II. Mass-Losing Stars in Different Stages of Evolution

Chair: A. Maeder and P. Wood

STELLAR MASS LOSS AND ATMOSPHERIC INSTABILITY

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Abstract: A review is given of rate of mass-loss values $\dot{M}$ in the upper part of the Hertzsprung-Russell diagram. Near the luminosity limit of stellar existance $\dot{M} = -10^{-4}\ M_{\odot}\ yr^{-1}$. Episodical mass loss in bright variable super- and hypergiants does not significantly increase this value. For Wolf-Rayet stars the rate of mass loss is larger by a factor 140 than for non-evolved stars with the same T_{eff} and L; for C stars this factor is ten. This can be explained qualitatively. Rotation appears hardly to influence the rate of mass loss except for v_{rot}-values close to the break-up velocity. This is in accordance with theory. We suggest the existence of a Red Supergiant Branch; along that branch mass loss is virtually independent of luminosity. Stellar winds along the upper limit of stellar existence are mainly due: to radiation pressure for hot supergiants ($\gtrsim$ 10 000 K); to turbulent pressure for cool supergiants (3000-10 000 K), and to dust-driven and pulsation-driven winds for cooler stars. The turbulent pressure may originate in large-scale stochastic motions as observed in Alpha Cyg. Episodical mass loss, as observed in P Cyg, HR 8752 and other Very Luminous Variables may be due to occasional violent stochastic motions, resulting in a shock-driven episodical mass-loss component.

1. Mass loss of chemically not evolved stars

Values for the rate of mass-loss $-\dot{M}$ from stars are mostly derived from the following data:

- middle-ultraviolet resonance line profiles (C IV, Si IV and others);
- profiles of subordinate lines, like Hα, mainly in the visual spectral range;
- infrared continuum photometric data (assumed due to free-free emission);

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- microwave continuum data (free-free emission);
- infrared molecular lines, mostly C-components;
- microwave maser lines.

A few more $\dot{M}$-values were derived from other sources.

Although the various methods are based on very different approaches, the intercomparison of $\dot{M}$-values for the same stars demonstrated that the various methods yield values for the rate of mass loss that do not differ systematically. Also, the average scatter of the data per method is about the same: 0.45 dex. On the basis of these findings an interpolation formula has been derived giving $-\dot{M}$ as a function of log T_{eff} and $\log(L/L_{\odot})$ for the whole upper part of the Hertzsprung-Russell diagram (De Jager et al., 1987); cf. Figure 1. Although one would expect that in such a representation over a broad (T,L) domain the accuracy of the adaption would be less than in interpolation formulae restricted to smaller parts of the Hertzsprung-Russell diagram, this appears not to be the case: other representations have also a one-sigma scatter of 0.5 dex per determination or show even larger scattering.

The choice of the parameters may be a point for discussion. A (T,L)-representation is essentially an (R,L)-representation. It does not appear difficult, though, to add a third parameter, such as the stellar mass M, and this investigation is under way by the present authors.

An (R,M,L)-representation is, however, not physically better founded than an (R,L) or (T,L)-representation. As Vardya (1987) showed: such representations, like virtually all those published so far (cf. Table 1) are essentially numerically- (not physically-) based interpolation formulae, because the constant A in the representation

$$\dot{M} = A.L^{\alpha} M^{\beta} R^{\gamma}, \tag{1}$$

is for most of the representations of Table 1 not dimension-less, and therefore it only represents an approximated constant zero-order value of a function A(L,M,R). If one wishes A to be without dimensions, then the solution of eq (1) is:

