Mass Loss from Late type Stars : Observations

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ABSTRACT

The evidence for the existence of stellar winds in late-type stars is reviewed, and the inferred properties of these outflows are summarized. There appears to be (at least) three different 'modes' for mass loss in such stars:

(i) In dwarf stars, and giant stars of spectral types G and early K, it is believed that mass loss occurs in the form of solar-type winds, i.e., the plasma is at coronal temperatures ($T \geq 10^6$ K), has a high terminal velocity (of order of the surface escape velocity v_{esc}), and a relatively low mass flux. There is, however, little quantitative information on winds of this type (other than for the Sun).

(ii) In late K and M giants (and their Carbon-rich counterparts), the winds are very different than the solar wind: The maximum temperature attained in the wind of a red giant is $\leq 2 \times 10^4$ K, the terminal velocity is low ($\ll v_{esc}$), and the mass flux can be ≥ 100 times the solar value. There are a wide variety of observational indicators of mass loss in red giants, and considerable progress has been made recently in inferring the radial structure of the outflows in these stars.

(iii) In K bright giants, and, perhaps mid-K giants, there is evidence of outflows that show characteristics of both solar-type and red giant-type winds. The nature of these 'hybrid-atmosphere' winds is still a matter of debate, and fundamental quantitative parameters are as yet rather uncertain.

The properties of mass loss in pulsating stars such as Cepheid and Mira variables are also discussed, and compared with those of non-variable stars of similar effective temperatures and gravities, in order to see if there are any systematic differences between them. Finally, future observations that may yield more accurate data on the winds of late-type stars are discussed, with particular emphasis on methods which have the potential of providing information on the radial and azimuthal structures of these outflows.

1. INTRODUCTION

It seems probable that all stars suffer mass loss at some rate throughout their evolution. However, for most of their lifetime ($\sim 90\%$), when they are on the main sequence, or in their early post-main sequence phase as subgiants, this mass loss process is very difficult to observe, let alone obtain quantitative information from. Even when such a star attains the red giant phase, the indications that mass loss is ocurring are quite subtle, except perhaps for a short-lived, glorious phase of a 'superwind' just prior to the transition from red giant to white dwarf. Most of the present review will concentrate on the observed mass loss properties of low-mass stars, i.e., stars of $\leq 2M_\odot$ which are of spectral type later than A0 on the Zero-Age Main Sequence (ZAMS), and of higher mass stars which have evolved past the blue edge of the instability strip. Dave Abbott will discuss in his review the observed mass loss properties of the hot stars that have been excluded here.

Perhaps the most fundamental conclusion of this talk is that mass loss from cool stars, even when it has been conclusively established (by showing that matter is outflowing at a speed in excess of the local escape velocity), it is often very difficult to quantify. One of the primary reasons for this is that, in order to derive a mass loss rate using observations of some species s (which could be an atom or molecule or even a dust component), one needs to know the physical conditions in the wind region sufficiently well that one can estimate the correction factor $f = < N_{tot}/N_s >$ by which to multiply the observed specific mass loss rate $\dot{M}_s$ so as to obtain the total mass loss rate $\dot{M}_{tot}$. If $f \sim 1$, this is clearly a trivial constraint, but, in practice, $f \gg 1$ is often the case, and the error in the adopted value of f will dominate the uncertainty in the resultant mass loss rate.

In this review, I will concentrate on the results that have been obtained using direct and indirect methods of determining mass loss parameters in non-pathological, 'normal', single (or at least widely separated from any companion, if in a multiple star system) cool stars. Data derived from studying close and/or interacting binaries, such as the Algol and cataclysmic classes of semi-detached binaries, are difficult to extrapolate to single stars because of the difficulty in separating properties of the mass loss intrinsic to the individual stars from those properties resulting from their environment (i.e., their being in a binary system). Nevertheless, mass loss from cool stars was first conclusively proven from a study of the wide binary α^{1+2} Herculis (Deutsch 1956), and the study of such systems has the potential of yielding perhaps the most accurate mass loss rates. In addition, due to space considerations, I will also exclude from this review observations of mass loss from pre-main sequence stars and from Population II stars.

It is impossible in a short review to cover exhaustively all of the observational indicators of mass loss in all of the various types of cool stars. I will instead concentrate (rather perversely) on those stars in which the evidence for winds is the most tenuous, since, after all, most cool stars belong to this category. Many studies have been made of the massive winds of the coolest giants and supergiants of spectral types M (if oxygen-rich) and C (if carbon-rich). A recent symposium (Morris and Zuckerman 1985) was dedicated to mass loss from such stars and contains review papers on the signatures of mass loss in the ultraviolet (Linsky 1985), the optical (from spectroscopy by Goldberg 1985, from interferometry by Beckers 1985), the infrared (from spectroscopy by Wannier 1985, from interferometry by Beckwith 1985, and from photometry by Werner 1985), and the radio regions (from molecular line emission by Morris 1985, from maser emission by Bowers 1985, and from continuum and H I emission by Knapp 1985a). A recent review on mass loss from luminous M stars is also given by Goldberg (1987). Other recent more general reviews on mass loss from late-type stars have been given by Dupree and Reimers (1987), Dupree (1986), Drake (1986a), and Willson and Bowen (1986).

2. MASS LOSS FROM A TO M MAIN SEQUENCE STARS

Dwarf stars later than about F0 are predicted to have convective envelopes, and, by analogy with the Sun, expected to have dynamo-generated activity. Observations confirm that all such stars do, in fact, appear to have regions in their outer atmospheres similar to the solar chromosphere, transition-region, and corona, and thus, one would expect that they would also have the equivalent of the solar wind, with a net outflux of material. How can this be confirmed and how can the rate of mass loss be measured for such 'coronal' winds (i.e., winds with $T_e \geq 10^6$ K)? Or, to put it another way, if the Sun were moved from its present distance of 5×10^{-6} parsecs (pc) to 10 pc, would one be able to infer it was losing mass?

As a partial answer to the above questions, I would state that the number of cool main sequence stars with mass loss rates known to a factor of 3 or better total ...... 1, the Sun, a G2V star, with $\dot{M} = 10^{-13.5}\mathrm{M}_{\odot}\mathrm{yr}^{-1}$, as determined from *in situ* plasma measurements. Despite many decades of high spectral-resolution observations of all or part of the solar disk, there are only a few spectroscopic indications of mass loss that have been found to be present in lines formed in the regions of the solar atmosphere from above the temperature minimum up to temperatures $\sim 1 \times 10^6$ K at the top of the transition region. For example, Rottmann *et al.* (1982) and Orrall *et al.* (1983) have found small ($\sim$ 10 km/sec) systematic blueshifts in EUV lines of O V $\lambda\,629$Å and Mg X $\lambda\,625$Å observed in coronal hole regions of the Sun, and similar upflows in coronal hole regions may have been detected in C IV$\lambda\,1550$Å (Mullan and Waldron 1987) and Ca II K (Holt and Mullan 1986). However, for most of the solar surface, and particularly over active regions, the dominant motion of material at 10^5 K as measured from the Doppler shift in emission lines like C IV $\lambda\,1550$Å is downward, i.e., towards the surface of the Sun, at $\sim$ 10 km/sec, e.g., Gebbie *et al.* (1981), Dere (1982), and Roussel-Dupre and Shine (1982). Thus, in a disk-averaged spectrum in which the active region emission would be the predominant contributor, one would see a net downflow in such TR lines. Indeed, Ayres *et al.* (1983) have used high-resolution IUE spectra of a number of nearby coronal-type stars to show that a downward velocity field does prevail in these stars' transition regions.

