposed transition-region dividing line in the sense that they lie to the right of the line yet exhibit a bright emission line spectrum. However, no star has yet been detected which shows evidence for a coronal temperature within the apparently forbidden region of 10^4 K < T_{cor} < 2×10^5 K. Even the hybrid stars show all of the emission lines up to N V in roughly their solar ratios, indicating that $T_{cor} > 2\times10^5$ K.

The existence of this apparently forbidden range in T_{cor} can probably be understood as a simple consequence of thermal instability. McWhirter, Thonemann, and Wilson (1975), among others, have computed the radiative power loss, P_{rad} (ergs cm^3 s^{-1}) of an optically thin solar abundance plasma in steady-state ionization equilibrium. They find that P_{rad} rises steeply with increasing temperature until T = 15,000 K, but then is roughly constant for 15,000 K $\lesssim$ T $\lesssim$ 5×10^5 K. Thus if the heating rate is sufficient to force the plasma to be hotter than about 15,000 K, the maximum plasma temperature will then run away to 10^6 K where cooling by thermal conduction and wind expansion can balance the energy input. If the wind expansion is inhibited by closed field lines, then one would expect an energy balance at somewhat higher temperatures and pressures as cooling would be dominated by conduction and radiation only.

(5) Cool winds in late-type stars are readily detected by blue-shifted circumstellar absorption features in chromospheric emission lines and by chromospheric emission lines in which the red emission peak is brighter than the blue emission peak (cf. Chiu et al. 1977, Dupree 1980). Stencel (1978) noted that the K giants and G-M supergiants typically show asymmetric chromospheric Ca II emission lines indicative of a massive cool wind in the chromosphere, whereas the G giants exhibit symmetric emission lines or even infall-type profiles (cf. Basri and Linsky 1981). Stencel and Mullan (1980) and Stencel et al. (1980) found that the Mg II resonance lines at 2796 Å and 2803 Å typically are asymmetric indicative of massive cool winds to the right of the dividing line labeled M in Figure 1, whereas no large wind is indicated for stars to the left of this line in the H-R diagram.

The rapid onset of massive cool winds at the same boundary in the H-R diagram where hot coronae are no longer observed is highly suggestive of the following scenario. I know of no reason why the outer atmosphere heating rate should change abruptly as one crosses the boundaries indicated in Figure 1. However as a star evolves from left to right across the boundary, its radius r_* increases and the largest possible T_{crit} (given by $r_{crit} = r_*$) decreases. Near $T_{cor} = 1\times10^6$ K, the coronal plasma becomes thermally unstable, as previously described, and the maximum temperature falls to 10^4 K. The radiative loss rate is unchanged but conductive losses fall to zero. The excess input energy not balanced by radiative losses then somehow drives a cool wind. Clearly this speculative scenario needs to be worked out in detail.

(6) Hartmann et al. (1980) found that α Aqr (G2 Ib) and β Aqr (G0 Ib) exhibit both transition region emission lines (up to and including N V) and Mg II absorption components blue-shifted by up to

125 km s^{-1}, indicative of cool winds. They designated these stars as "hybrid." Additional stars like α TrA (K4 III) (Dupree 1980) fall in this class. However, Ayres et al. (1981) find that α Aqr and β Aqr are not X-ray sources with X-ray surface flux upper limits comparable to observed surface fluxes in solar coronal holes. Three explanations are possible: (i) the maximum temperature lies in the narrow range 2×10^5 K $< T_{cor} < 1\times10^6$ K, perhaps violating the thermal instability argument cited above, (ii) these stars have 10^6 K coronae but with very low surface fluxes, or (iii) they have bright coronae but the X-rays are absorbed by the cool wind. Ayres et al. (1981) argue for the latter alternative on the basis that the column density of neutral hydrogen corresponding to $\dot{M} = 1\times10^8$ M_{sun} yr^{-1} has an optical depth of >100 for soft X-rays.

If the hybrid stars have both cool (10^4 K) winds and hot (10^6 K coronae), then what is the geometrical relation between these two components? One possibility is that the wind cools away from the star to produce the observed blue-shifted absorption components seen in the Mg II lines. Alternatively, the outer atmosphere has two components -- a hot component confined to closed magnetic flux tubes and a cool wind component where the field lines are open, analogous to coronal holes.

c) In What Regions of the H-R Diagram are Thermally Driven Winds Likely to Occur?

Although empirical data on the maximum temperatures reached in the outer atmospheres of cool stars are still limited, enough is known to begin to decide where in the cool half of the H-R diagram thermally-driven winds are likely to occur. Table 2 summarizes data on T_{cor}, estimates of stellar parameters, and the largest possible values of T_{crit}, corresponding to the case where the critical radius is placed just above the stellar photosphere ($r_{crit} = r_*$). For the three dwarfs in Table 1, T_{cor} is a factor of 2-4 lower than this maximum value of T_{crit}. As a result, the location of the critical point is at 2-4 stellar photospheric radii. Assuming that the density distribution is close to hydrostatic equilibrium, as appears to be valid for the Sun, then the densities are low at the critical point and the mass loss rates are, consequently, very small. This argument suggests that thermally-driven winds with small mass loss rates should characterize main sequence stars of spectral type F-M. There are no observations that contradict this statement.