$$\dot{M} = A\ (L\ M^2/R^2)^{1/3}\ , \tag{2}$$

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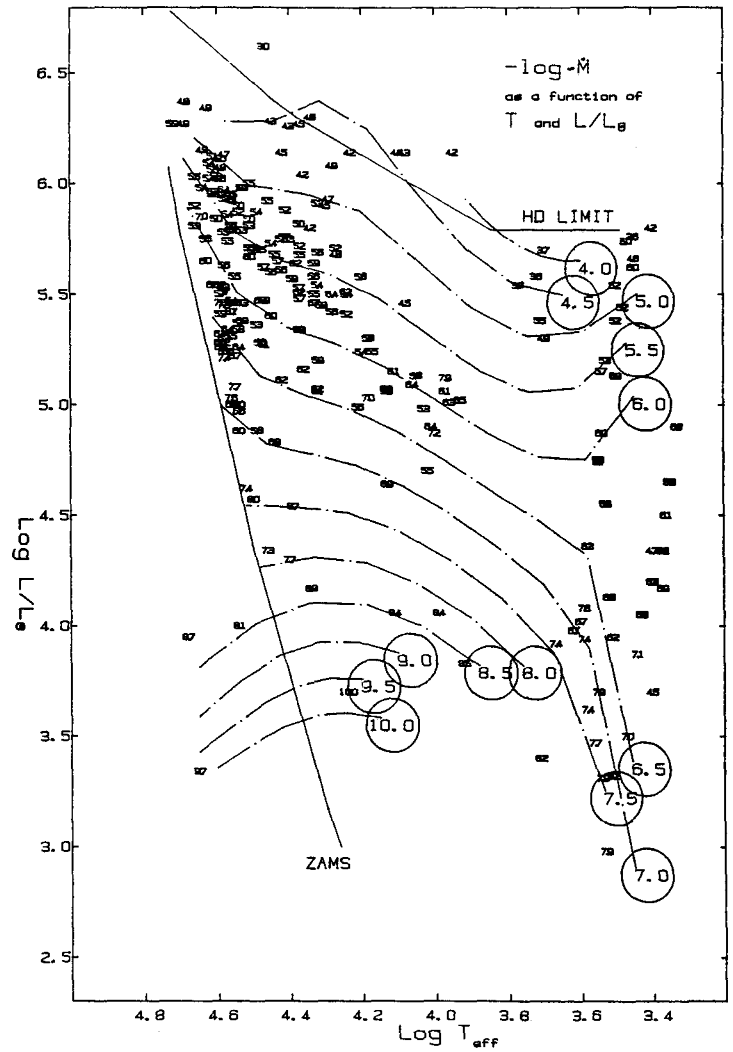

Figure 1: Mass loss over the Hertzsprung-Russell diagram. The numbers give values of -log (-$\dot{M}$) for individual stars, to one decimal. The lines are interpolation lines according to a formula given by De Jager et al. (1987).

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Table 1. Interpolation formulae for the rate of mass loss (partly after Vardya, 1984)

Reference	$\dot{M}$ x const.
McCrea (1962) and Reimers (1975)	$L\ R\ M^{-1}$
Abbott et al. (1980)	$L^{1.8}$
Chiosi (1981)	$L^{0.72}(R/M)^{5/2}$
ibid	$L^{5/4}(R/M)^{13/8}$
ibid	$L^{2}(R/M)^{7/2}$
Andriesse (1979) and Chiosi (1981)	$L^{3/2}(R/M)^{9/4}$
Lamers (1981)	$L^{1.42}R^{0.61}M^{-0.99}$
Garmany et al. (1981)	$L^{1.75}$
Vardya (1984)	$L^{815}(R/M)^{9/10}$
ibid	$L^{7/4}(R/M)^{9/8}$
ibid	$L^{2}(R/M)^{3/2}$
De Jager et al. (1987)	$\phi(T_{eff},L)$
Nieuwenhuijzen and De Jager (1988)	$f(T_{eff},L,v_{rot})$

but since that representation appears not to fit to the observed data, Vardya (1985) proposed after some attempts:

$$\dot{M} = (A/(G^{1/2}c^{2}))L^{2}(R/M)^{3/2}, \qquad (3)$$

where G and c are the gravitation constant and the speed of light, respectively. The formula (3) has not yet been applied to the $\dot{M}$-values over the whole HR-diagram.

