MASS LOSS IN STARS OF MODERATE MASS BY STELLAR WINDS AND EFFECTS ON THE EVOLUTION

C. de Loore

Astrophysical Institute

Free University of Brussels
Belgium

1. INTRODUCTION

Some 30 years ago it became clear that the solar corona is a plasma with a temperature of the order of 10^6K. As the underlying layers have only temperatures of 5000 K a mechanism had to be discovered, capable to explain this high temperature. A solution to the problem was found when it was realized that mechanical energy losses, by shock dissipation of wave energy can heat up a plasma to such high temperatures. This mechanical energy is formed in the deeper layers of the atmosphere and transported outwards. Dissipation becomes significant in regions where the density is sufficiently low.
Wave propagation in a compressible medium in the presence of gravity and magnetic fields has been treated as a general problem, among others by Ferraro and Plumpton (1958). Three basic parameters are present : compressibility of the medium, gravity and magnetic field.
Here solutions will be discussed for cases where magnetic fields are not included.
Biermann (1946) and Schwarzschild (1948) suggested that gravity modified sound waves are, by shock dissipation responsible for the heating of the outer atmosphere. A few years later Lighthill (1952) and Proudman (1952) derived quantitative expressions for quadrupole sound generation. Starting from these data, de Jager and Kuperus (1961) and Kuperus (1965) were the first to construct models of the corona and the transition region to the chromosphere which at least qualitatively explain the high temperature of the corona and the sudden temperature rise in the transition region; later considerable improvements were made of the physical theory by Ulmschneider (1967, 1971a,b) and Stein (1968), and improved models were calculated by de Loore (1971). The computation of stellar coronae is based on these ideas developed for the calculation of the solar corona

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and transition region.

2. MECHANICAL FLUXES

In convection regions turbulence is caused by large scale convective motions. Starting in these regions waves will penetrate the radiative layers. Generally gravitational waves, or sound waves are considered (see de Jager, 1975). Gravitation waves propagate through changes in the local gas pressure as a consequence of the change of the air mass above a certain horizontal plane in a hydrostatic equilibrium medium. They can propagate only for frequencies below the Brunt-Väisälä frequency

$$\omega_{bv} = (\gamma-1)^{1/2}\, g\, c^{-1}$$

Sound waves (compression waves) propagate as a consequence of increase and decrease of the gas pressure by compression or dilatation of the gas. The phase velocity λ/P depends on the period, so the waves will disperse. Vertical propagation is inhibited for frequencies below the limit frequency

$$\omega_s = \gamma g/(2c)$$

The diagnostic diagram (Figure 1), i.e. the dispersion relation $F(\omega,k)$, shows the possible waves for an isothermal atmosphere. The solutions in the upper left corner represent the gravity modified sound waves; the gravity wave solutions occupy the lower right part.
Whitaker (1963) proposed gravity waves for the coronal heating because sound waves with wavelengths comparable to the dimensions of the granules (Bahng and Schwarzschild, 1961) would not be able to propagate through the region of temperature minimum. However, it was pointed out by Souffrin (1966) that the short radiative relaxation time in the low photosphere (order of 1^s) would rapidly eliminate these oscillations. In the region of the temperature minimum the cut-off frequency for sound waves is 0.0233 s^{-1}, and the most representative frequency of sound waves generated by the Lighthill mechanism is $\omega \sim 0.2\ s^{-1}$. Hence the mechanical flux generated by sound waves can to a large extent penetrate into the chromospheric regions. During the sixties (Osterbrock, 1961; Kopp, 1968) the heating of the chromosphere was almost generally attributed to acoustic waves with typical periods of ~ 5 min (however see Kuperus (1965, 1969)). Now it is known that the 5 minute oscillations (Leighton, 1960; Leighton et al. 1962) are produced by nonradial pulsations. More than five dis-

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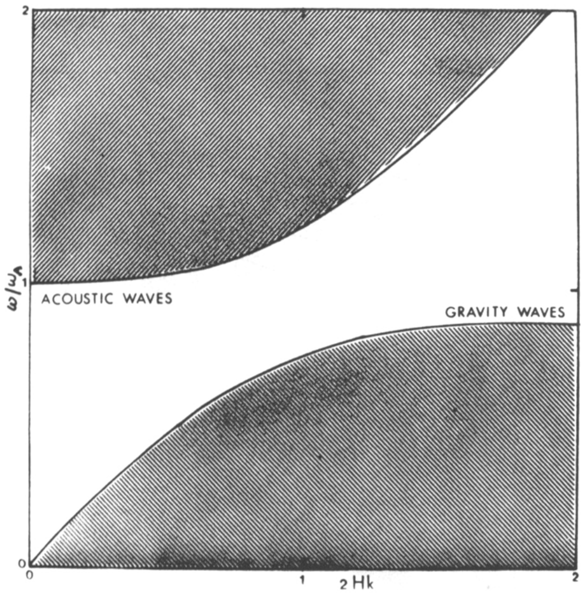