Thus, with the absence of direct diagnostics of mass loss in cool dwarfs, one is forced to use indirect means to obtain limits or order of magnitude-type estimates for their mass loss rates, which are expected, in general, to be very small: if $\dot{M} \propto R^2$, and I use the Sun to determine the constant, the predicted values of $\dot{M}$ range from $10^{-13.0}\mathrm{M}_{\odot}\mathrm{yr}^{-1}$ for an F0 V star to $10^{-14.5}\mathrm{M}_{\odot}\mathrm{yr}^{-1}$ for an M5 V star.

One means of putting an upper limit on the mass loss rate from a coronal-type star is to use the observed emission measure of X-ray emitting material, which presumably includes both closed magnetic field structures ('loops') not participating in an outflow, and open regions ('coronal holes'). If one examines, say, all G V stars observed by the Einstein Observatory IPC detector, one finds a range of at least 500 in the observed soft (0.2 - 4.5 keV) X-ray luminosities from log $L_x = 26.7$ to 29.4 (Maggio *et al.* 1987), which is fairly similar to the observed range of the Sun in the same X-ray band as it is covered by various filling factors of quiet versus active structures (Vaiana and Rosner (1978) estimate log $L_x = 26.7$ for a Sun covered by coronal holes compared to log $L_x = 29.3$ for a Sun covered by active regions). Thus, I will make the assumption that, for a given group of similar stars, those stars with the *minimum* X-ray luminosity have coronae that are probably predominantly open wind regions, and derive the volume emission measure EM_v of their winds. To derive a mass loss rate, one needs to have a velocity law in addition to an emission measure. Using the solar example as our lodestone, it is thought that the solar wind accelerates rapidly from $\sim$ 10 to $\sim$ 100 km/sec as the radial distance increases from 1 to $\sim 2R_{\odot}$, and attains its terminal velocity ($\sim$ 500 km/sec) by $10R_{\odot}$ (e.g., see Pneumann 1986). [It is interesting that the outflow velocity at the inner coronal boundary is $\sim$ the microturbulent velocity of the upper transition region/inner corona, which is $\sim$ 15 km/sec (e.g., Kjeldseth-Moe and Nicolas 1977)]. Making a crude power law assumption that $\alpha \sim 2$, where $v(r) = v(R_\odot) \times (r/R_\odot)^\alpha$, using $v = 10$ at $r = R_\odot$, adopting $T_e = 2.5 \times 10^6$ K for a typical inner coronal temperature, and using the standard plasma emissivity calculations to convert the observed X-ray luminosity into an emission measure, I derive $\dot{M} = 10^{-12.7} M_\odot \mathrm{yr}^{-1}$ for $\log L_x = 26.7$, appropriate for coronal-hole covered G dwarfs. As expected, this method tends to overestimate the mass loss rate (by $\sim$ 0.8 dex in the case of the Sun). It also implicitly assumes that the corona of the Sun is a prototype for all G stars in its temperature and velocity structure: the only evidence that this is true comes from the rather crude temperature information obtainable from IPC data which typically show $T_e \sim 3 \times 10^6$ K for solar-type dwarfs (Maggio *et al.* 1987).

F dwarfs are typically stronger X-ray emitters by about an order of magnitude than G stars. The survey of Schmitt *et al.* (1985) found a range in $\log L_x$ from 27.6 to 29.5 (excluding one spectroscopic binary with $\log L_x = 30.0$). Assuming that the minimum observed level corresponds to a coronal hole-dominated corona, using $R_* = 1.5 R_\odot$, and making exactly the same assumptions as for the G dwarfs, I derive $\dot{M} = 10^{-12.2} M_\odot \mathrm{yr}^{-1}$, a factor of 3 higher than the G dwarfs, consistent with the expected R^2 scaling mentioned previously.

K and M dwarfs have the widest range of X-ray luminosities of all, with measured $\log L_x$ values ranging almost 4 decades from 26.1 for Barnard's Star (M5 V) to 29.9 for AU Mic (M2.5 Ve), according to Golub (1983). Making the same assumptions as for the hotter dwarfs, and using $R_* = 0.33 R_\odot$ and the X-ray limit of 26.1, I derive $\dot{M} = 10^{-13.3} M_\odot \mathrm{yr}^{-1}$, a factor of 4 lower than the value derived for coronal-hole covered G dwarfs, as apposed to the factor of 10 predicted by the R^2 scaling. Given the uncertainties in this method, this difference is probably not significant. In fact, for the active dMe stars, which can have flare rates of 100 flares per day, with a time-averaged flare energy release rate of $1\% L_{bol} \sim 10^{29.5}$ erg/sec, the mass loss in the flare blast waves is potentially comparable or even greater than that lost through a steady stellar wind. Coleman and Worden (1976) use arguments based on extrapolating the parameters of scaled-up solar flares to these stars and estimate $\dot{M} \sim 10^{-12.7} M_\odot \mathrm{yr}^{-1}$ for a typical dM5e flare star, due to this process alone. This rate is a factor of 4 higher than my (probably too high) estimate of $\dot{M}$ for an inactive dM star, indicating that 'flare-initiated' mass loss may predominate for all but the least active M dwarfs.

Some additional information on mass loss in cool dwarfs can be gleaned from observations of such stars in binary systems where the companion star is also of low luminosity. Cataclysmic variables are semi-detached systems containing a cool dwarf (usually) and a white dwarf, but such high mass loss rates (eg., $\dot{M} \sim 10^{-10.5} M_\odot \mathrm{yr}^{-1}$ from HR Del and TT Ari by Krautter *et al.* 1981) have been inferred for these systems, as to indicate that these systems are not good paradigms for single cool dwarfs. In detached binary systems containing cool dwarf components, the mass loss rate does not appear to be so enhanced: Sion and Starrfield (1984) infer a mass loss rate for the K V component of the binary Feige 24 of $\sim 10^{-13} M_\odot \mathrm{yr}^{-1}$ on the basis of a model of mass transfer onto the white dwarf secondary. Hall and Kreiner (1980) derived much larger rates ($\dot{M} \sim 10^{-10} - 10^{-7} M_\odot \mathrm{yr}^{-1}$) for cool dwarfs in (detached) RS CVn binary systems, based on an interpretation of the observed changes in the orbital period as being due to asymmetric mass loss from coronal hole-type regions. These large rates can be ruled out observationally because they would produce much more X-ray and radio continuum emission than is actually observed; also, there are alternative ways of producing the observed period changes which do not require any mass loss or transfer whatsoever (e.g., van Buren and Young 1985). Thus, though potentially useful, binaries with cool dwarfs have not to date yielded much information on their intrinsic mass loss properties that can be applied to single dwarfs.

