MASS-LOSS FROM SPINNING STARS

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ABSTRACT

The effects of mass-loss and angular momentum loss on the evolution of massive stars are discussed bringing out the main results as well as the limitations of recent studies. It is pointed out that an acceptable theory of stellar winds in early as well as late type stars is needed as well as a satisfactory assessment of a number of instabilities in these contexts for an adequate understanding of the evolutionary consequences for a wide variety of population I and polulation II stars, which are affected by mass-loss.

1. INTRODUCTION

In the last twenty years since Deutsch (1956) inferred that stars may be losing mass, considerable progress has been made to understand the basic problem of mass-loss from stars. It is now generally recognized that the sun as well as stars of different types lose mass in varying proportions. But the detailed physics of the mechanisms of mass-loss remains still to be fully understood. Observationally, *in situ* measurements of the solar wind have been accomplished since 1963 and there is a growing community of research workers dedicated to the study of the solar wind as evidenced by the series of four conferences devoted to the solar wind. Ground-based, Rocket and Satellite observations of mass-loss from early type stars in the seventies have provided renewed opportunities to examine this problem. A number of reviews already exist in published form on the subject of Mass-Loss from Stars (Deutsch 1960, 1968; Weyman 1963; Woolf 1974; Reimers 1975; Conti 1976, <u>1978</u>, de Loore 1976, <u>1979</u>; Chiosi <u>1978</u>, Renzini <u>1978</u>, <u>1979</u>;) and on Solar and Stellar Winds (Parker 1963; Brandt 1970; Axford and Holzer 1970; Hundhausen 1972; Casinelli <u>1978</u>). I shall therefore concentrate on those aspects of the subject that require further study and/or clarification, after recapitulating the main results. I shall omit detailed explicit references if more than one group is involved and there is agreement. Individual results will be referred to the sources. Full particulars of references can be obtained from the review papers which are underlined.

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2. THE NATURE OF THE PROBLEM

It is now believed that mass-loss from stars is not confined to some isolated instances but that it is a more common occurrence in the lifetime of many different types of objects. Starting from the pre-main sequence, still unformed stars such as T Tauri objects, to the old population II giants such as Mira Variables, from the quiet sun to the exploding Supernovae, Mass-Loss appears to be a phenomenon that should be recognized for the role it plays either in the solar-planetary environment or in affecting the evolutionary history of stars. As is well-known, the chemical evolution of the galaxy and the dynamics of the interstellar medium are influenced by such mass-loss. The characteristics and spectral features of Wolf-Rayet Stars, the variability of some early type stars of spectral types O, B and A, the formation of shells and occurrence of nebulae ground Oe/Be stars, Wolf-Rayet and Planetaries respectively are manifestations of mass-loss. Even the cepheids would perhaps be better understood if the role mass-loss might play in the associated physics of these objects is recognized (J.P. Cox, 1979).

Currently three different mechanisms are thought to be responsible for non-catastrophic mass-loss in stars.

(i) Radiation pressure in some selected resonance lines on the atmospheres of early type stars. (Cold Wind) (Lucy and Solomon 1970; Castor,Abbott and Klein 1975).

(ii) Dissipation of non-thermal acoustic energy flux generated in the outer convection zones of stars of spectral type F and G (Parker 1958). (Hot Wind).

(iii) Radiation pressure on the grains in the atmospheres of cool giants and supergiants. (Salpeter 1974; Lucy 1976).

The necessitv to understand the presence of highly ionized elements such as oxygen in the atmosphere of early type stars, studied by means of the Copernicus satellite, has prompted research workers to postulate additional sources of heating (see Casinelli 1978 for a recent review) in early type stars and a different source of non-thermal energy may be present in these objects (Martens 1979; Sreenivasan and Wilson 1979; Mazurek 1979). Rotational energy from the loss of spin in early type stars due to mass-loss is an excellent candidate for this. Early observations from the satellite Einstein appear to confirm the presence of hot coronae in OB stars (Rosner *et al.* 1979) by the associated X-ray emissions. Centrifugal winds are thought to play an important role in the braking of the angular momentum of proto-stars (Bodenheimer 1971). Abbott (1979) has recently extended the work of Castor *et al.* (1975) and suggests that it is possible to indicate the areas in the H.R. diagram where winds may originate from stars located in them. He indicates also areas where winds can be sustained by radiation pressure if they are catalysed by some other mechanism. His diagram is reproduced below.