Figure 1. Diagnostic diagram showing the dispersion relation F(ω,k). The coordinates are normalised. The upper left part represents the acoustic wave solutions, the lower right part the gravity wave solutions (after de Jager, 1975).

crete stable modes of the 5 min oscillations could be resolved by Deubner (1976) in the average k,ω diagram. They agree with the predicted modes of trapped acoustic waves in the subphotospheric regions and especially with the solutions of linear nonradial oscillations of the solar envelope, obtained by Ando and Osaki (1975). Ulmschneider (1970,1974) argued in favour of the short-period nature of the waves, by comparing the theoretical dissipation rate of acoustic shock waves for different mechanical fluxes and periods with the computed chromospheric radiation losses. A study of the radiatively damped acoustic waves in the solar atmosphere is being performed by Ulmschneider et al. (1976a), Kalkofen and Ulmschneider (1976) and Ulmschneider and Kalkofen (1976). Theoretical computations of the spectrum of acoustic flux produced in the solar convection zone were performed by Stein (1968). He made computations for mechanical fluxes for several different turbulence spectra and found a flux maximum at periods of ~ 30 s.
Computations of mechanical fluxes for stars of various types were made by : Kuperus (1965), for stars of solar composition, with T_{eff} ranging from 4400 K to 7000 K; de Loore (1967,1970) for stars of solar composition, with T_{eff} ranging

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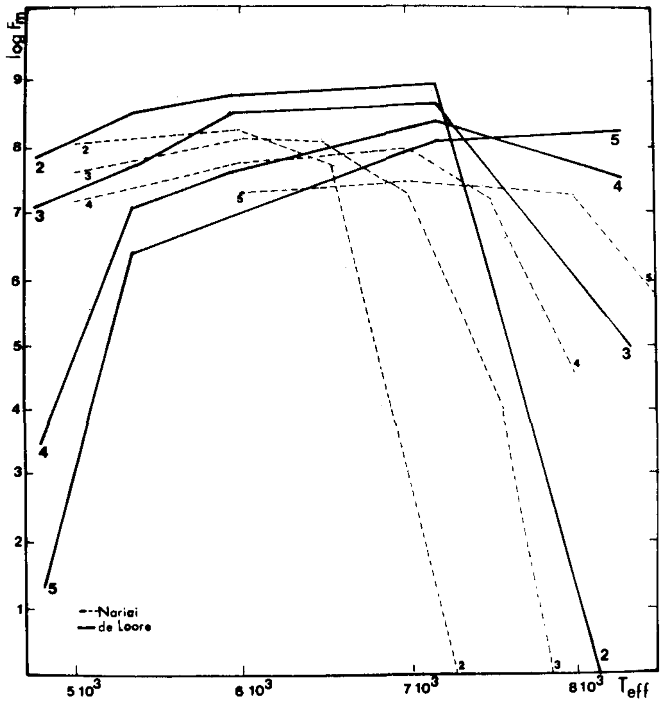

Figure 2. Comparison between the mechanical fluxes computed by de Loore and Nariai.

from 2500 K to 16630 K; Nariai (1969) for helium rich stars; Böhm and Cassinelli (1971) for helium rich stars, with T_{eff} from 5790 K to 30000 K. The results of the computations of de Loore (1970) and Nariai (1969) are shown in figure 2. Curves of constant mechanical fluxes are shown in figure 3. All this is rather uncertain and subject to some criticism. First of all, as was demonstrated by Stein (1968) by computing the mechanical energy for different turbulence spectra, the acoustic power output is highly sensitive to the high frequency tails. His computations yield an uncertainty factor of the order of one magnitude. In the second place the result is highly dependent on the turbulent velocity amplitudes (the acoustic emission is a function of the fifth power of the turbulent Mach number). However, actual refined computations of stellar mechanical fluxes by Ulmschneider et al. (1976b) are in rather good agreement with our previous calculations, with observations and with other refined calculations (Stein 1968).

