MASS-LOSS FROM COOL STARS

WHAT IS THE ESSENTIAL PHYSICS OF MASS LOSS FROM LATE-TYPE STARS?

Jeffrey L. Linsky[1]
Joint Institute for Laboratory Astrophysics, University
of Colorado and National Bureau of Standards, Boulder,
Colorado 80309-0440

ABSTRACT

In this review I consider what clues the data are providing us con-
cerning the mass loss from late-type stars. I consider in turn the
major classes of mass-loss mechanisms (thermally-driven winds, radia-
tively-driven winds, and wave-driven winds), and consider whether the
empirical mass loss rates and other data are consistent with any of
these mechanisms acting alone. It is likely that several mechanisms
act together to produce the large mass loss rates in the Mira and non-
pulsating M supergiants. Studies of the solar atmosphere suggest that
thermal bifurcation driven by molecular condensation instabilities may
play a critical role in cooling the atmospheres of luminous cool stars
and forming silicate dust. It is possible that several metastable
modes of atmospheric structure may exist for a given set of stellar
parameters.

1. INTRODUCTORY REMARKS

Historically mass loss has been investigated because of the roles it
can play in stellar evolution and because it is one important process
(the other being stellar explosions) that chemically enriches the
interstellar medium. In a recent review Iben (1985) pointed out that
for stars less massive than 10 $M_\odot$, mass loss does not appreciably af-
fect evolution on the main sequence, but when stars exhaust the hy-
drogen and helium fuel in their cores rapid mass loss from the asymp-
totic giant branch stars leads to rapid evolution to white dwarfs
(M < 1.4 $M_\odot$) rather than supernovae, which would have occurred had the
stellar mass remained above 1.4 $M_\odot$. This example calls attention to

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

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the intimate role mass loss plays in stellar evolution scenarios. Cassinelli (1979), Dupree (1981,1986), Dupree and Reimers (1987), Wannier (1985), Linsky (1985), Goldberg (1985), Knapp and Morris (1985), Drake (1986), and Lada (1985), among others, have reviewed empirical estimates of mass loss rates which employ a broad range of techniques. While these techniques are being pursued vigorously, uncertainties in the empirical estimates remain large, especially at the critical pre-main sequence and the asymptotic giant branch stages of evolution. Stellar evolution calculations, therefore, are generally based on parameterized scaling laws such as the so-called Reimer's law $\dot{M} = cL/gR$, where $c \approx 4 \times 10^{-13}$ in solar units (Reimers 1975). Such laws are often applied to ranges of stellar parameters far beyond the range for which they were derived. In particular, Iben (1985) called attention of the failure of this law to account for the low rate of supernovae in the galaxy and thus mass loss during the asymptotic giant branch. Furthermore, the use of such parameterized scaling laws implicitly assumes that mass loss depends only on the stellar parameters (i.e., L, g, R), independent of stellar age, interior structure, and history. None of these assumptions may be valid.

In reading through the literature I sense a strong, almost philo- sophical, predilection toward a clean and simple approach to the topic of mass loss involving:

(1) the use of various diagnostics to measure mass loss rates for stars in different regions of the H-R diagram and stages of evolution;

(2) the determination of semi-empirical scaling laws that relate mass loss rates to such stellar parameters as L, T_{eff}, R, M, g, and chemical composition;

(3) the identification of plausible mass loss mechanisms for dif- ferent regions of the H-R diagram consistent with the scaling laws;

(4) the prediction of observables on the basis of the mass loss mechanisms and the critical test of the mechanisms by the comparison of predictions with observations.

This straightforward approach may, unfortunately, ignore some of the essential physics of mass loss. For example, stars are likely spatially complex. The Sun may provide us with a useful prototype in that the mass loss rate is negligible in magnetically closed regions so that all the mass loss occurs in the magnetically open regions primarily at the poles. Second, mass loss can be transient as is likely the case for pre-main sequence stars (Mundt 1984; Herbig 1977). Third, several mechanisms may operate together (examples will be given below) so that no one mechanism may explain mass loss for each type of star. Finally, certain instabilities and nonlinearities may be important such that the mass loss rate may depend nonuniquely on the stellar parameters. Thus history may be important and stars could have "individuality." If so, then the mass loss rate for a given star at any given time may be overconstrained and thus not predictable.