Estimates of T_{cor} are available for two giants: α Boo (K2 III) and Capella Ab (F9 III). For α Boo there is no evidence for any material hotter than 1×10^4 K, which is a factor of 30 times cooler than T_{crit} at the photosphere. As a result the critical point should lie at 30 stellar radii and the mass loss rate should be negligible. Haisch, Linsky, and Basri (1980) have in fact computed thermally-driven mass loss rates for α Boo assuming a range of temperatures ($T_{cor} < 2\times10^4$ K), temperature distributions, and flows in diverging geometries. These rates are negligible ($\dot{M} < 10^{-16}$ M_{sun} yr^{-1}) as expected, but α Boo

Table 2. Stellar Parameters for Thermally-Driven Winds

Star	Spectral Type	T_{cor} (K)	$\frac{M_*}{M_{sun}}$	$\frac{r_*}{r_{sun}}$	T_{crit} (K) at $r=r_*$	r/r_{sun} at $T_{crit}=T_{cor}$
Sun	G2 V	2×10^6	1.	1.	8×10^6	4.
π^1 UMa	G0 V	$\sim4.5\times10^6$	1.07	1.05	8.2×10^6	1.9
Proxima Cen	M5.5e V	$\sim4\times10^6$	0.4	0.19	16.8×10^6	0.8
Capella Ab	F9 III	5×10^6	2.55	7.1	2.9×10^6	4.1
		28×10^6	2.55	7.1	2.9×10^6	0.7
α Boo	K2 III	1×10^4	~1.	26.	3.1×10^5	800.
α Aqr	G2 Ib	3×10^5?	5?	100?	4×10^5	130.
		2×10^6?	5?	100?	4×10^5	20.
α Ori	M2 Iab	1×10^4	10?	500?	1.6×10^5	8000.

clearly shows asymmetric Mg II emission lines from which Chiu *et al.* (1977) estimate a mass loss rate $\approx10^{-8}$ M_{sun} yr^{-1}. The thermally-driven wind mechanism is clearly inadequate for α Boo and similar stars with cool outer atmospheres.

Capella, a spectroscopic binary with components of spectral type G6 III and F9 III, presents a very different case. Swank *et al.* (1981), using the SSS on *Einstein*, find bright, variable X-ray emission, which can be characterized by a two-component plasma with temperatures of 5×10^6 K and 28×10^6 K. We do not know for sure whether this hot plasma (or plasmas) is associated with the F or G stars or with the system as a whole, but Ayres and Linsky (1980) find that essentially all of the transition region emission follows the radial velocity of the F star. Thus it seems reasonable to assume that the X-ray emission also comes from a corona about the F star. If so, both components of the hot plasma are hotter than T_{crit} and thus cannot be bound to either star by gravity alone. One possibility is a massive wind. In fact, Dupree (1975) proposed such a wind on the basis of *Copernicus* observations of the O VI λ1032 line blue-shifted by 20±7 km s^{-1} with respect to the G star. Ayres and Linsky (1980) argued instead that this line should be emitted primarily by the F star like the other transition region lines, and −20 km s^{-1} is roughly the F star radial velocity compared to the G star at the time of the *Copernicus* observations. The other alternative, argued by Swank *et al.* (1981), is that large magnetic flux tubes confine the hot plasma, so that tension in the field lines provides the additional restoring force needed to confine the hot plasma to the F star. If this is correct, then one cannot apply the theory of thermally-driven winds to such stars without including magnetic restoring forces.

The two supergiants in Table 2, α Aqr (G2 Ib) and α Ori (M2 Iab), also provide an interesting contrast. For α Aqr the mass and radius are poorly known, but reasonable values predict a maximum T_{crit} of 4×10^5 K. If X-rays are not detected because T_{cor} is too cool, then a reasonable estimate is $T_{cor} \approx 3\times10^5$ K so that the critical point is close to the photosphere and the mass loss rate should be large. If X-rays are not detected due to absorption by the wind, then $T_{cor} > 3\times10^5$ K, perhaps 2×10^6 K, and the star should have a massive hot wind. As previously discussed, the geometry of a cool (10^4 K) wind seen in the Mg II lines and a warm (10^5 K) wind perhaps indicated by a broad C III λ1909 line profile (Dupree 1980) is unclear. In principle, however, a thermally-driven wind can produce large mass loss in a hybrid star like α Aqr. By contrast a thermally-driven wind by itself cannot produce significant mass loss in an M supergiant like α Ori because the critical point is located very far from the photosphere ($\approx 16\ r_*$). In order for this star to have its large observed mass loss rate (cf. Goldberg 1979), some other mechanism must operate to lift matter this far from the star. In this case the thermal mechanism is irrelevant.