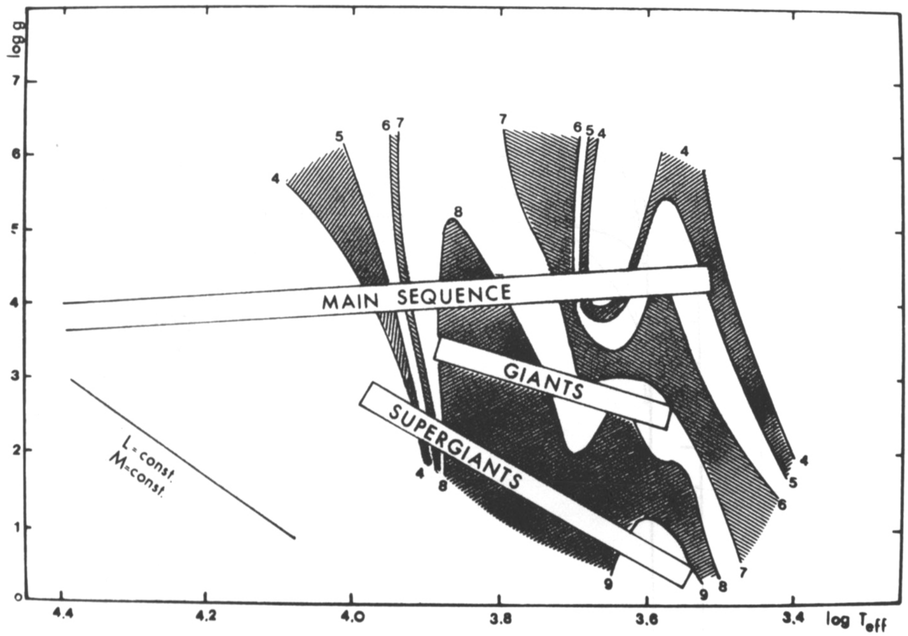

Figure 3. Curves of constant mechanical flux as computed by de Loore (according to Kippenhahn,1972).

3. HEATING OF THE CORONA

It is assumed that the mechanical flux F_m generated in the convection zone is known (e.g. from computed models of this zone). Spatial dissipation of this flux becomes only then important when the shock front is attained; this dissipation can be described by a local absorption coefficient.
The balance between the different energy terms, dissipation, radiative energy losses and stellar wind energy losses is closed by conductive energy losses from corona to chromosphere. The heat conductivity of a fully ionized gas is a function of the temperature; hence the temperature can be calculated. The hydrostatic equilibrium equation furnishes the density. De Jager and Kuperus (1961), and Kuperus (1965) did not include the effects of stellar winds and started the integration at the photosphere. Inclusion of a velocity kinetic energy term complicates the problem extremely. For this reason one assumes the initial value of the flow speed to be a supplementary parameter. Iteration of this value leads to a given outer boundary condition. The behaviour of the various fluxes for the solar transition region is given in figure 4. Results of de Loore (temperature and density) for some stellar coronas are shown in figure 5. This leads

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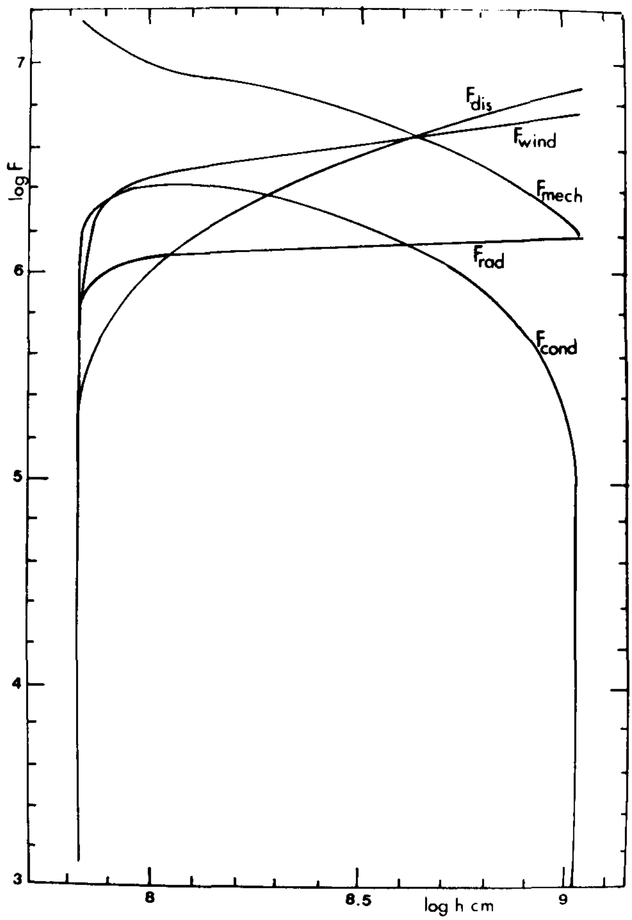

Figure 4. Behaviour of the various fluxes for the solar transition region.

essentially to the conclusion that coronal temperature and density in the range covered by the calculations seem to be monotonic functions of the mechanical energy flux.
A new discussion of the mechanical energy fluxes for main-sequence stars and supergiants was given by Lamers and de Loore (1974,1976). In order to get a better insight in the mechanism that drives microturbulence in supergiants the energy flux associated with the observed microturbulence was calculated for different spectral types. It was assumed that the microturbulent motions are outward propagating sound waves.