Thus, the X-ray emission of F - M dwarfs is consistent with an increase of about a factor of 10 in the mass loss rates of main sequence stars as one progresses from M5 ($M_* = 0.15 M_\odot$) to F1 ($M_* = 1.5 M_\odot$), and thus $\dot{M} \propto M_*$ for these stars. The only other presently practical method of measuring the emission measures of coronae is to use sensitive radio continuum observations at centimeter wavelengths to detect the predicted thermal bremsstrahlung. For the nearest late-type dwarfs with Einstein X-ray fluxes of 10^{-11} and greater, the predicted cm fluxes are ~ 20 to 100μJy, detectable only by the Very Large Array facility of NRAO, and then only in very long observations (≥ 5 hours). In fact, no single F or G dwarf has ever been detected as a steady radio source, with the present best upper limits being $\sim 200\mu$Jy at 6 cm. (Linsky and Gary 1983; Pallavicini *et al.* 1985). Late K and M dwarfs have been detected at levels of ~ 1 mJy, but the emission is variable, and sometimes polarized, and thus appears to be non-thermal in nature. Due to the limited amount of monitoring done of such stars, it has still not been established whether there is a weak, relatively steady free-free component also present.

As first pointed out by Weber and Davis (1967), the mass outflow of the solar wind from the rotating, magnetized Sun causes a net loss of angular momentum $dJ/dt \sim \Omega r_a^2 \dot{M}$, where Ω is the angular rotation rate and r_a is the Alfven radius (the radius at which the ouflow velocity equals the Alfven velocity $v_a = B_r/(4\pi\rho)^{0.5}$, where B_r is the radial magnetic field). For the present Sun, $J/(dJ/dt) \sim 7\times 10^9$ years. Thus, given two G2 V stars identical except for their rotation rates, one could, in theory, if one knew that their initial conditions were also similar, use such an equation to argue that the slower rotator must have had an integral mass loss over its history greater than that from the faster rotator. This method involves knowledge of the time evolution of the magnetic field and the rotation rate of the stars in question in order to produce quantitative estimates, and is actually very difficult to do properly; besides, in addition to the torque applied by a stellar wind, there are other effects which can alter the angular momentum of a star (or, perhaps just the outer layers) such as its moment of inertia changing with time, or the application of a magnetic dynamo. Thus, I do not believe it is possible to obtain reliable mass loss estimates from such an approach.

Finally, what about mass loss rates for A dwarfs? Well, if it was known whether these stars had stellar winds, and what their physical parameters were, then presumably one could answer this question! If they have coronal-type winds, then their emission measures must be extremely low, since single A stars, in general, were not detected as X-ray sources by Einstein. The most plausible detection is that of α Aquilae (A7 IV-V) at log $L_x = 26.6$ (Golub *et al.* 1983); applying the same analysis as for the later type stars, I derive a coronal mass loss rate of $10^{-12.6} M_\odot \mathrm{yr}^{-1}$, similar to that derived by this method for the Sun. Hotter A stars than α Aql such as Sirius (A1 V) have only upper limits for X-ray emission: log $L_x \leq 26.6$ for this nearest A star to the Sun. Thus, we conclude that A dwarfs cannot have coronal-type winds with mass fluxes any greater than that of the Sun, and most may not have such outflows at all.

What if A dwarfs have winds at cooler temperatures? As long as $T_e \geq 10^4$ K, such winds should be mostly ionized and hence emit free-free radiation, potentially detectable at centimeter wave lengths: no such emission has ever been detected. Hollis *et al.* (1985) obtain an upper limit of $\dot{M}_{ion} < 10^{-9.5} M_\odot \mathrm{yr}^{-1}$ from their VLA 6 cm observations of Vega (A0 V), assuming a wind velocity equal to the escape velocity. If $5 \times 10^3 < T_e < 2 \times 10^4$ K, one might expect a wind to produce blue-shifted components or P Cygni profiles in resonance lines of species such as Ca II, Mg II, or Fe II: no such features are seen in A dwarfs, and an approximate upper limit of 10^4 K mass outflow of $10^{-10.7} - 10^{-9.7} M_\odot \mathrm{yr}^{-1}$ is inferred by Hollis *et al.* (1985) for Vega.

There are other grounds for believing that A stars have very low mass flux stellar winds: Michaud and Charland (1986) have studied the effects of mass loss on the outer atmospheres of A and early F stars in the the context of the Michaud theory that the peculiar abundances seen in $\sim 25\%$ of the stars in this part of the main sequence are due to chemical separation caused by differential radiative acceleration. They find that mass loss $\sim 10^{-15} - 10^{-14} M_\odot \mathrm{yr}^{-1}$ results in model atmospheres with heavy element overabundances of the same order as those observed in Am-Fm stars, while $\dot{M} \sim 10^{-13} M_\odot \mathrm{yr}^{-1}$ produces model underabundances similar to those seen in the much less common class of λ Boo stars. I further extrapolate their results to infer that $\dot{M} \sim 10^{-13.5} M_\odot \mathrm{yr}^{-1}$ would produce no significant abundance pattern relative to the solar abundance scale: i.e., mass loss at such a rate is consistent with the abundances seen in 'normal' A stars. Thus, we reinforce the conclusion that A dwarfs have $\dot{M} < \dot{M}_\odot$.

3. MASS LOSS FROM STARS IN THE CEPHEID INSTABILITY STRIP

Stars undergoing pulsational instablilities might be expected to have enhanced mass loss relative to similar, non-pulsating stars, due to the deposition of momentum from the outward-directed pulsations as they steepen into shocks. The classical 'Instability Strip' intersects the Main Sequence in the region of the A dwarfs (where the variables are referred to as δ Scuti stars, if Population I, or RR Lyrae stars, if Pop. II) and, progressing to higher luminosities, encompasses the region of the F bright giants and supergiants (the classical Cepheid variables).[See Fig. 1]. At the highest luminosities ($M_v \sim -5$), the Instability Strip may broaden towards cooler stars to include the late F to K supergiant RV Tauri and R Coronae Borealis variables.

The most convincing evidence for mass loss of stars in this region of the HR Diagram comes from infrared observations, which have shown that some of the most luminous (and hence the longest-period) Cepheids, and essentially all of the RV Tau and R CrB variables have substantial infrared excesses over that due to the photospheric radiation. These IR excesses are due to circumstellar dust absorbing a portion of the stellar radiation and re-radiating it at wavelengths around the black-body peak corresponding to the dust equilibrium temperature (typically $\sim 100 - 1500$ K). Simple thermal modelling of the dust properties combined with the observed IR excess can then produce a fairly dependable estimate of the mass M_d of the dust shell; combining this with an outflow velocity v_w obtained from observed circumstellar absorption radial velocities, one can derive a dust mass loss rate $\dot{M}_d$; finally, adopting a value f_d that is representative of the dust to gas ratio in the circumstellar envelope, one can obtain a total mass loss rate $\dot{M}_{tot}$.