It is my belief, based on these limited data, that thermally-driven winds operate in late-type dwarfs, producing small mass loss rates, but they are not responsible for the massive cool winds in M supergiants or even the K giants. This mechanism may be important in the G giants and supergiants, but one must properly take into account the geometry and strength of the magnetic fields.

d) Recent Theoretical Work on Thermally-Driven Winds

Hearn (1975) proposed that the properties of stellar coronae and winds could be predicted by minimizing the total energy loss due to radiation, conduction, and a thermally-driven stellar wind. This so-called minimum flux corona (MFC) concept was initially applied to a plane-parallel, hydrostatic corona with no magnetic fields, and it is roughly consistent with the observed corona and wind properties of the quiet Sun. It also predicted hot coronae for O-type stars that were subsequently observed by *Einstein* (cf. Vaiana *et al*. 1980). This theory fails, however, to predict the observed anticorrelation of high stellar wind speed (and large mass loss rate) with bright X-ray emission (due to higher temperatures and pressures) seen in the Sun and due to the existence of closed magnetic flux tubes (Vaiana and Rosner 1978). Hearn (1977) subsequently generalized the MFC concept to include the effects of inclined magnetic fields on conductive and wind cooling of a corona. The minimum flux corona hypothesis is highly controversial. Vaiana and Rosner (1978), Antiocus and Underwood (1978), among others, have criticized the theory on thermal stability and other grounds, and Hearn (1980b) has confronted his critics. It is not my intention to join in this controversy, but rather to point the reader to the papers so that he can judge for himself.

In a widely quoted paper, Mullan (1978) developed the concept of the supersonic transition locus (STL) in the H-R diagram. He assumed Hearn's (1975) formulation of the MFC to provide a functional relation between coronal loss rates, pressure, and temperature. He then assumed the functional relationship between the pressure at the top of the chromosphere and stellar gravity, $P_{TC} \approx g^{0.57}$, proposed by Kelch et al. (1978) for quiet chromosphere stars. Baliunas et al. (1979) properly point out that this relation cannot be valid for active chromosphere stars. Mullan then assumed that the coronal base pressure is somewhat smaller than P_{TC}. He argued that as a star evolves to the right of the H-R diagram through the K giants, the photospheric radius increases, the critical point moves down to the top of the chromosphere where the densities are large, and the mass loss rate rises abruptly. He estimated that the mass loss rate should increase by the ratio of chromospheric to coronal densities, roughly a factor of 50, along a boundary in the H-R diagram close to the empirical line marked M in Figure 1.

While this paper was useful in stimulating thought, it cannot be complete or correct for the following reasons. First, there is no energy equation, but a source of energy is necessary to drive the wind. Mullan suggests that jets of gas (perhaps similar to solar spicules) supply the energy, but this begs the question. Second, the STL concept violates the continuity equation. Along a surface separating the chromosphere and corona the product nvA must be a constant. Thus as n decreases a factor of say 50 from the chromosphere to the corona, v must increase by a factor of 50, and the mass loss rate is unchanged. Third, there is no evidence for any material hotter than 1×10^4 K in most K giants. Thus, at the location in the H-R diagram where the wind is supposed to increase rapidly due to the critical point dipping into the chromosphere, hot coronae apparently disappear and the thermally-driven wind mechanism can no longer work. Mullan (1981) now supports a very different wind mechanism (see below) and the STL concept is of interest now only for historical reasons.

Nevertheless, there does appear to be a real boundary in the H-R diagram along which hot coronae disappear as large cool winds appear. Castor (1981) proposed a different interpretation of this boundary. He calls attention to two important time scales: the radiative cooling time

$$t_c = E \left(\frac{dE_R}{dt}\right)^{-1} = \frac{nkT}{n_e^2 \; P_{rad}(T)} \quad , \qquad (6)$$

and the expansion time for sonic flows

$$t_{exp} = \frac{r_*}{v_{sound}} \quad . \qquad (7)$$

As previously noted, the radiative power loss $P_{rad}(T)$ is roughly constant over the temperature range $15{,}000 \text{ K} \lesssim T \lesssim 5\times10^5$ K, but it is roughly a factor of 10^2 lower for $10^6 \text{ K} \lesssim T \lesssim 10^7$ K. To the left of the boundary, $T_{cor} \gtrsim 10^6$ K so that $P_{rad}(T)$ is small and $t_c >> t_{exp}$. Thus the wind remains hot as it leaves the star. To the right of the boundary, $T_{cor} < 5\times10^5$ K so that $P_{rad}(T)$ is a factor of 10^2 larger and $t_{exp} >> t_c$. The wind thus rapidly cools if it started hot. However, as a result of the radiative instability previously described, there may be no outer atmospheres with 15,000 K $\lesssim T_{cor} \lesssim 5\times10^5$ K.