$$F = \frac{1}{2} \rho \; a^2 c$$

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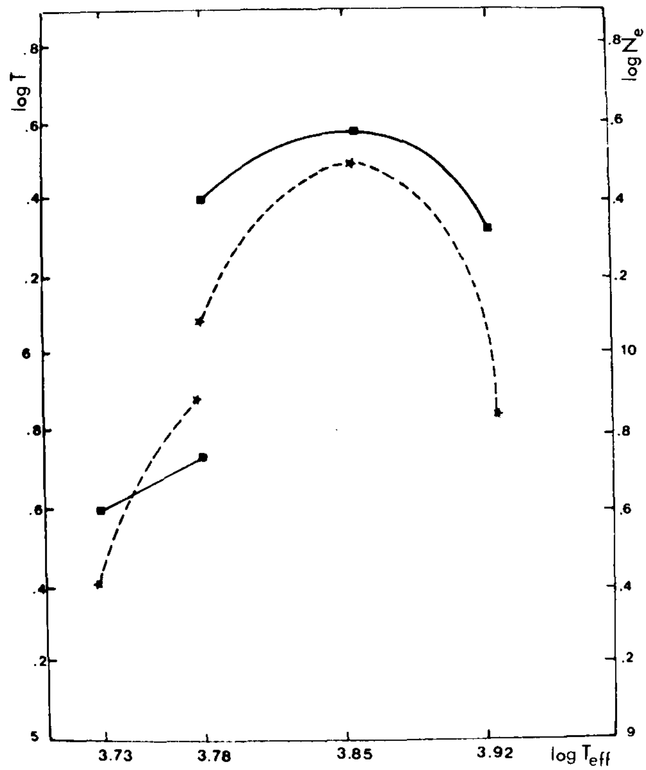

Figure 5. Temperature (full curves) and density (dashed curves) for some stellar coronas as a function of the effective temperature. For the lower curves log g = 5, for the upper curves log g = 4 (after de Loore, 1970).

with ρ density

c the local sound speed

a is assumed equal to the "observed" turbulent velocity, as adopted in the model atmospheres from Kurucz, Peytremann and Avrett (1974) and in those for the F and G supergiants from Parsons (1967). These fluxes can then be compared with computed mechanical fluxes; for stars with convection zones values of de Loore (1970) were used, for hot stars the mechanical fluxes produced by radiation-driven sound waves of Hearn (1973) were used. It turns out that the overall agreement between "observed" and predicted fluxes is reasonable, but should not be exaggerated. In any case, it turns out that the flux associated with microturbulence shows a minimum around type A; this could mean that microturbulence in stars earlier than A is created by another mechanism than

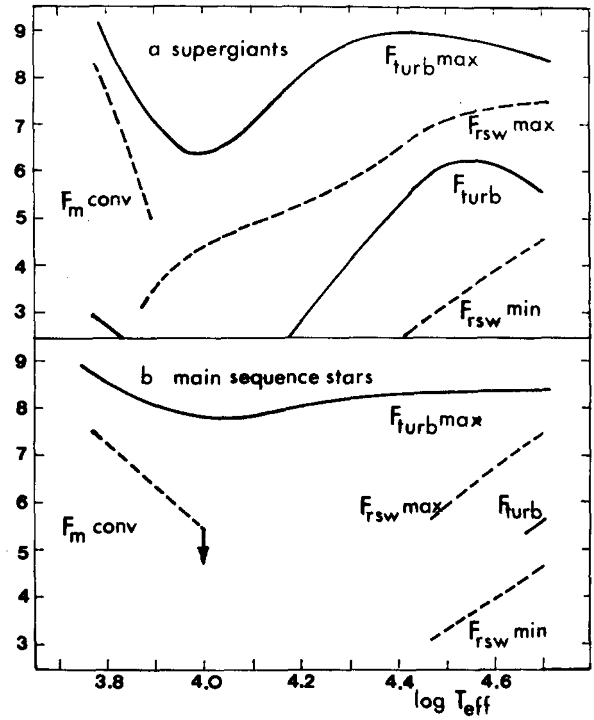

Figure 6. Predicted and observed mechanical fluxes versus T_{eff} for early-type supergiants and main-sequence stars. For cool stars the mechanical fluxes generated by convective turbulence are used (F_m(conv)). For hot stars Hearn's mechanism of radiation driven sound waves is considered (dashed lines). The solid lines are derived from observed values of the microturbulent velocity component, and with the assumption that the turbulence propagates outward with sound speed.

in late types. Figure 6 shows the results of the computations.