The uppermost part of the Hertzsprung-Russell diagram is of particular interest since the stars in that area are apparently close to their limit of existence, which is shown by their stochastic variability, pulsations, large rate of mass loss and occasional episodic mass loss. The curve above which no stars appear to exist is called the Humphreys-Davidson limit (Humphreys and Davidson 1979; De Jager, 1980); cf. Figure 2. Stars close to that limit exhibit many of the properties listed above. In that area one also finds the Luminous Blue Variables, which are stars that erratically expell a large amount of mass. At some distance from the star the gas condenses into dust particles and thus the star becomes reddened. Sometimes the expelled gas is optically

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thick enough to shift the star's photosphere outward, thus lowering the star's effective temperature and changing the spectral type, while the bolometric luminosity remains constant: the star's position then undergoes horizontal excursions in the HR-diagram. Well-known examples of LBV's are S Dor, R 127 and P Cyg.

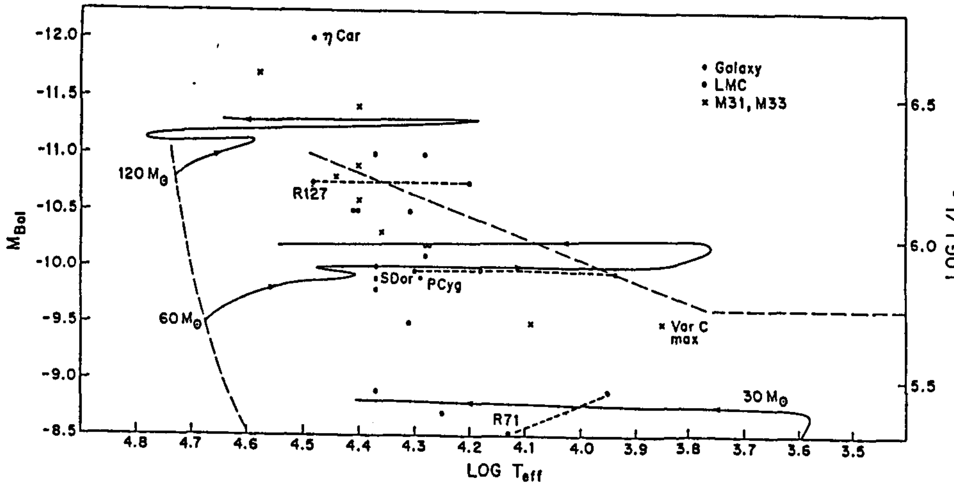

Figure 2: Stars and evolutionary tracks near the Humphreys-Davidson limit. From Humphreys (1987).

But such behaviour is not really restricted to the Luminous Blue Variables. Humphreys (1987) described a cool star ("variable A") that shows the same behaviour, and so does the cool hypergiant HR 8752 (Piters et al., 1987): here an episodical mass ejection started around 1968; the star obtained a later spectral type; the expelled gas remained detectable till 1980-1982. It would make sense to include such variables in the sample and to speak just of Very Luminous Variables, hence adding the word "Very" and deleting "Bright".

It is sometimes claimed or assumed that the episodic mass loss of stars near the HD limit is so large that its contribution would significantly increase the average (over the centuries) rate of mass loss, over the quiet-star's value. But that viewpoint seems hard to maintain for it would demand much larger or more frequent episodic mass loss events than actually observed. We therefore suggest to take $\dot{M} = -10^{-4}\ M_\odot yr^{-1}$ along the Humphreys-Davidson limit as the present best value.