III. RADIATIVELY-DRIVEN WINDS

Historically the second mechanism considered for the acceleration of winds in late-type stars was radiation pressure on circumstellar dust grains. Cassinelli (1979), Hagan (1980), and Castor (1981) have recently reviewed the empirical evidence for large mass loss rates in the M supergiants. The specific values proposed by different authors for individual stars and the functional dependence of the mass loss rate on stellar parameters are, unfortunately, in a highly confused state (cf. Goldberg 1979) and can provide only rough guidance concerning the mass loss mechanism.

Woolf and Ney (1969) first discovered broad emission features at 10-14μm in M supergiants (but not carbon stars), which they argued could not be photospheric or chromospheric in origin. Instead, they argued that these emission features must be circumstellar and are probably due to thermal emission from silicates as the wavelength dependence of the emission feature is similar to the opacity of silicate grains like olivine. On the basis of molecular equilibrium calculations, Gilman (1969) showed that the likely constituents of grains that condense out of circumstellar gas are refractory silicates for oxygen-rich stars (M stars), carbon grains in carbon-rich stars (C stars), and silicon-carbide grains in stars for which the O/C ratio is close to unity (S stars). Subsequently, Gilman (1972) showed that the important physical processes in radiatively-driven mass loss are first momentum transfer from the radiation field to the grains, and then momentum transfer to the gas by grain-gas and then gas-gas collisions. Gehrz and Woolf (1971) then presented infrared observations of many late-type stars and estimated mass loss rates and terminal velocities on the basis of momentum coupling of the gas and dust.

Subsequent development of the radiatively-driven wind theory consisted of treating in detail grain condensation and growth, momentum deposition on the grains, coupling of the grains to the gas, and properties of the flow itself. Castor (1981), Kwok (1980), and Cassinelli (1979) have summarized this work at length, but here I would like to mention some important points. One question is whether the flow passes through the sonic point at the radial distance where the grains condense as assumed by Salpeter (1974) and Lucy (1976). In a detailed model in which they computed grain condensation rates properly taking into account radiative transfer to derive local gas and grain temperatures, Menietti and Fix (1978) showed that the grains do indeed condense near the sonic point. Their models are consistent with $\dot{M} \approx \Delta L/v_\infty c$, where

ΔL is the total power radiated by the grains in the 10μm feature, v_∞ is the flow velocity far from the star, and c is the speed of light. A second question is the value of v_∞, which is typically 10 km s^{-1} for stars like α Ori (M2 Iab). Salpeter's (1974) calculations predict v_∞ a factor of 10 larger, but Kwok (1975) finds that sputtering can easily destroy grains when they drift faster than 20 km s^{-1} relative to the gas. Taking this into account, he computed v_∞ in the range 6-30 km s^{-1} for a wide range of stellar parameters. Draine (1981), however, argues that grains can survive drift velocities up to 100 km s^{-1}, so the idea that sputtering moderates the drift velocities is in doubt.

It is clear that this radiatively-driven wind mechanism is feasible in principle only for those stars with circumstellar grains. This limits the mechanism to the M supergiants and C and S stars for which infrared excess and polarization data indicate the existence of grains. Hotter stars generally do not and should not have appreciable grain column densities. Even within this limited range of the H-R diagram, the radiation mechanism has at least three severe problems as a candidate for explaining the observed mass loss rates.

(1) As previously noted, the models of Menietti and Fix (1978) in which the grains are assumed to be dirty (i.e. impure) silicates predict large 10μm emission features and $\dot{M} \approx \Delta L/v_\infty c$. Their models assuming clean (i.e. pure) silicates generally show no 10μm emission features. A simple interpretation of this mass loss relation is that the grains emit near 10μm (ΔL) all the energy they absorb and the momentum input to the grains (ΔM_{grain}) is entirely given to the gas (ΔM_{gas}) by drag,

$$\Delta M_{gas} = \Delta M_{grains} = \frac{\Delta L}{c} \frac{Q_{ext}}{Q_{abs}} \approx \dot{M} v_\infty \quad . \tag{8}$$

If the grains are dirty silicates, then their albedo (Q_{scatt}/Q_{ext}) is small throughout the infrared and the efficiency (cross section/πa^2) for absorption of photospheric light in the near infrared (Q_{abs}) roughly equals that for extinction near 10μm (Q_{ext}). Castor (1981) has estimated $\dot{M}$ using the infrared photometry of Hagan (1978). These rates turn out to be unreasonably small; for example, $\dot{M}(\alpha\ \mathrm{Ori}) \approx 1\times10^{-7}\ M_{sun}\ yr^{-1}$, $\dot{M}(\alpha\ \mathrm{Sco}) \approx 3\times10^{-9}$, and $\dot{M}(\alpha\ \mathrm{Her}) \approx 2\times10^{-9}$. These mass loss rates could be increased to reasonable observed rates (typically a factor of 10 larger) only in the unlikely event that in the near infrared $Q_{ext} >> Q_{abs}$ (for which there is no theoretical or empirical evidence), or that most of the grain emission is outside the 10μm bump, or that the 10μm feature is optically very thick. If none of these unlikely events is true, then the wind must be driven by another mechanism, at least for M supergiants.