4. X-RAY FLUXES EXPECTED FROM STELLAR CORONAS

On the basis of earlier work of de Loore (1970), de Jager and de Loore (1971) derived values for the expected X-ray fluxes of some nearby stars, the dominant emission mechanism being free-free emission by electrons. The ratio between the expected X-ray flux of a star F_{x*} and that of the sun $F_{x\odot}$ is given by

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$$\frac{F_{x*}}{F_{xo}} = \left(\frac{R_*}{R_\odot}\right)^2 \left(\frac{Ne_*}{Ne_\odot}\right)^2 \left(\frac{H_*}{H_\odot}\right)\left(\frac{d_o}{d_*}\right)^2$$

with R and d radius and distance respectively, Ne the electron density at the basis of the corona, and H the coronal scale height.
For the sun the observations of Friedman (1959) were used, i.e. 0.13 erg cm^{-2} s^{-1} at sunspot minimum and 1 erg cm^{-2} s^{-1} at sunspot maximum, corresponding with 0.2 and 1.5 photons cm^{-2} s^{-1} at earth distance.
Some good candidates for X-ray research are given in table 1 (de Jager and de Loore, 1971).

	spectral type	expected photon flux	
Procyon	F5	0.016	0.12
α Cen	G2	0.008	0.06
β Cas	F2	0.0007	0.005

Table 1. The expected minimum and maximum soft X-ray photon fluxes for some F and G stars.

Minimum flux coronae in dwarfs and giants were calculated by Mullan (1976), using a method of Hearn (1975) : it is assumed that the corona has a strictly radial magnetic field and adjusts itself such that the sum of radiative, conductive and stellar wind fluxes, for a given pressure at the base of the corona is minimal. It is assumed that the flux loss is compensated by an input of mechanical energy from the star. By assuming that the fraction of the total stellar luminosity which is used for the coronal heating is the same as for the sun (certainly a very strong assumption!) stellar coronal temperatures and densities can be predicted. Coronal temperatures ranging from 280 000 K (for M6) to 4 980 000 K (for O5) MS stars are found. Red dwarfs turn out to have coronas 3-10 times cooler.

5. OBSERVATIONS OF STELLAR CORONAS

The Astronomical Netherlands Satellite (ANS), in a systematic search for stellar coronas examined some 30 stars, in order to find possible soft X-ray fluxes. Most of these stars showed no detectable flux, and only upper limits could be given. (Mewe et al. 1975,1976). Figure 7 shows these upper limits for main-sequence stars, compared with observations. Two stars showed a detectable soft X-ray flux, α CMa (Sirius), and α Aur (Capella).
Observations made with OAO-3 (Dupree, 1975) also indicate

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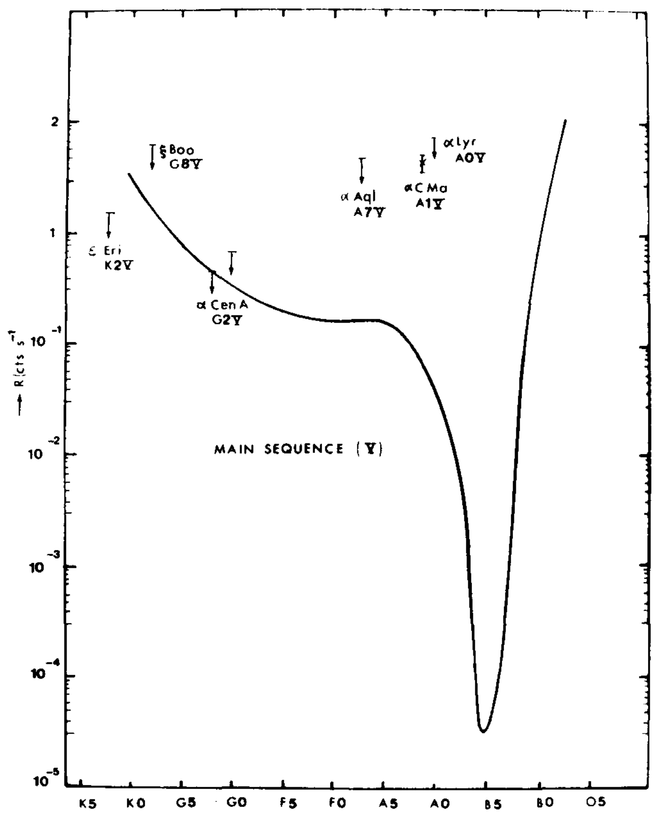

Figure 7. Predicted count rate (full line) for the soft X-ray channel of ANS for main-sequence stars, compared with recent observations (mostly upper limits) after Mewe et al. (1976).