The early IR studies of Cepheids were made by Gehrz and Woolf (1970) who found moderate IR excesses in 2 Long-Period Cepheids. Recent IRAS observations of the far-IR region of a large number of Cepheids (McAlary and Welch 1986; Deasy and Butler 1986) indicate that most 'Classical' Pop I Cepheids do not have IR excesses. About 20% of the detected Cepheids showed small to moderate IR excesses: interpreting this as dust emission (rather than say free-free emission from an extended chromosphere or shock cooling region), McAlary and Welch (1986) estimate $\dot{M}_{tot} \sim 10^{-9} - 10^{-8} M_\odot \mathrm{yr}^{-1}$. Deasy and Butler (1986) derive $\dot{M}_{tot} \sim 10^{-9} - 10^{-6} M_\odot \mathrm{yr}^{-1}$ for classical Cepheids using a similar analysis; they also model the observed IR excess as being due to free-free emission, and find that the inferred mass loss rate to fit a given IR excess in this way is about 10 times greater than that obtained from the dust model. Thus, the IR data suggest that for most Cepheids (particularly the shorter period variables), $\dot{M}_{tot} \leq 10^{-8} M_\odot \mathrm{yr}^{-1}$, but that a fraction of the longer period Cepheids may lose mass at somewhat greater rates.

The prototype of the R CrB class has long been known to have a considerable IR excess (cf., Gehrz and Woolf 1971). Schaeffer (1986) has examined the IRAS database of R CrB observations and found that such excesses are a common property of the class. He derived $\dot{M}_d = 10^{-8.3} M_\odot \mathrm{yr}^{-1}$ for R CrB itself. The outer layers of these stars are hydrogen-deficient and carbon-rich, so that it is difficult to estimate f_d. If we guess $f_d \sim 30$, then $\dot{M}_{tot} \sim 10^{-7} M_\odot \mathrm{yr}^{-1}$. There is also evidence that at least some R CrB stars have had enhanced mass loss at some prior epoch: Schaeffer (1986) has pointed out that 2 of the 3 R CrB variables in his sample that have IR spectra rising between 25 and 60μm are inside planetary nebulae. Also, Gillett *et al.* (1986) have used IRAS data to discover that R CrB has a large, (18 arcminutes in diameter, corresponding to 8 parsecs at the distance of R CrB) extended 60 and 100 μm emission region which they tentatively identify as the fossil remnant of this star's hydrogen-rich envelope. This previous shell ejection phase lasted 1.5×10^5

years, ejected $\sim 1 M_\odot$, and stopped $\sim 3 \times 10^4$ years ago. Thus, the present mass loss rate of R CrB is $\sim 1\%$ its mass loss rate during this earlier epoch.

RV Tauri variables have large IR excesses (e.g., Gehrz and Woolf 1970; Gehrz 1972). Jura (1986) has studied 17 RV Tau stars detected by IRAS at 60μm: he derives $\dot{M}_{tot} \sim 10^{-5} M_\odot \mathrm{yr}^{-1}$ for the dust which is emitting at 60μm. This dust is now $\sim 10^3$ A.u. from the star, and was emitted ~ 500 years ago. The IR spectrum implies a density dependence of r^{-1}, which Jura interprets as being due to a present mass loss rate 100 times smaller than that 500 years ago.

Thus, IR observations can yield information on the mass loss history of a star because of the characteristic large spatial scale of such emission. The most likely progenitors of RV Tau (and possibly R CrB) stars are cool, luminous stars on the Asymptotic Giant Branch, that stage in a star's life in which, it has long been suspected from theoretical and empirical grounds (e.g., Renzini 1981), a sizable fraction, if not the bulk, of the total time-integrated mass ejected by the star is lost (the so-called 'superwind' phase). In fact, mass loss rates of $10^{-5} - 10^{-4} M_\odot \mathrm{yr}^{-1}$ have been derived for the very cool Carbon star IRC +10216 (Kwan and Linke 1982; Knapp *et al.* 1982) suggesting that this star may be presently in precisely this evolutionary phase.

What other evidence is there that mass loss is occurring in these pulsating stars? In what state is the wind material between the stellar photosphere and the dust emission region, i.e., between $1 - 500 R_*$? It has long been known (Kraft 1957) that Cepheids exhibit Ca II H and K emission during part of their pulsation cycle, ususally around maximum light. Schmidt and Parsons (1982,1984a,b) have used IUE spectra of Cepheids to study their chromospheric and 'transition-region' lines in the ultraviolet and confirmed that this same behaviour is also present in other chromospheric lines such as the Mg II h and k lines. They also noted that this emission is stronger and detectable over a larger part of the cycle in the longer period Cepheids ($P \geq 10$ days). A similar IUE study of δ Scuti stars (Fracassini and Pasinetti 1982) found that weak Mg II emission is also present in at least the cooler δ Scuti stars. Little is known about the prevalence of higher temperature plasma: Schmidt and Parsons (1984b) detected C IV emission (formed at $T_e \sim 10^5$ K) in only 1 Cepheid (the longest period one in their sample). Bohm-Vitense and Parsons (1983) failed to detect any Cepheids as X-ray sources (with 1 possible, low-significance exception), but because of their relatively large distances, the X-ray upper limits are quite high (log $L_x < 29.0 - 30.3$). X-ray emission has been detected from at least two δ Scuti stars (Schmitt *et al.* 1985; Zarro and Zirin 1986), β Cas and ξ Ser at levels of 28.4 and 29.4 in log L_x, respectively, but because both are binaries, the X-ray emission can not be unambiguously identified with the δ Scuti variables.

Little quantitative modelling has been attempted on the inner wind regions of Cepheids. High-resolution studies of the Mg II lines (Schmidt and Parsons 1984a; Deasy and Wayman 1986) have discovered that the line profiles are complex and variable with both blue-shifted and red-shifted absorption components with velocities relative to the stars as high as 200 km/sec. Deasy and Wayman (1986) calculate $\dot{M}_{tot} \sim 10^{-10.4} - 10^{-9}$ for the 10 day Cepheid ζ Gem, from an analysis of its Mg II line profile during the phase interval of about half a cycle when an absorption at -140 km/sec is present. Presumably, this mass loss rate is not too unrepresentative of the cycle-averaged mass loss rate from this star.

Finally, no Cepheid has been detected as a radio continuum source, implying upper limits to ionized mass loss as low as $10^{-7.5} M_\odot \mathrm{yr}^{-1}$ in the case of δ Cep (which has a 3σ upper limit of 0.5 mJy at 6 cm in a VLA observation that I made in 1985). Thus, the UV and radio continuum studies of Cepheids are consistent with the IR observations in ruling out substantial ($>\sim 10^{-7} M_\odot \mathrm{yr}^{-1}$) in the majority of this class of stars, and are consistent with a mass loss of $\leq 10^{-9} - 10^{-8} M_\odot \mathrm{yr}^{-1}$, where the lower bound applies to the shorter period stars, and the upper bound to the longer period stars.