(2) The second problem is that both clean and dirty grains cannot drive these winds. The measured properties of pure silicates like olivine, the so-called clean grains, are such that they absorb mainly near 10μm and very little in the near infrared where most of the photospheric radiation is located. As a result the grains act as inverse

greenhouses so that $T_{grain} < T_e$ and $T_{grain} < T_{rad}$. These grains can therefore condense close to a star, roughly 1.06 r_* for α Ori (Draine 1981), where densities are high. However, they absorb only a small portion of the stellar light and the resulting mass loss rates are low. By comparison, dirty silicates absorb well in the near infrared and near 10μm, so that they evaporate close to a star. Draine (1981) calculates that they cannot exists within 4.5 r_* of α Ori, for example. This estimate is confirmed by Sutton's (1979) 11μm heterodyne interferometry measurement (cf. Sutton et al. 1977) that the inner radius of the dust shell is at least as large as 5 r_* and Low's (1979) interferometric measurement that the inner radius is at least 10 r_*. At these distances the density must be low (and thus the mass loss rate small) unless the flow of gas out to 4.5 r_* is produced by a different type of mechanism. Also, Goldberg (1979) cites evidence that $v \approx v_{esc}$ already deep in the chromosphere for α Ori. This argument suggests that the radiatively-driven mechanism is likely irrelevant.

(3) The third problem is that gas and dust column densities are uncorrelated in M supergiants contrary to expectation if radiation pressure on dust is driving mass loss, which is primarily the outward flow of the gas. Hagan (1978) observed circumstellar line profiles and obtained infrared photometry of nine bright M supergiants. She derived gas column densities by comparing observed and theoretical line profiles and by correcting for the ionization equilibrium. Such corrections are highly uncertain because they depend sensitively on poorly known ultraviolet radiation from these stars. She then derived dust column densities by matching observed infrared spectra with computed spectra (cf. earlier work of Jones and Merrill 1976), taking into account extended geometries and grain self-absorption. Calculated mass loss rates increase rapidly with the dust/gas ratio, but the observed mass loss rates for this sample of stars is independent of the dust/gas ratios.

On the basis of these arguments we must conclude that the radiation pressure on grains mechanism is not important anywhere in the H-R diagram. A related mechanism is radiation pressure in the Lyman alpha line originally proposed by Wilson (1959) and studied recently by Haisch, Linsky, and Basri (1978). They found that this mechanism can initiate flows in the chromosphere K giants and perhaps M supergiants, but some other mechanism must take over and provide acceleration when the Lyman alpha lines become optically thin. Thus no type of radiatively-driven wind mechanism appears to be able, by itself, to explain observed mass loss rates in the late-type stars.

IV. ALFVÉN-WAVE-DRIVEN WINDS

Hollweg (1974) has reviewed the extensive in situ measurements of hydromagnetic waves in the solar wind made by spacecraft. The existence of these waves has led several authors (e.g. Belcher 1971; Parker 1975) to suggest that undamped Alfvén waves can impart momentum to the solar wind and thereby affect the flow properties. Belcher (1971), for example, suggested that Alfvén waves can provide the primary energy flux needed to drive the wind, and can produce a combination of high velocities ($\simeq$700 km s^{-1}) and low densities ($\simeq$2 particles cm^{-3}) often observed at 1 AU. Jacques (1977, 1978) solved the MHD equations for radially-propagating Alfvén and fast mode magnetoacoustic waves in the solar corona as a function of the wave energy density at the base of the corona. He found that the principal effect of these waves is to bring the critical point closer to the solar surface, which increases the flow speed and mass loss rates to be consistent with values measured for high speed streams near the Earth. Recent work has concentrated on explaining both the wind and heating of the solar corona by these waves, but Leer and Holzer (1980) have pointed out that if Alfvén waves deposit most of their energy beyond the critical point, then the asymptotic flow speeds will tend to be unreasonably large.

Why Alfvén winds impart momentum to a gas can be understood simply using an argument given by Castor (1981). Since the Alfvén speed is $v_A = B(4\pi\rho)^{-1/2}$, the energy density in an Alfvén wave is $\varepsilon = 1/2\ \rho(\delta v)^2 = (\delta B)^2/8\pi$, where δv and δB are fluctuations about the mean flow speed and magnetic field strength. The energy flux is $F = 1/2\ \rho v_A(\delta v)^2 = 1/2\ (\rho/4\pi)^{1/2}\ B(\delta v)^2$. In a flux tube of cross sectional area A, BA is constant and FA is also a constant for negligible damping. These relations imply that F/B is a constant, so that $\delta v \sim \rho^{-1/4}$ and $\varepsilon \sim \rho^{1/2}$. Since the pressure is proportional to the energy density, the pressure decreases outward from the star. In other words, there is an outward radial force. Typical solutions for pure Alfvén-wave-driven winds are characterized by $v_{exp} \approx \delta v \approx v_{esc}/2$ at a critical point which is located at 1-2 r_*.