the presence of hot outer layers for α Aur and for α Aqr. The soft X-ray flux from Sirius is probably generated in the white dwarf companion, Sirius B. Indeed Sirius A has spectral type A1, T_{eff} ~ 10.000 K, hence too hot for allowing a convection zone. As pointed out by Böhm (1972) the helium convection zone persists to very high temperatures, and in dense stars, a large part of the energy must be transported by convection. So for Sirius B the conditions dor the production of a large mechanical flux and possibly for a chromosphere and corona are probably present.
ANS observations gave also indications for the presence of a corona in α Pup (Mewe et al., 1975a). Indications for a corona in β Gem (Ko III) were presented by Gerola et al. (1974), with a temperature of 140 000 K - 260 000 K, fairly

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Star	Spectral type	Coronal temperature-indication	Reference
α Aur	G5 III + Go III	600000	ANS - Mewe et al., 1975 OAO-3 Dupree, 1976
α CMa	A1 WD		ANS - Mewe et al., 1975
ζ Pup	O4f	200000	Lamers and Morton, 1976
β Gem	Ko III	140000-260000	Gerola et al., 1974
α CMi	F5 IV V	$3.10^5 - 6.10^6$ $10^5 - 1.3\ 10^6$	Evans et al., 1975
α Cyg	A2 Ia	320000	Hearn, 1975
α Car	Fo Ib	Mg II emission	Evans et al., 1975
α Boo	K1 III	asymmetries $T > 10^6$	Dupree, 1976 Gerola et al., 1974
α Tau	K5 III	Ly α - Mg II	Dupree, 1976
α Aqr	G2 Ib	asymmetries Mg II	Evans et al., 1975
ε Peg	K2 I	asymmetries Mg II	McClintock et al., 1976
τ Sco	Bo V	$1 - 5.10^5$	Rogerson and Lamers,1975

Table 2. Observational evidence on stellar coronas.

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well in agreement with the calculations of de Loore (1970). Furthermore the discovery of O VI and Si III emission lines in the uv spectrum of Procyon (Evans et al.) indicates a transition region to a corona with a temperature between 3.10^5 and 6.10^6 K, confirming a suggestion of de Jager and de Loore (1971) that Procyon may have a corona.

6. MASS LOSS BY STELLAR WINDS

For a wide variety of stars mass loss has been observed, as summarized in table 3.

Type	$\dot{M}$ in $M_{\odot}$ yr^{-1}	Reference
WR	10^{-6} - 10^{-5}	Underhill, 1969
OB SG	10^{-6}	Morton, 1967 Hutchings, 1976
Bo V	10^{-8}	Lamers & Rogerson,1975
B,A SG	10^{-9} - 10^{-8}	Hutchings, 1968
A2Ia	3.10^{-10}	Kondo et al., 1975 Lamers, 1975
P Cyg	10^{-5} - 10^{-4}	Hutchings, 1968 De Groot, 1971
	3.10^{-6}	Kuan & Kuhi, 1975 Wright & Barlow, 1975
F2Ia	10^{-8}	Sargent, 1961
F8 SG	10^{-5}	Sargent, 1961
Sun	2.10^{-14}	Hundhausen, 1972
Mo III	$2.5\ 10^{-9}$	Reimers, 1975
M1 III	4.10^{-9}	Reimers, 1975
M3 III	10^{-8}	Reimers, 1975
M5 III	3.10^{-8}	Reimers, 1975

Table 3. Observed mass loss rates for different types of stars.

An upper limit for the mass loss rate $\dot{M}$ was derived by Thomas (1973) following an approach of Williams (1970). These authors considered that the upper limit is determined by the ratio of the nuclear energy output in the sphere where core burning occurs, to the escape energy for that sphere. The values of Thomas (1973) are shown in table 4.

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Spectrum	WR	Bo	Ao	Fo	Go	Ko	Mo
dwarf		-3.8			-7.5		-8.4
giant					-5.6	-5.0	-4.2
supergiant	-1.5	-2.3	-2.7	-2.9	-2.7	-2.3	-1.5

Table 4. Upper limit for the mass-loss rates $\dot{M}$ for different types of stars according to Thomas (1973) (the table shows log $\dot{M}$).

Mass loss calculations for F and G stars were performed by de Loore (1968). The results are given in table 5. The values in the table were found by reducing the straight-forwardly computed values (obtained from the computed density and flow velocity) by an efficiency factor, determined as the ratio between the observed solar mass loss rate of 2.10^{-14} and the straightforwardly computed values of $1.1\ 10^{-11}\ M_{o}\ yr^{-1}$.

	Te	log g	v	$\dot{M}$ (in $M_o\ yr^{-1}$)
G5	5350	5	19	$4.4\ 10^{-15}$
Go	5940	5	17	$8.4\ 10^{-15}$
G2	5800	4.45	12	$2.2\ 10^{-14}$
Fo	7130	4	9	$4.8\ 10^{-13}$
A5	8320	4	7	$9.6\ 10^{-14}$

Table 5. Calculated mass losses for F and G stars. In the table are given the spectral types, effective temperatures, gravity acceleration, outflow velocity in km s^{-1} at temperature maximum and the mass flow in $M_o\ yr^{-1}$.