My purpose is not to disparage the study of mass loss from stars, but rather to point out the need to identify the essential physics of mass loss and to confront theory with observations continuously. In this review, I will attempt to do so by discussing each proposed mass loss mechanism and the relevant data together.

2. MASS LOSS MECHANISMS: GENERAL CONSIDERATIONS

There are a number of excellent reviews of mass loss mechanisms rele-
vant to late-type stars including reviews by Cassinelli (1979), Holzer
(1980,1987), Castor (1981), and Holzer and MacGregor (1985). Concep-
tually, the three broad classes of mechanisms may be distinguished by
the relative importance of different terms in the momentum equation
for steady-state radial flows,

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

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 accel-
eration, 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 respon-
sible for the solar wind, but as discussed by Holzer (1979) this mecha-
nism 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 ac-
celeration mechanism. 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.

   This classification says nothing directly about the energy
equation, the temperature distribution, the geometry, the role mag-
netic fields play in channeling the flow, 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.

3. THERMALLY-DRIVEN WINDS

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 flows ($r < r_{crit}$) and supersonic flow ($r > r_{crit}$).
At the critical point, the temperature, T_{crit}, is

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

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

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

and when hydrostatic equilibrium is valid

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

$$H = \frac{kT_{cor}}{\mu g} \quad . \tag{5}$$

For the Sun, empirically $T_{cor} \approx 2 \times 10^6$ K, so that the density scale height $H \approx 0.15 \ r_{sun}$ 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 $T_{cor}/T_{crit} \ll 1$, 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 in proportion to this density increase. An essential point is therefore to investigate conditions for which the effective density scale height can exceed the thermal value. The large photospheric linewidths in α Ori (cf. Goldberg 1979) imply that scale heights in M supergiants can be far larger than thermal.

3.1. Empirical Estimates of Coronal Temperatures

Whether or not a thermally-driven wind can produce significant mass loss depends on the temperature of the hot gas in the stellar corona, the density at the radial distance of the critical point corresponding to $T_{crit} = T_{cor}$, and whether or not the hot plasma is confined by closed magnetic loops. The latter two questions are difficult to answer, but the Einstein X-ray Observatory has provided us with valuable information on which types of stars emit X-rays and thus have coronal gas hotter than 1×10^6 K (cf. Rosner, Golub and Vaiana 1985 for a recent review). The X-ray data for late-type stars indicate that dwarfs have coronae with 10^6–10^7 K plasma as do giants earlier than about spectral type K2 III (Ayres et al. 1981; Haisch and Simon 1982). No bright single giants and supergiants have been detected, except for Canopus (F0 Ib-II), β Dra (G2 Ib-II), and α TrA (K4 II) (Brown 1986), and the upper limits are often much lower than for the Sun. Pre-main sequence stars are often detected as bright X-ray sources as are the "naked T Tauri" stars, which are as young as the classical T Tauri stars but without evidence for circumstellar gas (Walter 1986). Each

of the stellar types detected as X-ray sources could have thermally-driven winds if the hot plasma is not magnetically confined.

Plasma as hot as 150,000 K can be detected by IUE as emission in the C IV 1550 Å and N V 1240 Å lines. The IUE observations of late-type stars (see Linsky and Jordan 1987 for a recent review) are consistent with the findings from Einstein. In particular, dwarfs, giants earlier than spectral type K2 III, and pre-main sequence stars emit spectral lines indicative of plasma at least as hot as 150,000 K. One of the important results from IUE was the discovery of a fundamental change in atmospheric structure as one proceeds to the right in the H-R diagram from the yellow giants (spectral types earlier than Kl III) to the red giants. Whereas the yellow giants have spectra with all of the high-temperature lines present, the spectra of red giants contain none of these lines (Linsky and Haisch 1979; Simon, Linsky and Stencel 1982). Instead red giant spectra contain such low temperature species as O I, Si II, Fe II, and S I, as well as blue-shifted absorption features in the Mg II and Ca II lines indicative of cool winds (Stencel and Mullan 1980). Dupree (1986) and Dupree and Reimers (1987) have summarized the evidence for the onset of cool winds in the red giants. The hottest plasma in the well-studied red giant α Boo (K2 III), as indicated by the Ly-α, C II 2325 Å multiplet, and Si III] 1892 Å lines (Ayres, et al. 1987), is probably cooler than 20,000 K. These IUE data indicate that the red giants cannot have appreciable thermally-driven winds.