2. Influence of atmospheric chemical composition on the rate of mass loss

It is remarkable that He-rich stars appear to have a higher rate of mass loss than stars with solar-type atmospheres with the same T_{eff}- and L-values: The Wolf-Rayet stars have, on the average, $\dot{M}$-values that are 140 times larger than the values for corresponding O and B type stars (De Jager et al., 1987). This may be due to the fact that WR stars, with their large Helium abundance, are relatively closer to their Eddington limit than the most luminous O-type stars.

The C stars are another case: their average mass loss is slightly more than 10 times the value for solar-type stars with the same atmospheric parameters. This must indicate that C-star mass loss is dust-driven, for the driving efficiency of Carbon dust particles is about ten times the value for silicates (Sedlmayr, private comm. 1987).

3. Rotation and mass loss

Vardya (1985) has published an interesting diagram suggesting a strong dependence of the rate of mass loss on (projected) stellar rotation v_R sin i. Nieuwenhuijzen and De Jager (1988) could confirm his result for a larger material. But, as also shown by the latter authors, that result is certainly not correct, physically speaking. For, both $\dot{M}$ and v_R sin i vary more or less monotonically over the HR diagram, and both quantities tend to increase for increasingly luminous stars. This explains why a plot of $\dot{M}$ against v_R sin i has to show correlation although the two phenomena are perhaps physically hardly correlated. As theoretical predictions by De Grève et al. (1972), Poe and Friend (1986), Friend and Abbott (1986), and Pauldrach et al. (1986) have suggested: $\dot{M}$ increases only by a few tens of percent for an increase in v_R by a factor of ten. It is only close to the critical equatorial (or: breakup) rotational velocity that $\dot{M}$ increases quicker. These theoretical predictions were confirmed by Nieuwenhuijzen and De Jager (1988) in a differential analysis of 140 stars in which it was attempted to avoid running into the trap of a quasi correlation.

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The Be-stars need special mention. The $\dot{M}$-values derived from UV resonance line profiles are by about a factor 100 smaller than those found from infrared continuum measurements. This can be explained if we accept, following Lamers and Waters (1987), that the UV data refer to mass flow from the high-latitude parts of the stellar surface, while the IR data give the mass flow from the stars' equatorial discs. Apparently, the mass flow from Be stars comes essentially from the equatorial discs, while only about one percent of the contribution comes from the high-latitude parts. It appears also that the observed mass flux from the discs is somewhat higher than the values from a theoretical prediction by Poe and Friend (1986).

4. Mass loss from red stars; the Red Supergiant Branch

The diversity of groups of stars in the extreme red part of the HR diagram is reflected in the fact that the $\dot{M}$ data in that region hardly allow for a smooth numerical-mathematical representation. Clearly, the common assumption that $\dot{M} \sim L$ is certainly unjustified here. We mentioned already the C-stars, with their rate of mass loss about ten times that of other stars at the same location in the HR diagram. The explanation for these large values: dust-driven winds involving carbon particles implies that the mass loss of other stars at the same location as the C stars is also dust-driven, via silicates, which have ten times lesser efficiency. Gail and Sedlmayr (1987) and Sedlmayr (these Proceedings) have shown that the mechanism of dust-driven winds works for $T < 3000$ K, and high luminosities ($L/L_{\odot} \gtrsim 4$).
Many of the red stars are pulsating and/or show irregular or semiregular variations of brightness and radial velocity. For the Mira stars the mechanism of pulsation-(shock-)driven mass loss has been proposed (Wood and Cahn, 1977; Hill and Willson, 1979), but it appears difficult to make quantitative predictions.