7. MASS LOSS IN RED GIANTS AND SUPERGIANTS

A semi-empirical estimate of the mass loss by stellar wind in red giants and supergiants has been made by Fusi-Pecci and Renzini (1975). They computed for stellar envelope models the quantity $\dot{\mu} = R.L_{ac}/(GM)$, with R and M stellar radius and mass respectively and L_{ac} the acoustic energy output in the convection zone. The real mass loss rate $\dot{M}$ is then related to $\dot{\mu}$ as

$$\dot{M} = \eta.\dot{\mu}$$

with η an efficiency factor, in the case of the sun $\eta_o = 8 \times 10^{-4}$.
For red horizontal branch stars and $\eta \sim \eta_o$ the mass loss rate is $\sim 10^{-10}\ M_o\ yr^{-1}$. Red supergiants of intermediate

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mass ($1.4\ M_\odot < M < 8\ M_\odot$) lose a negligible amount of mass during core helium burning and previous evolutionary phase. By estimating the mass of the white dwarf remnant when the outer layers are blown away and by evaluating the time, final mass loss rates of $10^{-5}\ M_\odot$/yr are found, comparable with the value required by Paczynski (1974) for the formation of planetary nebulae.

8. EVOLUTIONARY IMPLICATIONS

As can be seen from figure 8 there are two regions in the Hertzsprung-Russell diagram where mass loss is sufficiently large to be of possible evolutionary importance.

a) the region of the massive main-sequence stars ($M>20\ M_\odot$)
b) the red-giant and red-supergiant region.

Whether or not the mass loss has important consequences depends on the time the star spends in that region and on the mass-loss rate. These times are shown in table 6, taken from various evolutionary computations.

mass (in $M_\odot$)	main sequence lifetime	hydrogen shell burning	helium core burning
15	10^7	450000	1.39×10^6
9	2.10^7	60000	410000
5	$6.5\ 10^7$	650000	17.47×10^6
3	$2.27\ 10^8$	$5.3\ 10^6$	77×10^6
1.5	$1.57\ 10^9$	$227\ 10^6$	
1	$8.06\ 10^9$	$639\ 10^6$	

Table 6. Lifetimes in various evolutionary stages for moderate mass stars (e.g. cf. Iben 1967; Stothers, 1972).

mass (in $M_\odot$)	main sequence lifetime	final mass	average mass loss
50	$4.1\ 10^6$	26.29	$6.5\ 10^{-6}$
40	$4.6\ 10^6$	22.80	$4\ 10^{-6}$
30	$5.4\ 10^6$	19.10	$2\ 10^{-6}$
20	$7.9\ 10^6$	14.00	$0.75\ 10^{-6}$

Table 7. M.S. lifetimes, final mass and the average mass loss in $M_\odot\ yr^{-1}$ for massive stars, losing mass by stellar winds.

a) For stars of moderate mass the mass-loss rate during the main-sequence stage is unimportant. Stars of 1-3 $M_\odot$ spen-

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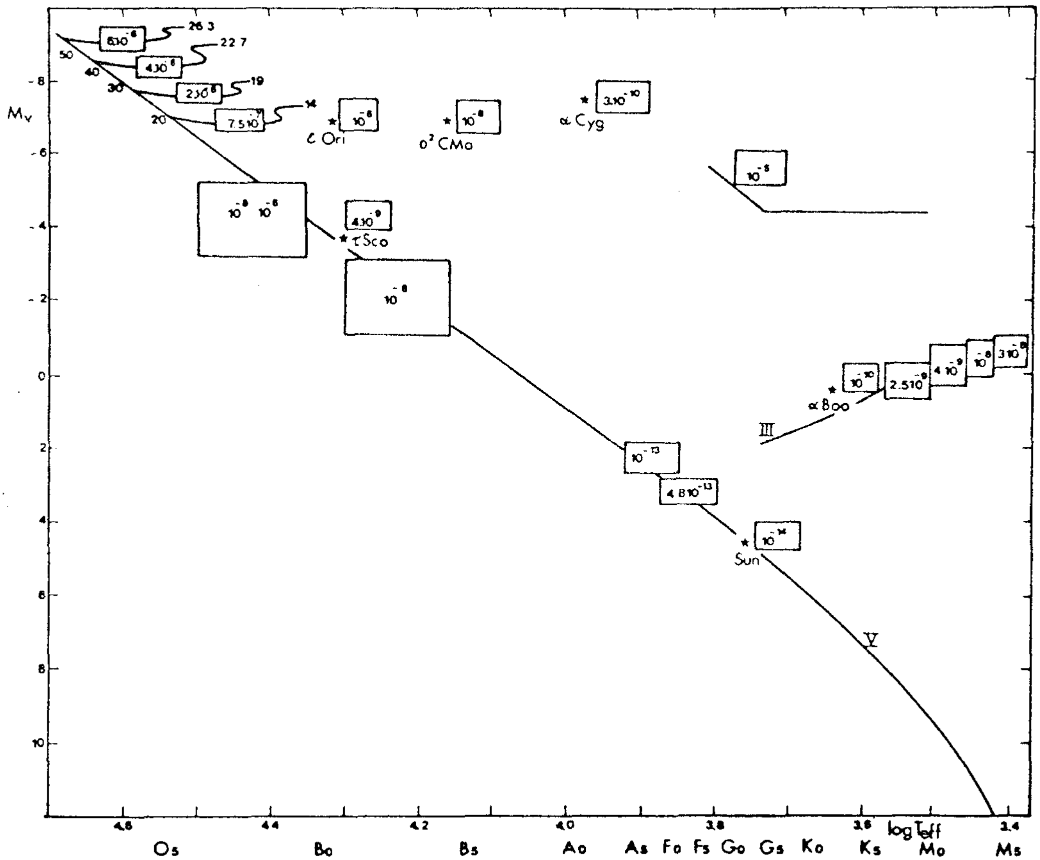