IUE observations also led to the discovery of a new class of stars called the "hybrid" stars (Hartmann, Dupree and Raymond 1980) which are K bright giants and G supergiants with C IV and N V emission, indicative of plasma at least as hot as 150,000 K, and blue-shifted Mg II absorption features, indicative of cool winds. The highest temperature plasma in these stars is not known because only one member of the class, α TrA (K4 II) has been detected as an X-ray source (Brown 1986). The winds in these stars could be radiatively-driven if the 10^5 K gas is located at a critical point near 3 r_* (see Table 1) and the blue-shifted Mg II absorption features are formed in overlying gas that has cooled to ~6000 K. If this picture is valid, then one should see blue-shifted emission in the C IV 1548 Å resonance line and C III 1909 Å intersystem lines at roughly half the expansion velocities seen in Mg II (100-200 km s^{-1}) but no expansion has been detected in either C IV or C III (Hartmann et al. 1985; Brown, Reimers and Linsky 1986). Thus the winds in hybrid stars are probably accelerated by another mechanism and the hot plasma may be magnetically confined.

The IUE spectra of late-type giants and supergiants either show emission lines of essentially all ions up to the highest temperature lines (C IV and N V) observable by IUE or they show no lines formed at temperatures above 10,000-20,000 K. No post-main sequence star has yet been detected with a maximum temperature between 20,000 and 150,000 K, although some pre-main sequence stars may be contrary examples.

The existence of this apparently forbidden range in T_{cor} may be a simple consequence of thermal instability. McWhirter, Thonemann and

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Table 1. Predicted critical temperatures for thermally-driven winds

Class	Example	Spectral Type	$\frac{M_*}{M_\odot}$	$\frac{r_*}{r_\odot}$	T_{crit} (K)		
					$r_{crit}=r_*$	$r_{crit}=3r_*$	$r_{crit}=10r_*$
Main Sequence	Sun	G2 V	1	1	8×10^6	2.7×10^6	8×10^5
Pre-Main Sequence	T Tau	K1	~1	~4	2×10^6	6.7×10^5	2×10^5
Red Giant	α Boo	K2 III	~1	25	3.3×10^5	1×10^5	3.3×10^4
Hybrid	α Aqr	G2 Ib	~5	~100	4×10^5	1.3×10^5	4×10^4
M Supergiant	α Ori	M2 Iab	~10	~1000	8×10^4	2.7×10^4	8×10^3

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 higher temperatures and pressures as cooling would be dominated by conduction and radiation only.

Castor (1981) proposed a somewhat different explanation for the simultaneous disappearance of hot plasma and onset of cool winds in the early K giants. He called attention to two important time scales: the radiative cooling time

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

and the expansion time for sonic flows

$$t_{exp} = \frac{r_*}{v_{sound}} \quad . \tag{7}$$

The radiative power loss $P_{rad}(T)$ is roughly constant over the temperature range 15,000 K $\lesssim$ T $\lesssim$ 5 × 10^5 K, but it is roughly a factor of 10^2 lower for 10^6 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 $t_c \gg t_{exp}$. Thus the wind remains hot as it leaves the star. To the right of the boundary, $T_{cor} < 5 \times 10^5$ K so that $P_{rad}(T)$ is a factor of 10^2 larger and $t_{exp} \gg t_c$. The wind thus rapidly cools if it started hot. As a

result of the radiative instability there may be no outer atmospheres with $15{,}000 \text{ K} \lesssim T_{cor} \lesssim 5 \times 10^5$ K.