4. MASS LOSS FROM F TO M GIANT STARS

As a low-mass star exhausts its central hydrogen content it evolves towards the cooler, more luminous regions of the H-R Diagram. What happens to its wind during this evolution? This to some extent is a function of its initial mass, since this determines the precise trajectory in the H-R Diagram. For example, a 1.5 to 2.0 $M_{\odot}$ star, which will be an A star on the main sequence, about whose wind properties we know almost nothing, will evolve as shown in Fig. 1: notice that dwarf and giant A and early F stars are often pulsationally unstable, and are called δ Scuti variables if Population I objects.(See §3). Whatever the type of wind that they possess in the Instability Strip, it is known that around the time that such a star crosses the red edge of the δ Scuti region and develops a convective envelope, it also develops an active chromosphere and transition region, and an X-ray emitting corona. There is no such complication for stars of mass $M_{*} < 1.5 M_{\odot}$: such stars are of F or later spectral type on the main sequence, and hence already have chromospheres and coronae: as they evolve into the sub-giant and giant regions of the H-R Diagram, how do their winds evolve? The answer is that there is surprisingly little change in the gross structure of their winds for the period of time when they are evolving horizontally in the H-R diagram, but that, at or shortly after they start ascending the Red Giant Branch, their winds undergo a major transformation.

The X-ray luminosities of single F, G, and early K giants as observed by Einstein lie in the range of $27.5 < \log L_{x} < 30.5$, quite comparable to those found for the cool dwarfs, and thus, because of their greater radii compared to main sequence stars, the X-ray surface fluxes of giants tend to be lower than those of the dwarfs. Using the same technique to derive coronal mass loss rates as before, applied to the inactive K0 III star β Gem ($\log L_x = 27.8$) yields an inferred $\dot{M}_{cor} \sim 10^{-11.3} M_{\odot} \mathrm{yr}^{-1}$; the radio data (Drake and Linsky 1986) yield an upper limit to the total ionized mass loss for β Gem of $\dot{M}_{ion} < 10^{-9.7} M_{\odot} \mathrm{yr}^{-1}$. Given that this star has $R_{*} = 10 R_{\odot}$, the coronal mass flux ($\dot{M}_{cor}/R_{*}^{2}$) is $10^{-13.3} M_{\odot} \mathrm{yr}^{-1} \mathrm{R}_{\odot}^{-2}$, compared to $10^{-12.7} M_{\odot} \mathrm{yr}^{-1} \mathrm{R}_{\odot}^{-2}$ for a coronal-hole covered G dwarf. Thus, despite the intuitive idea that the combination of larger surface area and lower surface gravity might be expected to produce an enhanced coronal mass flux in coronal giants compared to dwarf stars, this is apparently not the case.

For cooler, mid-K and M giants (corresponding to the stars both ascending the Red Giant Branch and also post-Helium flash giants making a 'blue loop' as far as $\sim$ G5) which are not in close or interacting binary systems, the Einstein IPC made no detections, with upper limits as low as $\log L_x < 26.4$ in the case of α Boo. Single giants of this type also have been extensively observed by IUE and do not show evidence for any plasma with temperature $> 2 \times 10^{4}$ K: this dichotomy in the properties of the outer atmospheres of evolved stars, which for MK Class III stars occurs at a spectral type of K1.5, was first pointed out by Linky and Haisch (1979) for the transition-region emission and by Ayres *et al.* (1981) for coronal emission, and the locus in the H-R Diagram separating the two classes (the LH Dividing Line) is indicated in Fig. 1. [See also Simon *et al.* 1982]. The implication that there is a sharp division in the H-R Diagram (corresponding to a fast temporal evolution) has been criticized (Dupree 1986) and, in fact, there is now one counter-example of a late K, apparently single giant (α TrA; K4 IIIa) with both C IV emission detected by IUE (Hartmann, Dupree, and Raymond 1981) and X-ray emission detected by Exosat (Brown and Drake 1987) that lies on the 'non-coronal' side of the LH Dividing Line. Finally, Stencel and Mullan (1980a,b) have pointed out that the morphology of the Mg II λ2800Å resonance lines in cool giant spectra is different for late K and M giants compared to earlier giants: the former have typically a blue-shifted absorption feature of 10 to 50 km/sec which is most easily interpreted as being formed in an expanding region of $T_e \sim 10^{4}$ K, while the latter have typically a near central 'reversal' similar to that seen in the solar spectrum. The placement of this 'wind dividing line' in the HR Diagram is very similar to that of the LH Dividing Line.

As one moves towards the cooler (and usually also more luminous) giants the indications of mass loss start to become evident in the visible region of the spectrum, with the appearance of blue-shifted circumstellar components (at about the same radial velocity as those seen in the Mg II line profiles; e.g., Drake 1986b) in lines of neutral metals with formation temperatures $T_e <\sim 5 \times 10^3$ K occurring at about M0. At about M5, the additional detection of infrared excesses due to dust and of molecular lines in the infrared and millimeter region indicate the presence of winds that have substantial components that are even cooler ($T_e <\sim 2 \times 10^3$ K).

(i) Winds in K2 to K5 giants

There are two main observational indicators of mass loss in such stars:

(a) The previously mentioned blue-shifted absorption components in the Mg II emission lines: the inferred wind velocities are typically $\sim 10 - 70$ km/sec blue-shifted relative to the stellar photosphere, although this is probably due in part to a selection effect (discussed below), related to the intrinsic width of the emission lines (FW0M $\sim 200 - 250$ km/sec for K giants). Notice that the inferred wind velocities are less than the surface escape velocities v_{esc} of $\sim 100 - 200$ km/sec for these stars: This is the typical situation for red giant-type winds, so that additional data on the radial extension of the winds is needed before it can be strictly proven that the observed outflows are true winds. In order to get mass loss rates from such features, some fairly complex line profile modelling is necessary, since the observed line is in a sense a convolution of a self-reversed chromospheric emission line with a P Cygni profile; also, being a resonance line, partial redistribution (PRD) effects may be important in the radiative transfer. Drake (1985) derived a mass loss rate of $2 \times 10^{-10} M\odot \mathrm{yr}^{-1}$ for the K2 III star α Boo from fitting its Mg II k line, using a spherically symmetric, co-moving frame solution of the radiative transfer equation that included PRD. Because of uniqueness problems, and a crude treatment of the ionization balance, this value is probably only accurate to a factor of 3, at best. Chiu *et al.* (1977) modelled the Ca II K and Mg II k lines of the same star using a plane-parallel, observer's frame solution of the radiative transfer assuming complete redistribution in the lines, and obtained a rather larger mass loss rate of $\sim 1 - 8 \times 10^{-9} M_{\odot} \mathrm{yr}^{-1}$;

(b) The detection of radio continuum emission, interpreted as free-free emission from the ionized fraction of the stellar wind. For K2 to K5 giants, Drake and Linsky (1986) infer *ionized* mass loss rates of $\sim 10^{-10} M_{\odot} \mathrm{yr}^{-1}$ from the observed radio fluxes and using the Mg II derived wind velocities. The inferred angular diameters at 6 cm are $\sim 2 \times \phi_*$, where ϕ_* is the photospheric angular diameter, confirming the extended size of the radio emission region. Also, the implied ionization fraction of the α Boo wind is $\sim 1 - 30\%$, depending on the adopted total mass loss rate.

How reliable are the wind velocities derived from the Mg II lines?