Figure 8. Observed and calculated mass-loss rates for main-sequence stars, giants and supergiants. The $\dot{M}$ values for stars of 50, 40, 30 and 20 $M_\odot$ and their evolution tracks at the upper left, were computed by de Loore et al. (1976) using a simplified Lucy-Solomon model; the numbers at the right end of these tracks give the remaining mass after the stellar wind mass loss. The values for MS Fo and F5 stars are according to de Loore (1968). $\dot{M}$ values at the right end of the giant branch are given by Reimers (1975).

ding between 80.10^6 and 200.10^6 years in the red giant stage, with mass-loss rates between 2.5 10^{-9} and 3.10^{-8} lose at least 0.2 $M_\odot$. No detailed calculations with mass loss included have been performed for single stars in this phase. However, computations of de Loore and De Grève (1975) for a 10 $M_\odot$ + 8 $M_\odot$ binary system for the second stage of mass transfer, i.e. the remnant of 1.66 $M_\odot$ of the first stage starting again mass transfer, show that after a time interval of 3.2 10^6 year a mass of 0.52 $M_\odot$ is transferred towards

the companion, and then the mass transfer tends to its end. The average mass-loss rate of 0.16 10^6 is comparable with the mass-loss rate of these moderate mass stars at the red giant phase, hence we may conclude that they will evolve towards the left part of the HRD and will end as white dwarfs (Rose and Smith, 1970; Paczynski, 1970).
b) Massive stars lose during their main-sequence stage a considerable fraction of their initial mass. The results of evolutionary computations with mass loss included (de Loore et al., 1976) are shown in table 7.
c) When the stars evolve towards the right-hand part of the Hertzsprung-Russell diagram the mass-loss rate, during the first part at the same value as before, decreases slowly with the luminosity. However, as the star moves quickly through this stage, the total amount of mass loss in this phase is quite unimportant (see table 6).

9. MASS LOSS IN T TAURI STARS

T Tauri stars and other young objects show most probably evidence for mass loss. Computations by Larson (1969,1972) show that for protostars of masses $\leq$ 10 $M_{\odot}$ for core masses of 2-3 $M_{\odot}$, due to heating of the central layers, radiative energy transfer becomes important near the centre of the core in a timescale shorter than the accretion time. The heating of the outer layers, caused by the increase of the core luminosity may increase the radiation pressure and the envelope may be blown away. Model calculations of Appenzeller and Tscharnuter (1974) for a 60 $M_{\odot}$ protostar show that 4.5 10^4 years after the core formation, and when the core mass is 18 $M_{\odot}$, the outer layers expand in such a violent way that the entire envelope attains the escape velocity and a remnant of ~ 17 $M_{\odot}$ is left.
More calm processes that involve the stellar core and which may be important in protostars are stellar winds. Outflow of matter occurs already in objects which are very young (10^5 years). This was observed in Herbig-Haro objects by Strom et al. (1974). The objects are still completely hidden in dust clouds. These stars possess deep convection zones and these may be associated with the occurrence of chromospheres and stellar winds. Moreover, there is spectroscopic evidence for enhanced chromospheric activity as mentioned by Strom et al. (1974); in the youngest T Tauri stars the mass-loss rate is apparently so large that it has dominant effects on the stellar spectrum (strong emission lines which can be attributed to dense circumstellar material or extended outflowing matter). As mentioned by Larson (1975) mass loss could play an important dynamical role by dissipating protostellar envelopes and in limiting the growth in mass of stellar cores.

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