Recently, Antiochos and Noci (1986) and Antiochos, Haisch and Stern (1986) have found that for low gravity stars magnetic loops with $T < 10^5$ K appear to be thermally stable. This work points out the complexity of thermal stability analyses when closed magnetic fields are included, but it does not alter the previous arguments that should be valid for open or no fields, which is likely when winds are present.

4. 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), Zuckerman (1980), Castor (1981), and Drake (1986) have reviewed the empirical evidence for large mass loss rates in luminous cool stars. 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 10-14 μm 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. 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 collisions. Gehrz and Woolf (1971) presented infrared observations of many late-type stars and estimated mass loss rates and terminal velocities.

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), Cassinelli (1979), Nuth and Donn (1982) have summarized this work at length. Menietti and Fix (1978) showed that the flow does pass through the sonic point at the radial distance where the grains condense. 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 10 μm feature (and presumed equal to the total radiative power absorbed by the gas), v_∞ is the flow velocity far from the star, and c is the speed of light.

One can speak of winds as radiatively driven only if radiation pressure on the dust results is most of the momentum deposition to the gas __and__ if this momentum deposition has occurred before the gas

achieves sufficient outward velocity to escape the star. The first
question is whether there is enough dust opacity in the wind. Assum-
ing good momentum coupling of dust and gas, the radiative acceleration
on the gas will exceed the gravitational acceleration when

$$g_R = \frac{kL_*}{4\pi r^2 c} > \frac{GM_*}{r^2} \qquad (8)$$

(cf. Holzer 1987 for an opacity correction term to this equation).
Jura (1986a,b) argues that most of the luminosity L_* for M supergiants
is in the 1-2 µm region and for $M_* = 2$ $M_\odot$ and $L_* = 10^4$ $L_\odot$, k(1-2 µm)
need only be as large as 3 cm^2 g^{-1}. Since for gas/dust ratios typical
of the interstellar medium k(1-2 µm) ≈ 30 cm^2 g^{-1}, there is probably
sufficient dust opacity to produce mass loss in M supergiants. Note,
however, that Hagen, Stencel and Dickinson (1983) conclude on the
basis of a similar calculation that there is insufficient dust opacity
for radiation pressure alone to account for the observed mass loss
rates of M supergiants.

     The second question is whether there is sufficient momentum in
the stellar radiation field to explain the observed mass loss, i.e.

$$L_*/c \geq \dot{M} v_{exp} \qquad . \qquad (9)$$

This inequality is satisfied for all M supergiants (Jura 1986a),
except for a few rapidly evolving stars for which L_* could have been
ten times larger than its present value as recently as 1000 years ago.
However, the high velocity molecular (CO) outflows for many pre-main
sequence stars violate this condition (Lada 1985); thus radiation
pressure from the central objects cannot explain these outflows.

     These two arguments make radiation pressure on dust a possible
candidate to explain mass loss from post-main sequence stars that ex-
hibit evidence for circumstellar dust grains -- the M supergiants and
the C and S stars. Even for these stars, however, there are several
problems that appear to rule out this mechanism acting alone as the
likely cause of mass loss.

     (1) Radiation pressure on grains cannot initiate the flows. The
measured properties of pure silicates like olivine, the so-called
clean grains, are such that they absorb mainly near 10 µm 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 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 throughout the near infrared and near 10 µm, so
that they evaporate close to a star. Draine (1981) calculates that
they cannot exist within 4.5 r_* of α Ori, for example. This estimate
is confirmed by the 11 µm heterodyne interferometry measurement (cf.
Sutton et al. 1977) that the inner radius of the dust shell is about
12 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 mechanism.

(2) Escape velocities are reached before the grains form. For
α Ori, Goldberg (1979) cites evidence for v ≈ v_{esc} already deep in the
chromosphere. Also if grains form typically at 10 r_*, then some other
source of momentum deposition has already provided 90% of the work
needed to lift the gas out of the stellar gravitational potential.