There are two problems which reduce the level of reliability: the first complication is that of interstellar Mg II absorption, which can be significant even in very nearby stars. The bulk of the Local Interstellar Medium has a fairly well-defined velocity vector v_I relative to the Sun of $\sim 20 - 25$ km/sec towards $\alpha \sim 7^h, \delta \sim 15^o$. (cf., Crutcher 1982). Thus, for a star with a heliocentric radial velocity of v_{rad} and a direction in the sky differing by θ from this direction, the LISM absorption relative to the stellar rest frame will be $v_I cos\theta - v_{rad}$. Thus, for $\sim 50\%$ of the stars in the solar neighbourhood, a blue-shifted LISM absorption component is expected. Due to the relatively low spectral resolution of IUE (~ 25 km/sec), this feature is often blended and/or confused with the self-reversal or low-velocity circumstellar absorption in the Mg II lines of cool stars.

The second problem is the selection effect against detecting high-velocity components mentioned previously: Any absorption that is blueshifted by ≥ 100 km/sec will lie in the faint wings of the chromospheric emission, or in the very dark photospheric absorption wings, and will be only detected in very long high-dispersion exposures. As an example of the surprises that such deep spectra can produce, Fig. 2a shows the Mg II k line profile obtained in a 4 hour LWP-HI exposure of δ And (K3III; $V = 3.27$) by Drake *et al.* (1987): There appears to be a high-velocity absorption present, extending out to ~ -250 km/sec, which is a much higher velocity wind than ever seen previously in any cool giant, and is even in excess of the surface escape velocity of ~ 200 km/sec. Fig. 2b shows the SWP-LO spectrum of this star (9.5 hour exposure): C IV emission and (probably) Si IV emission are present, in violation of the LH Dividing Line. The presence of both high-velocity absorption in Mg II and of C IV emission indicates that δ And is a 'hybrid-atmosphere' star, as originally defined by Hartmann, Dupree, and Raymond (1980, 1981) to apply to a small number of G and K supergiants and bright giants which also exhibit such spectra. Since few of the many hundreds of IUE spectra of cool giants have been obtained with similarly deep exposures, it is difficult to estimate how 'abnormal' δ And really is; given the sensitivity limitations of IUE, this question will probably need the Space Telescope HRS capabilities in order to be properly answered.

(ii) Winds in M0-M5 Giants

A large amount of work has been done in the last 50 years on the cool winds of red giants, and it is impossible to mention all of it herein. Good reviews of the 'classical' studies of M giant winds have been given by Deutsch (1960), Reimers (1975, 1977), and Goldberg (1979). The primary indication of mass loss used is the presence of the low-velocity (10 to 30 km/sec), blue-shifted 'circumstellar' ('CS') absorption features seen in lines of neutral metals (and often in the Ca II H and K emission lines) in all M giants. From a variety of arguments, the region where the neutral CS features are formed must be located in a shell with inner radius at some distance r_s from the star. To derive an accurate mass loss rate from the CS features, one uses the equation of continuity, viz:

$\dot{M}_{tot} \propto N_c^s f_n v_w r_s,$

where the column density N_c^s of species s is obtained from the strength of the absorption, and the fudge factor f_n is the ratio N_c^{tot}/N_c^s that contains excitation, ionization and abundance ratios, and is usually obtained semi-empirically. r_s is the big difficulty: Differing assumptions about its size were the principal reason for the wide range of 2 to 3 orders of magnitude in estimates for the mass loss rates in M giants. For example, Sanner (1976) used $r_s \sim 3r_*$, Bernat (1977) used $r_s \sim 7-300r_*$, and Hagen (1978) used $r_s \sim 1-2r_*$. My best estimates for the mass loss rates of the M0 to M5 giants (MK Class III) (those that do not have significant IR excesses) are $\sim 10^{-9} - 10^{-8} M_\odot \mathrm{yr}^{-1}$, with the later giants having the larger mass loss rates.

What lies in the 'cavity' between the photosphere and the neutral wind? IUE observations of early and mid-M giants (e.g., Stickland and Sanner 1981; Carpenter 1986) revealed a rich chromospheric emission-line spectrum with strong lines of Mg II, Fe II, C II, and O I, and the large emission measures and also some density-sensitive line ratios suggested that the answer to this question is an 'extended chromosphere'. with a characteristic temperature of $\sim 8 \times 10^3$ K. As mentioned above, the observed blue-shifted absorption components in Mg II typically have radial velocities that are the same as those seen in the optical CS features which suggests that the wind acceleration region is quite close to the photosphere. Such a geometrically extended, partially ionized region should be a significant source of free-free emission, and, indeed, Drake and Linsky (1986) detected 1 M III star and 2 M II stars as 6 cm sources, with inferred $\dot{M}_{ion} \sim 10^{-10} - 10^{-9} M_\odot \mathrm{yr}^{-1}$.

(iii) Winds in M5 and Later Giants

The coolest M giants are those which have the greatest mass fluxes of stellar winds of all of the cool giants. They are also almost invariably pulsationally variable, being either Mira, Semi-Regular, or Irregular variables. It seems likely that these two properties of this class of evolved star are related. In addition to the CS features in the optical, these cool giants have other obvious indications of considerable ongoing mass loss. Essentially all stars of this type show infrared excesses over the anticipated photospheric radiation, e.g., Gehrz and Woolf (1971), Rowan-Robinson and Harris (1983a). Gehrz and Woolf (1971) model the observed infrared excesses to derive mass loss rates of $\sim 10^{-7} - 10^{-5.3} M_{\odot}\mathrm{yr}^{-1}$ for such stars, with an average value of $10^{-5.7} M_{\odot}\mathrm{yr}^{-1}$, assuming a standard gas-to-dust ratio of 250 and outflow velocity of 10 km/sec. More recent IR studies use the IRAS 60 and 100 μm fluxes determined for cool giants to infer dust mass loss rates, e.g., Herman *et al.* (1986).

It might be expected that, in a circumstellar region cool enough for substantial dust formation, the gas would largely or completely be in molecular form, and, in fact, molecular thermal emission is observed to be present in late M giants (and the C giants of similar effective temperature). The most widely observed such lines are due to the abundant molecules CO and SiO. The observed line profiles of the $J = 2-1$ and $J = 1-0$ transitions of CO at 1.3 and 2.6 mm have been used by Knapp and collaborators (Knapp *et al.* 1982; Knapp and Morris 1985; Knapp 1985b) and other groups (e.g., Wannier and Sahai 1986) to derive quantitative information on the cool stellar winds of a large number of such stars using an analysis based on theory developed by Morris (1975, 1980). The centroid of the CO line observed in a given star gives its radial velocity, while its FW0M corresponds to twice the wind terminal velocity. The shape of the line is a function of its optical depth: for unresolved sources, the line will be parabolic in shape if optically thick, or be flat-topped if optically thin. Making the standard simplifying assumptions (spherical symmetry, the outflow is constant with time, the chemical composition and outflow velocity are constant (i.e., independent of radius) in the molecular envelope), the observed CO emission can then be modelled to yield the mass flux of CO molecules; finally, adopting a characteristic value for the ratio of CO to H_2, the total mass loss rate can be derived. The papers by Knapp yield values of $\dot{M}_{tot}$ of the same order as those obtained by Gehrz and Woolf (1971): for objects visible optically the values range from $\sim 10^{-8} - 10^{-5} M_{\odot}\mathrm{yr}^{-1}$, while for objects that are so heavily enshrouded by dust as to be visible only in the infrared, the typical $\dot{M}_{tot}$ is $\sim 10^{-5} M_{\odot}\mathrm{yr}^{-1}$, with some of the more luminous supergiants such as VY CMa (M5 Ia) and NML Cyg (M6 Ia) having mass loss rates in excess of $\sim 10^{-4} M_{\odot}\mathrm{yr}^{-1}$. Knapp (1985b) also uses the detailed Rowan-Robinson and Harris (1982, 1983a,b) models of the infared excesses to derive dust mass loss rates $\dot{M}_{dust}$, and hence to independently calculate f_{dust}. She finds that the dust-to-gas ratio for oxygen-rich and carbon-rich giants is independent of mass loss rate over an observed range of more than 4 decades, being ~ 160 for the former, and ~ 400 for the latter. Because these empirically determined values are close to the value of 250 assumed by Gehrz and Woolf (1971), it is not surprising that the total mass loss rates inferred by the latter are reasonable.