Given that momentum deposition by Alfvén waves in the solar corona has many attractive features, it was natural to consider this mechanism for stars in general. Some important papers are those of Belcher and Olbert (1975), Haisch, Linsky and Basri (1980), and Hartmann and MacGregor (1980). An important consideration is whether the Alfvén waves are damped or not beyond the critical point. Belcher and Olbert (1975) assumed that the waves are adiabatic (undamped) on the basis that Alfvén waves in astrophysical plasmas tend to be very difficult to damp. They pointed out that winds accelerated by such waves could be cool or hot if heated by another mechanism. Since densities are likely to fall off faster than r^{-2} while field strengths should be proportional to r^{-2}, the Alfvén speeds and field fluctuations can be very large far from the star. Their solutions also exhibit a cutoff Alfvén flux below which there is no mass loss.

Hartmann and MacGregor (1980) applied the Alfvén wave mechanism to late-type giants and supergiants (cf. Castor 1981). They considered Alfvén waves of low amplitude ($\delta B \ll B$, $\delta v \ll v_A$) with wavelengths small compared to the pressure scale height or variations in any stellar parameters. They also assumed radial fields with $B = B_o(r_o/r)^2$.

Since they did not consider closed loops, tension in the field lines is negligible and they implicitly considered only regions analogous to solar coronal holes. They found that solutions to the MHD equations assuming no damping result in terminal velocities ≈300 km s^{-1}, which are unrealistically large for late-type supergiants. Conversely, if the Alfvén waves are highly damped (dissipation scale lengths much less than a stellar radius), then the wave flux would be dissipated as heat in the high density portion of the corona close to the star and there would be negligible mass loss. Instead, they make the ad hoc assumption that the dissipation scale length is a stellar radius. This dissipation could be due to friction between ions and neutrals in a cool flow, damping in shocks, mode conversion, or nonlinear wave-wave interactions, but detailed studies are needed to understand these dissipative processes. Also the dissipation cannot be large enough to produce hot coronae in stars to the right of the corona boundary in Figure 1 (cf. Haisch, Linsky and Basri 1980). With this assumption for a dissipative scale length, they found that winds are cool ($T < 10^4$ K) for luminous ($\log g < 2$) stars and hot ($T > 10^5$ K) for giants and dwarfs ($\log g > 2$) with reasonable values of terminal velocities and mass loss rates.

The Hartmann-MacGregor paper is interesting, but a number of important details must be investigated. For example, mass loss rates of 10^{-5}-10^{-6} M_{sun} yr^{-1} are predicted for a star like α Ori only for coronal base fields of 10 gauss. It is hard to imagine how dynamos in extremely slowly rotating M supergiants could produce fields this large. Clearly the dissipation scale length plays a critical role in determining mass loss rates and terminal velocities, but much more work needs to be done. Finally the field lines are assumed radial so the solutions cannot be valid for those portions of a stellar corona where the field lines are closed. Thus the hybrid stars might be hybrid in the sense that the cool wind originates in open field regions while the hot gas is confined to closed loop structures. Broad line profiles, such as that for C III λ1909 in α TrA (Dupree 1980) could then be due to up and down flows within closed flux tubes. In any case Alfvén-wave-driven winds are an attractive possibility for explaining the cool flows in the late-type supergiants and perhaps also in the higher gravity stars.

Recently, Mullan (1981) has proposed a different mechanism whereby magnetic fields can produce mass loss. The onset of large winds (as determined by asymmetry in the Mg II lines) along a boundary in the H-R diagram (line M in Fig. 1) that is similar to the boundary (line C in Fig. 1) where coronae are no longer seen is suggestive that magnetic fields have closed configurations to the left but open configurations to the right. Pneuman (1968) first showed that solar helmut streamer structures, in which the field lines are closed below r_h and open above r_h, are unstable when $r_h = r_{crit}/2$. Thus closed coronal field lines cannot exist in stars for which $r_{crit} < 2\ r_*$. Mullan then argued that this criterion predicts a boundary in the H-R diagram similar to lines M and C in Figure 1, and that newly emerging closed field lines for stars with $r_{crit} < 2\ r_*$ will become distended, reconnect along an X-type neutral line, and eject discrete magnetic bubbles of gas at the Alfvén speed. He proposes this as a nonsteady state asymmetric mass loss mechanism for K giants, in particular for the K components of RS CVn systems, which likely have very large rates of magnetic flux emergence.

V. MASS LOSS BY PERIODIC SHOCK WAVES

Many M supergiants like Mira (gM6e) are long period variables that show evidence of large mass loss (10^{-5}-10^{-6} M_{sun} yr^{-1}) and low terminal velocities (≈ 10 km s^{-1}). Willson and Hill (1979) and Wood (1979) have presented numerical calculations of the dynamic response of a Mira star atmosphere to a periodic train of upward propagating shocks driven by a piston located at the bottom of the atmosphere.