(3) The gas and dust column densities are uncorrelated in M
supergiants (Hagen 1978; Hagen et al. 1983), contrary to expectation
if radiation pressure on dust is driving the mass loss.

We conclude that radiation pressure on dust by itself is not the
cause of significant mass loss anywhere in the H-R diagram. However,
Jura (1986a,b) noted the excellent correlation of 12 μm excess,
indicative of circumstellar dust, with pulsation for M supergiants.
This suggests a two-step process in which pulsations raise material to
large distances above the photosphere where grains can condense and
radiation pressure can contribute to the mass loss.

4.1. Does Dust Formation Quench Chromospheres?

Jennings and Dyke (1972) called attention to an empirical inverse corre-
lation between Ca II H and K line emission and 9.7 μm dust emission.
They concluded that chromospheres disappear just as dust appears in the
early M supergiants. Jura (1986a) reexamined this inverse correlation
using IRAS data with a similar conclusion, and Hagen et al. (1983)
found that M supergiants with large gas/dust ratios have no apparent
Ca II emission. These data all support Jenning's (1973) speculation
that dust formation "quenches" chromospheres in that energy that would
otherwise heat chromospheres to temperatures (T_e > 5000 K) where Ca II
could be collisionally excited is instead radiated in the infrared by
dust mixed with cool (T_e < 1000 K) outflowing gas. In this scenario
there appear to be two stable regimes for a circumstellar envelope --
either it is completely warm (chromospheric) and not dusty, or it is
completely cool and dusty.

To test this scenario Stencel, Carpenter and Hagen (1986) used
IUE to observe 15 K and M giants and supergiants (excluding Miras)
with different gas/dust ratios. They found that all of their sample
stars, including giants as late as M5 III, have Mg II, Fe II, Aℓ II],
and C II] emission features indicative of plasma at chromospheric tem-
peratures, but the radiative losses in these lines (indicative of the
heating rates in the chromosphere) in the dusty stars are an order of
magnitude smaller than those for the stars with large gas/dust ratios.
They concluded that dust formation can alter the outer atmospheric
structure but not eliminate the presence of matter at chromospheric
temperatures. These data reinforce the concept of thermal bistability
within a given atmosphere (see below).

5. MASS LOSS BY PERIODIC SHOCK WAVES

Many late M giants, like Mira (gM6e), are long period variables that
show evidence of large mass loss (10^{-6}–10^{-7} M_{sun} yr^{-1}) and low termi-
nal velocities (≈ 10 km s^{-1}). Willson and Hill (1979), Wood (1979),
Willson and Bowen (1985), and Bertschinger and Chevalier (1985) 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 base of the atmosphere. These cal-
culations may also be useful in understanding the essential physics in
other pulsating stars including the semi-regular variables, Cepheids,
and RR Lyrae stars. Nonpulsating cool giants and supergiants
generally have wide line profiles, implying turbulent velocities of
20–30 km s^{-1} (Reimers 1987). These stars may also be pulsating but
with many radial or nonradial modes.

Willson and Hill (1979) showed that mass loss is inevitable for
a periodic train of waves by the following argument. A star has a
natural gravitational period which is the gravitational return time,
$P_0 \approx 2r_0/v_0$, for a particle with velocity v_0 to return to its radial
position r_0. When the atmosphere is driven with a pulsation period
$P = P_0$, then particles are forced into periodic ballistic orbits in
which they return to their initial positions and there is no mass
loss. However, if $P < P_0$, 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_0 increases with increasing r such that there must be a
critical radius, r_{crit}, where the condition $P = P_0$ 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.

They also 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 far from the star
is essentially a steady flow rather than a series of discrete events
produced by individual shocks. Third, the ratio of the cooling to ex-
pansion time scales is a crucial parameter. Wood (1979), for example,
showed that in the isothermal limit (rapid cooling) there is no con-
tinuous mass loss, but rather occasional ejections of matter with a
time-averaged mass loss rate of ~10^{-12} M_{sun} yr^{-1}. In the adiabatic
limit, however, he computed unrealistically high mass loss rates
(0.02 M_{sun} 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 calcu-
lations 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.