5. WINDS IN G AND K BRIGHT GIANTS: THE HYBRID PHENOMENON

As mentioned in the last section, a third type of outer atmosphere has been identified in a small number (~ 12) of evolved stars that shares characteristics of both coronal stars (in the presence of lines like C IV λ1550Å that are formed at transition-region-like temperatures of $T_e \sim 10^5$K) and of cool wind stars (in the presence of blue-shifted absorption components in the resonance lines of Mg II and Ca II). These 'hybrid-chromosphere' stars are mostly K II (bright giant) stars, but also include 2 G supergiants, 1 G II star, and 2 K II-III stars, as well as the K III star δ And discussed in §4. The radial velocities of the centroids of the Mg II absorption components in these stars are typically about 70 - 150 km/sec blue-shifted relative to the stellar radial velocity, with measurable absorption extending out as far as ~ 200 km/sec in at least one case (α TrA; Hartmann *et al.* 1985). The locations in the HR Diagram of most of the hybrid stars correspond to the expected positions of evolved 4 to $7M_\odot$ stars (so that these stars are the descendants of B main-sequence stars), and thus the surface escape velocities would be $\sim 150 - 200$ km/sec, i.e., of the same order as the observed maximum outflow velocities.

The Mg II absorption features are very noticeable for their considerable strength compared to those seen in normal K giants, implying that there is a high column density of outflowing material at 10^4 K. The lines formed at higher temperature, however, such as Si III] $\lambda\,1893$Å and C IV, have no net blue-shift or P Cygni profile (cf. Hartmann *et al.* 1985), although the fact that even optically thin lines like Si III] have FWHM's $\sim 80 - 100$ km/sec, indicate that they are formed in a region undergoing considerable turbulence. Hartmann *et al.* 1985 have estimated the thickness of the region with $T_e \sim 1.6 \times 10^5$ K (which they refer to as a 'warm corona') to be $\sim 1R*$, and argue, in the context of the detailed Alfven wave-driven models of hybrid stars of Hartmann *et al.* (1981), that the 10^4 K wind region lies above the warm corona. Linsky (1985), on the other hand, has argued that, instead of a radial separation, there are azimuthal inhomogeneities similar to those in the Sun where the hybrids' surfaces are covered with a mixture of open magnetic field regions akin to coronal holes (where the Mg II wind originates) and closed magnetic field regions (where the C IV emitting material lies).

The detection of α TrA as an X-ray source of log $L_x = 30.5$ by Exosat (Brown and Drake 1987) suggests that there is also a 'hot corona' in at least this hybrid (since no others are known to be X-ray sources with relatively high upper limits in log $L_x < 29.0 - 31.0$), with a temperature $T_e \geq 10^6$ K. Despite the evidence for a strong, (partially?) ionized wind deduced from the Mg II lines, 6 cm observations of several hybrids by Drake and Linsky (1986) failed to detect any as radio continuum sources, with upper limits to the ionized mass loss as low as $10^{-8.7} M_\odot \mathrm{yr}^{-1}$ in three cases. Thus, it seems that the most fruitful way in which the mass fluxes of hybrid winds will be pinned down will be to model the Mg II line profiles using a Sobolev or Co-Moving Frame Radiative Transfer technique. These stars may be of great importance because they could hold the key to a better understanding of the evolution of a star's atmosphere from being of a solar-type to being of a red giant-type, so it is clearly necessary that more work be done on determining the morphology of their outer atmospheres and obtaining more quantitative data on their mass loss.

Finally, it should be pointed out that not all G and K bright giants are hybrid stars: Brown (1986) has noted that a significant fraction of them have C IV emission lines present in their UV spectra but show *no* evidence for wind absorption in their Mg II lines. Brown speculates that such stars are just a coolward extension in the HR Diagram of the coronal-type luminous stars. Thus, in at least this part of the HR Diagram, stars with two apparently very different types of outer atmospheric structures can co-exist, suggesting that there are factors additional to L_{bol} and T_{eff} that determine their atmospheres.

6. MASS LOSS FROM G TO M SUPERGIANTS

All stars in this region of the HR Diagram later than about G0 appear to have stellar winds with typical temperatures $T_e \leq 10^4$ K. (One hybrid star α Aqr (G2 Ib) also has been discovered among this group). There is a general trend for *decreasing* wind velocity and *increasing* mass loss rate as one progresses from earlier to later spectral types. I again segregate this general group into those of G and K spectral types on the one hand and of M spectral type on the other.

(i) G and K Supergiants

The most definite indicators of mass loss in these stars are the presence of blue-shifted absorption components in the Ca II and Mg II resonance lines (e.g., Reimers 1973; Stencel *et al.* 1980).

Other lines in which circumstellar features have been seen include the Ca II IR triplet (Linsky *et al.* 1979), Hα (Mallik 1982, 1986), and He I $\lambda\,10830$Å (O'Brien and Lambert 1986). The outflow velocities range from as low as 10 km/sec (e.g., ϵ Gem; G8Ib) to $\geq$ 100 km/sec (e.g., α Aqr with $v_w \sim 125$ km/sec; 22 Vul (G2 Ib + B9V) with $v_w \sim 170$ km/sec). These values can be compared to the surface escape velocities of ~ 150 km/sec for these evolved massive stars. There are few reliable estimates of mass fluxes for *single* G and K supergiants. Reimer's (1975) tabulation quotes values of $\dot{M} \sim 10^{-7.4} - 10^{-6.7} M_\odot \mathrm{yr}^{-1}$ for several G and K Ib stars, whereas Mallik (1982, 1986) finds $\dot{M} \sim 10^{-6} - 10^{-5} M_\odot \mathrm{yr}^{-1}$ in a sample of ~ 20 such stars. The latter values are based on an analysis of the Hα lines and are unexpectedly large: one would expect to see far greater manifestations of mass loss than are observed, if they were correct. Finally, Drake and Linsky (1986) obtain upper limits to the *ionized* mass loss rates of several G and K Ib stars observed at 6 cm of $10^{-8.7} M_\odot \mathrm{yr}^{-1}$.