Willson and Hill (1979) argue that mass loss is inevitable in this situation for the following reason. A star has a natural gravitational period which is the gravitational return time, $P_o \approx 2r_o/v_o$, for a particle with velocity v_o to return to its radial position r_o. When the atmosphere is driven with a pulsation period $P = P_o$, then particles are forced into periodic ballistic orbits in which they return to their initial positions and there is no mass loss. However, if $P < P_o$, then particles do not have sufficient time to return to their initial location but find themselves further from the star when the next wave arrives. Mass loss is thus inevitable. Furthermore, P_o increases with increasing r such that there must be a critical radius, r_{crit}, where the condition $P < P_o$ is satisfied. The mass loss rate depends on the density at r_{crit} and can be very large for stars with small values of r_{crit}/r_*. However the outflow velocity at r_{crit} is typically much less than the escape velocity at this point, contrary to the situation for thermally driven winds.

Willson and Hill (1979) called attention to several important effects. First, particles can accumulate kinetic energy from successive shocks and shocks can catch up to previous shocks and combine to enhance the mass loss. Second, contrary to intuition, the mass loss is essentially a steady flow rather than a series of discrete events produced by individual shocks. Third, the ratio of the cooling to expansion time scales is a crucial parameter. Wood (1979), for example, showed that in the isothermal limit (rapid cooling) there is no continuous mass loss, but rather occasional ejections of matter with a time-averaged mass loss rate of $\sim 10^{-12}$ M_{sun} yr^{-1}. In the adiabatic limit, however, he computed unrealistically high mass loss rates (0.02 $M_{sun} \cdot yr^{-1}$). Real flows should be an intermediate case with nearly isothermal shocks near the base where the densities are highest and nearly adiabatic shocks at the top where the densities are lowest. The inclusion of heating near the top of the atmosphere in the calculations of Willson and Hill (1979) results in higher pressures and enhanced mass loss. In effect these models begin to resemble thermally-driven winds but with enhanced densities at the thermal critical point due to the shock wave forces. Wood (1979) discussed another mixed acceleration flow in which the addition of period shock waves into a Mira atmosphere with a pre-existing wind driven by radiation pressure on grains enhances the mass loss rate by a factor of 40, while the terminal velocity of the flow is not significantly changed.

Additional calculations with more realistic shock conditions are needed to understand the periodic shock mechanism, but in principle the mechanism can explain the observed wind properties in the long period variable M supergiant stars. It is possible that this mechanism could also explain winds in the semiregular M supergiants like α Orionis, but it is hard to see how it can explain winds in warmer or less luminous stars as periodicity of the shock waves is an essential ingredient in explaining the winds and the late-type giants and G-K supergiants show no evidence for such waves. Thus the mechanism is interesting but of limited applicability in explaining winds throughout the cool half of the H-R diagram.

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DISCUSSION

DUPREE: 1) Although coronal holes can be the dominant source of mass loss at the minimum of the solar cycle, we must remember that the solar wind does not stop at the solar maximum where holes are not prevalent on the disk. Thus there may well be sources of the wind("open field regions") in a surface dominated by centres of activity such with ultraviolet and x-ray emission.

2) The plausibility of the Hartmann - McGregor assumption of wave damping in stellar atmospheres is emphasized by the necessity for heating and /or momentum deposition far from the solar surface in coronal holes as found by Munro and Jackson (Astrophys. J. 213, 874, 1977). Moreover Alfven waves have been identified in the solar wind, Belehm and Devis, (J. Geophys. Res. 76, 3534, 1971).

LINSKY: I agree on both.

KWOK: Regarding the situation of α Ori, if dust were indeed condensed far away from the star, the fact that the dust does not escape at 3000 km/s implies that the dust is momentum coupled to the gas and a large amount of momentum is being transferred to the gas. This necessarily change the velocity structure, i.e. accelerate the flow. It must be emphasized that the terminal velocity is always determined by radiation pressure on dust regardless of the mechanism of mass loss. If the gas velocity in the chromosphere is equal to the terminal velocity as suggested by Dr. Goldberg, dust must have condensed in the chromosphere and therefore responsible for the mass loss.

LINSKY: There is little doubt that the dust is momentum - coupled to the gas and that radiation pressure on the grains contributes to the mass loss rate. The important question is wheter the radiation pressure mechanism is the dominant component or a small component to the wind acceleration. As I stated in my talk, the radiation pressure mechanism faces at least three fundamental difficulties as a candidate for the dominant acceleration mechanism in M supergiants. These fundamental objections must be addressed. Of course, clean grains can condense in the chromosphere, but they must be transparent to most of the photospheric light (in the near infrared) to survive evaporation. Draine (1981) has suggested that clean silicate do condense close to the photosphere and become dirties and thus hotter wind accelerates as they move outward, but this does not explain the observed terminal velocities in the chromosphere. Perhaps Wood's (1979) calculation that the addition of periodic shock waves to a pre-existing Mira atmosphere with grains enhansing the mass loss rate by a factor of 40 is indicative of the relative contributions of these two mechanisms in the M supergiants.