More recently Willson and Bowen (1985) presented calculations for periodic waves in Miras and other pulsating stars in which the adiabatic or isothermal approximations are relaxed. One important result is that the atmospheres can become very distended, especially for long period waves. In other words, the dynamical density scale height can become very much larger than the static (i.e., thermal) scale height leading to orders of magnitude increases in density. A second important point is that the radiative relaxation time τ_{rad} increases with decreasing density and thus increasing radial position. The condition $\tau_{rad} = P$ determines the inner radius (r_{ad}) of an adiabatic zone since beyond this point the radiative relaxation time is too long for a shock to radiate its internal energy before the next shock appears. For stars with $r_{ad} \ll r_{crit}$, the gas from r_{ad} out to r_{crit} is heated and the wind is thermally driven. For stars with $r_{ad} > r_{crit}$ the gas below r_{crit} is cool and the thermal pressure gradient is a small contributor to the wind acceleration.

Willson and Bowen's (1985) calculations suggest that for large mass loss rate long period variables (i.e., Miras) the winds are driven by pulsations and radiation pressure on dust (cf. Jura 1986a), but for small mass loss rate Miras the winds are only driven by pulsations. They speculate that the winds for RR Lyrae and short period Cepheids are thermally driven. However, the phenomenology of Miras is exceedingly complex and such important observations as a stationary layer detected in CO data (Hinkle, Hall and Ridgway 1982) are not yet explained by the theory.

6. ALFVÉN-WAVE-DRIVEN WINDS

Hollweg (1974) 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. 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.

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. 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 fluctua-

tions can be very large far from the star. Their solutions also ex-
hibit 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 consid-
ered Alfvén waves of low amplitude ($\delta B \ll B$, $\delta v \ll v_A$) with wave-
lengths small compared to the pressure scale height or variations
in any stellar parameters. They also assumed radial fields with $B = B_0(r_0/r)^2$. 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, but not very
much larger than for the hybrid stars. 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 and 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.

A number of important details must still 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 (Holzer, Fla and Leer 1983) and must be calculated realis-
tically. 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. In any case Alfvén-wave-driven
winds are an attractive possibility for explaining the cool flows in
the nonpulsating K and M giants and supergiants as well as the hybrid
stars (Hartmann, Dupree and Raymond 1981) and perhaps the T Tauri
stars.

7.   SIMULTANEOUS METASTABLE ATMOSPHERIC MODES AND MASS LOSS

The preceding discussion provides a general picture of a non-Mira cool
giant or supergiant atmosphere consisting of a turbulent photosphere,
a warm (5000-8000 K) chromosphere extending out to roughly 10 r_* that
is distended either by turbulence or a complex interplay of radial and
nonradial pulsations, and a dusty circumstellar envelope beyond 10 r_*.
The mass loss mechanism may be a three-step process (i.e., Jura 1986a)
involving "levitation" by wave momentum deposition, dust formation,
and the final removal of the gas and dust by a mixture of the wave
pressure, radiation pressure on the dust, and thermal pressure terms.

The Miras may differ only in that the pulsations are easily observed because they are primarily in one radial mode and there may be no permanent chromosphere but rather transient heated gas behind the shocks. For both Miras and non-Miras, the feedback of dust formation on the existence of chromospheric gas is unclear.

Is this all of the essential physics implied by the data? The answer is probably no and the clue as to what is missing comes from an unlikely source -- the Sun. Ayres and Testerman (1981) and Ayres, Testerman and Brault (1986) showed that the infrared solar spectrum in the CO vibration-rotation bands is inconsistent with a homogeneous atmosphere but suggests instead thermal bifurcation into discrete structures (perhaps magnetic flux tubes) with steep chromospheric temperature rises and cool regions containing CO with no chromospheric temperature increases with height. Subsequent work by Ayres (1981), Kneer (1983), Muchmore and Ulmschneider (1985), and Muchmore (1986) has explored how cooling in the CO vibration-rotation bands can produce a condensation instability or molecular "catastrophe" in which the initial formation of CO, say by compression, radiatively cools the gas which produces more CO (since the association rate is highly temperature-dependent) and thus more radiative cooling. The thermal bifurcation of the solar atmosphere is thus driven by the destabilizing effect of the steep temperature dependence of the CO formation and radiative loss rate. Analogously, the interstellar medium has at least two stable thermal regimes (Field, Goldsmith and Habing 1969).