HR-diagrams of our or of other galactic systems (Humphreys and Davidson, 1984) show in the red a branch of supergiants, definitely differing from the Asymptotic Giant Branch, because they are much brighter. The lower part of this branch is marked by stars like α Sco and α Ori; at its upper part is the famous object VY CMa. The branch has an inclination of -7 in the ($\log T_{eff}$, $\log L$)-diagram, suggestive

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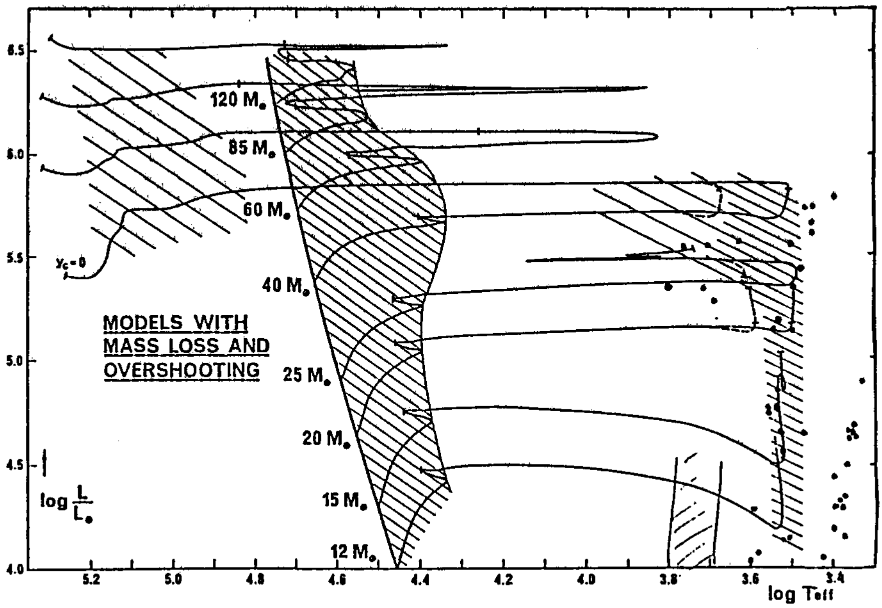

Figure 3: The upper part of the HR diagram with evolutionary tracks calculated by Maeder and Meynet (1987). The branch of dots in the red part is the proposed Red Supergiant Branch. Lower to the right (at log T_{eff} ≈ 3.4) is the uppermost part of the Asymptotic Giant Branch. The hatched area near log T_{eff} = 3.75 is the upper part of the Cepheid branch.

of a Hayashi-track. The rate of mass loss is roughly constant along the branch and equal to a few times 10^{-6} $M_\odot$ yr^{-1}, with the exception of VY CMa, however, for which $\dot{M}$ has been determined (De Jager et al., 1987), according to different methods, and with great accuracy: $\log(-\dot{M}) = -3.620 \pm 0.047$ $[M_\odot yr^{-1}]$.

What makes this branch interesting is that it contains more stars than can be expected on the basis of current ideas on stellar evolution. From Maeder and Meynet's (1987) evolutionary calculations it appears that the upper part of this Red Supergiant Branch (as we propose to call it) contains about 3 times more stars than one would expect on the basis of the counted numbers of main sequence O-type stars and evolutionary time schedules. Such high numbers, on the other hand, would rather be expected if stars of about 15 $M_\odot$ would climb up, in their evolution, along this Red Supergiant Branch, but so far there is no clear physical basis for supporting this idea.

5. Mass loss and stellar instability of cool stars

One of us (De Jager, 1984) has suggested that the Humphreys-Davidson limit is defined by the approximate balance of three accelerations in stellar atmospheres:

$$g_{grav} + g_{rad} + g_{turb} \approx 0.$$

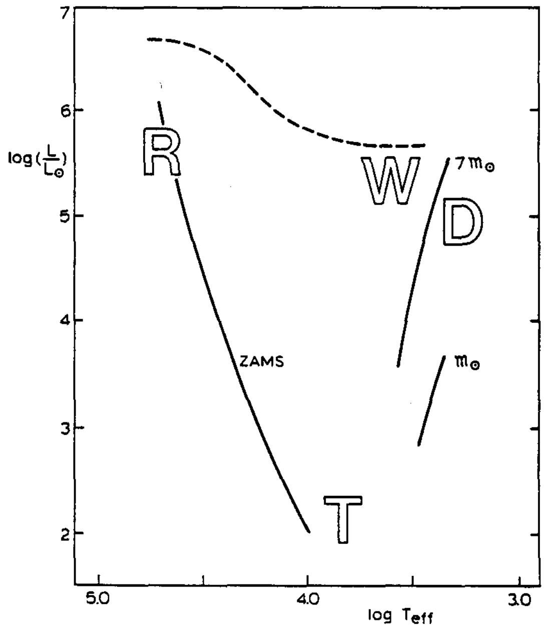

Figure 4: Proposed solar wind mechanisms in the Hertzsprung-Russell diagram. R = radiation driven winds; W = wave-(turbulence-) driven; D = dust-driven; T = thermal (coronal) winds.

The classical Eddington criterion is restricted to the first two terms, and, as Lamers and Fitzpatrick (1987) showed, accounts for the instability in hot stars, with $T_{eff} \gtrsim 10^4$ K. For cooler stars radiative acceleration is ineffective, but turbulent acceleration appears to be able to balance the gravitation term. The atmospheres of stars closest to the Humphreys-Davidson limit appear to be strongly turbulent, with microturbulent velocities equal to or even surpassing the velocity of

sound (Boer et al., 1988). There is considerable dissipation of turbulent energy, which causes transfer of momentum and energy. The consequent heating of hot gas is small, but the momentum transfer causes an outward directed turbulent acceleration (Figure 4).
For stars near the Humphreys-Davidson limit the value of the turbulent acceleration is about equal to that of the gravitational acceleration, but oppositely directed, which explains the instability of cool hypergiant atmospheres (Figure 5).

Microturbulence seldom occurs alone; it is generally driven by larger-scale motions: microturbulence is the high-wavenumber part of the atmospheric spectrum of turbulence. For the stars discussed here the origin of the motion field may be found in pulsations or in convective motions. Such motions have been discovered in α Cyg (Boer et al., 1987): they have up- and downward velocities of 14 km s^{-1} and the

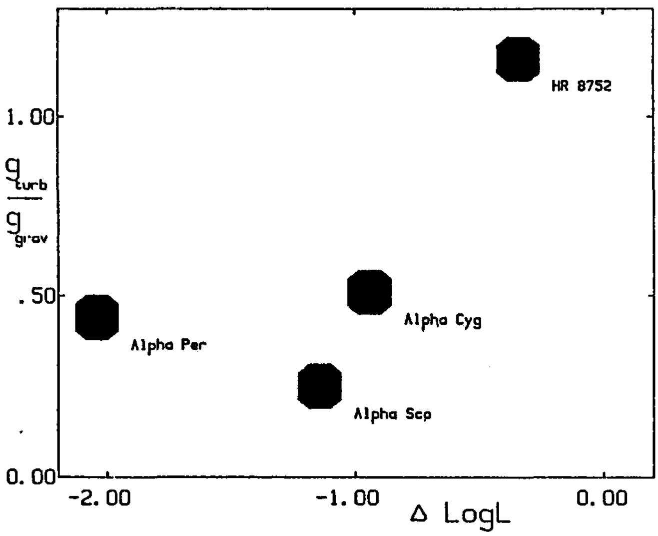

Figure 5: Values of $-g_{turb}/g_{grav}$ for a few well-studied super- and hypergiants suggest an increase of this ratio towards the Humphreys-Davidson limit (Boer et al, These Proceedings).

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elements have average diameters of about 30 million km. Whether these motions should be called convection, non-radial or stochastic pulsations is not just a matter of taste: we prefer the last suggestion, because the star is too hot for convection to develop, and too large for having an ordered system of non-radial pulsations.

The concept of stochastic pulsations offers also a natural mechanism to explain episodical mass loss as due to occasionally occurring exceptionally large or rapidly moving pulsation elements. In forwarding this suggestion we realize that its proof should still be given.

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