The best quantitative information on stars in this region of the HR Diagram comes from the studies of Reimers and collaborators on the stellar winds of G and K supergiants in eclipsing binary systems with B or A dwarf secondary stars, the so-called ζ Aurigae-type binaries. (e.g., Che, Hempe, and Reimers 1983; Reimers and Che-Bohnenstengel 1986). These binaries have orbital periods in the range of 1 to 10 years, and the inferred separations are so small ($\sim$ 3 to 10 A.u.) that the hot star actually lies within the expanding wind region of the cool supergiant. This is clear from high-dispersion *IUE* spectra of such systems which show phase-dependent P Cygni profiles and blue-shifted absorption features in resonance lines of Fe II, Si II, and S II in the composite spectra: such low-excitation features are not seen in single dwarf A or B stars. Thus, the hot secondary acts as a probe of the supergiant's wind region and, using the known orbital properties such as the physical separation and relative velocity of the two stars, accurate mass loss rates and wind velocities can be calculated. The largest remaining cause of uncertainty in the calculation is probably in the estimation of the ionization equilibrium of the wind, but, even so, the mass loss rates calculated by this method should probably be good to within a factor of 3 or so. The values of $\dot{M}_{tot}$ thus obtained for 4 such systems lie in a fairly narrow range from $10^{-8.2} - 10^{-7.6} M_\odot \mathrm{yr}^{-1}$, slightly lower than Reimers' (1975) less accurate estimates for single G and K supergiants. Ionized mass loss rates have also been determined for 2 or 3 of these binary systems with the hottest secondaries (earlier than B4) from radio continuum detections (Drake, Brown, and Reimers 1987) and they are of the same order as the *total* mass loss rates derived by Reimers' group, implying that the winds are substantially ionized. This is in contrast to single G and K supergiants where $f_{ion} < 10\%$ and suggests that the B secondaries are responsible for the anomalously high ionization. This fact, together with the unusually high wind velocities found for G and K supergiants in ζ Aur systems compared to single ones, suggests that the binary environment is influencing the properties of the supergiant's wind, and that caution should be used in extrapolating the inferred properties to single supergiants.

(ii) M Supergiants

These stars show strong unmistakeable evidence for substantial mass loss and, because of this, there have been an enormous number of studies of the low-velocity (10 to 20 km/sec) stellar winds from these stars. [A much more complete review of this subject can be found in Goldberg (1987).] For example, the nearby M2 Iab star α Orionis has had its mass loss measured in more than a score of papers using at least half a dozen independent methods ranging from fitting the surface brightness of the extended shell of K I emission visible around the supergiant (Bernat *et al.* 1978; Jura and Morris 1981; Mauron *et al.* 1984) to modelling the observed CO emission features at mm wavelengths (Knapp *et al.* 1980, 1982; Huggins 1985). Unfortunately, this extensive coverage has not yielded as high a degree of consensus on $\dot{M}$ as one might have hoped for: even if one excludes the older and possibly more inaccurate studies, the estimates range from as low as $\sim 10^{-7} M_\odot \mathrm{yr}^{-1}$

(Hagen 1978; Knapp 1985b) to as high as $\geq 10^{-5} M_{\odot}\mathrm{yr}^{-1}$ (Bernat 1977; Jura and Morris 1981).

There are several M supergiants that are known to lie in visual binary systems, including α Scorpii (M1.5Iab + B4Ve; angular separation Δs = 2.9 arcsec), and α Herculis (M5Ib-II + (G5III + F2V); Δs = 4.9 arcsec), and others that are found in spectroscopic binaries (e.g., δ Sagittae, M2II + B9V), where the secondaries are immersed in the cool supergiant's wind. Thus, similar techniques to those used for the ζ Aur systems can be applied to derive mass loss rates. Values so derived still disagree by as much as an order of magnitude (e.g., for α Sco, $\dot{M} \sim 10^{-6.2} M_{\odot}\mathrm{yr}^{-1}$ (Kudritzki and Reimers 1978), compared to $\sim 10^{-5.2} M_{\odot}\mathrm{yr}^{-1}$ (Bernat 1982)). Just discernible in the noise of the various $\dot{M}$ measurements for these luminous M stars, is a trend of increasing mass loss with increasing luminosity: Bright giants have $\dot{M} \sim 10^{-7.5} - 10^{-7.0} M_{\odot}\mathrm{yr}^{-1}$, Ib and Iab supergiants have $\dot{M} \sim 10^{-7.0} - 10^{-5.5} M_{\odot}\mathrm{yr}^{-1}$, and Ia supergiants have $\dot{M} \geq 10^{-5.5} M_{\odot}\mathrm{yr}^{-1}$.

7. CONCLUSION

The obvious conclusion that can be drawn from the data presented in this review is that basic quantitative information on the winds of cool stars, such as mass loss rates, temperatures, terminal velocities, and radial structures, is still, for the most part, either unreliable or unavailable. Until more data are obtained, it is difficult to meaningfully constrain the variously proposed theoretical mechanisms for generating mass loss in cool stars. For example, the properties of the winds from main-sequence stars are (with one honourable exception) completely unknown, except that their total mass loss per unit area cannot be significantly greater than the solar mass flux.

One weak conclusion that can be inferred from the data presented in sections 3 and 4 of this paper is that, to order of magnitude, there appears to be no discontinuity in the stellar wind properties as one crosses over boundaries in the HR Diagram separating pulsating from non-pulsating stars: It is not clear to me what the implications of this result, if confirmed, would be for the theoretical models for the winds of these two broad classes of cool stars, but it would seem naively to imply the possibility of a common underlying mechanism.

Rather perversely, the parameters of mass loss in the coolest, most luminous stars, such as the M supergiants, are much better determined than those for the common or garden dwarfs and giants that comprise 99% of the cool stellar population of the Galaxy. Thanks to a variety of newly available observing tools, such as *EINSTEIN, IUE,* and the VLA, we have been able in the last decade to at least place some constraints on the bulk properties of the winds of stars throughout the cool star region of the HR Diagram. I hope, as the data-gathering phase is succeeded by the data analysis and modelling phase, that these constraints will be replaced by 'hard' numbers.

Further observational studies on mass loss in cool stars remain to be done before significant advances in theoretical understanding of the underlying physical mechanisms can be made. Basic questions that need to be answered include:

(i) Do all main-sequence stars later than F0 have solar-type winds? How do the terminal velocities and mass loss rates vary (if at all) with spectral type? Are there any observational indicators of mass loss (eg., in the extreme UV) that have been identified (perhaps) in the solar case evident in the spectra of other main-sequence stars?

(ii) Do A dwarfs lose mass at all? If so, what is the physical state of their winds? Do the high rotational velocities of these stars imply that they have no winds (or just no magnetic fields)?

(iii) Do some stars (the hybrids) have both coronal-type winds and red giant-type winds? Why do hybrids appear to have such high-velocity cool winds? What are the mass fluxes of these winds?

(iv) Can the Mg II line profiles in K giants yield reliable mass loss rates? Are there any other spectroscopic indicators of mass loss? Can the Lyman α lines observed by IUE at high dispersion be used?

(v) For evolved stars, does the location in the HR Diagram uniquely determine the parameters of the mass loss? Is there an as yet unsuspected third (or fourth) parameter, such as angular momentum or average magnetic field strength?

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