Stencel, Carpenter and Hagen (1987) and Stencel (1986) have proposed that the CO condensation instability is an example of the essential physics that occurs in the chromospheres of M supergiants. Other molecules like SiO, CS, OH and H_2O (Muchmore, Nuth and Stencel 1986) can behave in a manner similar to CO. One plausible scenario is that a chain of molecular "catastrophes" can occur in which cooling by CO and the resultant pressure perturbation produce conditions ripe for SiO condensation that triggers formation of other molecules and eventually silicate dust and perhaps also SiO maser emission. A schematic outline of this scenario is shown in Figure 1.

If detailed calculations and observations give credence to this new picture of a cool supergiant atmosphere, we must recognize that the essential physics of these stars includes thermal instabilities, dynamic phenomena, the presence of very different thermal regimes in close proximity, and several mass loss mechanisms working together. The atmospheres of these stars thus appear to be highly complex and even chaotic. We must even consider the possibility that several metastable modes of atmospheric structure may exist for a given set of stellar parameters. The theory of mass loss from these stars must properly include all of this essential physics.

```
┌──────────────┐         ┌──────────────┐
│  SUBSURFACE  │────────▶│   PRESSURE   │
│  CONVECTIVE  │         │ PERTURBATIONS│
│  TURBULENCE  │         │  IN EXTENDED │
└──────────────┘         │ CHROMOSPHERE │
                         └──────────────┘
                                │
                                ▼
                         ┌──────────────┐
                         │ CONDENSATION │
                         │ INSTABILITY/ │
                         │   COOLING    │
                         └──────────────┘
                                │
  ┌──────────────┐              ▼
  │   CHROMO-    │       ┌──────────────┐
  │   SPHERIC    │──────▶│  MOLECULAR   │
  │  RADIATION   │       │ MASING/DUST  │
  │    FIELD     │       │  NUCLEATION  │
  └──────────────┘       └──────────────┘
                                │
  ┌──────────────┐              ▼
  │  RESONANCE   │       ┌──────────────┐
  │    LINE      │──────▶│ ACCELERATED, │
  │ SCATTERING/  │       │ EXPELLED DUST│
  │  QUENCHING   │       └──────────────┘
  └──────────────┘
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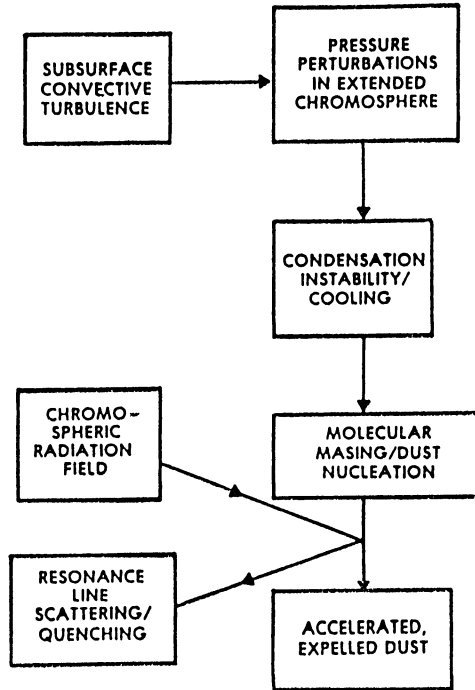
Fig. 1. A flow chart summarizing a mass scenario including the condensation instability and molecular cooling (from Stencel, Carpenter and Hagen 1986).

8. ACKNOWLEDGMENTS

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