HEARN: Yesterday we heard that a 1 million degree corona round a late type giant would not be observed by Einstein. What pressure in the transition region of a 1 million degree corona round a late type giant would not be observed by IUE?

LINSKY: At present we can only give upper limits on L_X and L_X/L_{BOL} for giants and supergiants based on Einstein IPC and HRI data. When the sensivity of these instruments to very soft x-ray becomes better known, then the upper limits on L_X can be converted into upper limits on the emission measure as a function of coronal temperature, EM (T_{COR}). One cannot determine upper limits on pressures in stellar transition regions without specifying the stellar angular diameter and transition region temperature gradient. One can specify a surface flux or an equivalent emission measure at the temperature corresponding to the maximum abundance of a given ion for a star of known angular diameter. For example, in a long exposure IUE low dispersion spectrum of Arcturus (K2 III), the upper limit on the C IVλ1549 flux is 7×10^{-13} erg cm^{-2} s^{-1}. This corresponds to a surface flux of 260 erg cm^{-2} s^{-1}, compared to 5800 erg cm^{-2} s^{-1} for the quiet Sun. For α Ori the C IV λ1549 surface flux upper limit is 10 erg cm^{-2} s^{-1}. Since these upper limits are far smaller than for the quiet Sun, I believe that they are saying that the emission measures of 10^5 K plasma in these stars are also far smaller than for the Sun.

DUPREE: It should be emphasized that the simple conclusion of a "sharp dividing line" in the HR diagram is not supported by the empirical evidence. Various aspects of the observations:"presence" of the C IV line, the existence of hybrid atmospheres, line asymmetries in Mg II and Ca II lines, and ratios of individual emissions line fluxes strongly suggest a continuity in the behavior of these extended atmospheres.

LINSKY: It is certainly correct that stars are more complicated than our approximation and that there should be and likely is a continuum of some outer atmosphere parameters for the late-type stars. However, I do wish to emphasize the following points: (1) There is now good evidence for a rather sharp boundary between stars with and without hot coronae as detected by Einstein (line C in Figure 1). (2) We have seen no evidence yet for stars with coronal temperatures in the range 14^4 K $\leq T_{cor} \leq 2 \times 10^5$ K. The hybrid stars could have temperatures in the range 2×10^5 K to 5×10^5 K, but I believe a more likely explication is that they have hot coronae with x-rays absorbed by cool gas in the wind. The most likely explication for the forbidden range of coronal temperatures is a thermal instability such as described in my talk. If so, than the coronal temperature is not a continuum variable. This suggests but does not prove, that the hybrid stars have two component outer atmospheres (hot gas in magnetic flux tubes and cool winds in magnetically open regions). (3) We need more IUE data to better understand where transition regions do and do not occur in the HR diagram. It would not surprise we if a boundary region with significant width emerges due to the range of stellar rotational velocities.

CARRASCO: What is your opinion on the role of magnetic field generation-rotation and hence stellar activity?

LINSKY: By stellar activity we generally mean relatively strong emission in lines formed in chromospheres and coronae and in coronal X-ray emission. It is now clear on observational grounds that rotation is one of the key parameters in explaining stellar activity in late-type stars.Presumably the mechanism involved is that rapid rotation in stars with convective zones is accompanied by differential rotation, which implies an efficient dynamo. We need to know better how dynamos operate and how stochastic magnetic fields in turbulent plasmas produce heat.

MONTMERLE: Do you have any comment on the extreme case of Eta Carinae where a large amount of dust (and gas) seems to be present, and in which Einstein has detected a strong X-ray flux, apparently coming from the same region?

LINSKY: I cannot really comment on this very interesting object other then saying that the Einstein measurements could refer to emissions either from a corona close to the star (if the spectrum is hard), hot plasma in the wind, or hot plasma in a shock at the wind/interstellar medium interface. Other data are needed to determine which of these three possible explanations are valid.

VIOTTI: To give an answer to the question of Dr. Montmerle about η Car, I would like to say that its ultraviolet spectrum has no resemblance with the IUE spectra of late type stars. We have identified NIII and very strong SiIII lines, but no very high ionization emission lines. FeII and FeIII are broad with a complex structure. Its spectral appearance is clearly the result of the very dense wind.

GOLDBERG: You have made the case for dust-driven winds worse than it need be by adopting a photospheric scale height of about 0.01 R_* for α Orionis, which makes the height of 4.5 R_*, where the dust grains condense, equal to 450 H. Yet the widths of photospheric spectral lines in supergiants are about 27 km/s, which may imply $H \approx R_*$.

LINSKY: I agree that including only gas pressure gives a minimum value to the pressure scale height and the inclusion of dynamic terms (due to turbulence or waves) will likely yield much larger values for the effection scale height. However, the problem remains that radiation pressure on dust cannot initiate a wind, it can only add momentum to a flow already initiated by a different mechanism.