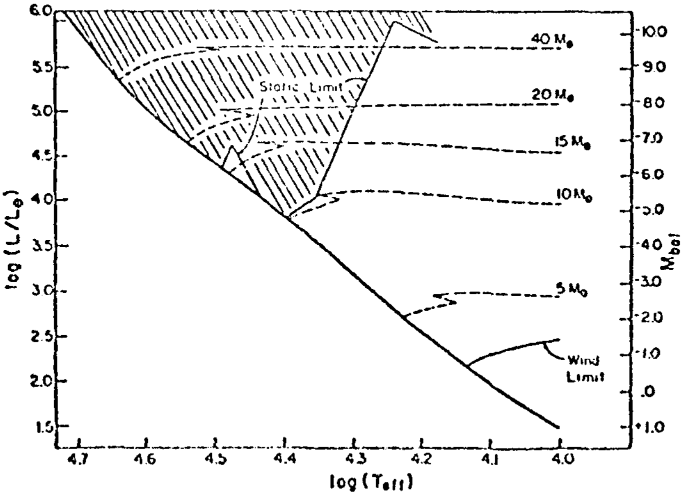

Figure 1 - Minimum luminosity required to initiate (static limit) and sustain (wind limit) a radiatively driven wind.

If one adds a region demarcated by the Hayashi line and the ordinate at about log $T_{eff} \cong 3.7$ to identify the regime of an acoustic flux driven wind (like the solar wind) and one identifies the region to the cooler side of the Hayashi line as the regime of proto-star centrifugal winds it is easy to realize that mass-loss is a very common phenomenon in stars.

3. MASS-LOSS FROM EARLY TYPE STARS

Following the discovery by Morton (1967) of the evidence for mass-loss from an Of star ζ Pup, and the extensive results obtained by Snow and Morton (1976) on mass-loss from the Copernicus measurements of P Cygni type line profiles, several workers have independently studied the effect of mass-loss on stellar evolution. Groups from Belgium, Canada, Holland, Italy, Japan, Poland and the U.S. have computed stellar evolutionary models of massive population I stars up to the exhaustion of helium in the core. As pointed out by Stothers and Chin (1979) they have essentially used an empirical prescription to remove mass along lines originally suggested by Kippenhahn and Weigert (1967) starting from the early studies of Tanaka (1966 a, b). Basically, there are four or five different recipes for removing mass:

(i) The McCrea equation (1962): $\frac{1}{2} \dot{M} V^2_{escape} = k_1 L$

(ii) The Lucy-Solomon equation (1970): $\dot{M}C^2 = k_2 L$

(iii) The Castor-Abbott-Klein equation (1975):

$$\dot{M} = \frac{\alpha k_3^{1/\alpha}}{CV_{th}} \left[\frac{\Gamma(1-\alpha)}{1-\Gamma}\right]^{\frac{(1-\alpha)}{\alpha}} L$$

(iv) Lamers, Van den Heuvel and Petterson (1976) equation:

$$\dot{M} = \frac{k_4 L}{V_{max} C}$$

(v) Barlow and Cohen (1977) equation:

$$\dot{M} = aL^b$$

where M is the mass of the star, L its luminosity and C is the speed of light in vacuum, V_{max} = maximum out flow velocity; V_{th} the thermal velocity of the (radiation) absorbing ion; k_1, k_2, k_3, k_4, a and b constants. While these prescriptions represent different degrees of sophistication, the effect on stellar evolution calculations is due to removal of a certain amount of mass. The different computations by several groups have the encouraging consequence that results obtained are in pretty good agreement. One has therefore the confidence that the results are generally code-independent. It should be remarked, however, that Stothers and Chin (1978, 1979) have also computed evolutionary models using the Carson opacities based on the Thomas Fermi model of the atom in addition to Cox-Stewart opacities. I shall only summarize the main conclusions based on Cox-Stewart opacities and refer to Stothers and Chin's papers for the results based on the Carson opacities due to limitations of space. Thus one has the opportunity to confront the predictions based on different opacities. Finally, there are also different compositions assumed by different authors, so that there is some possibility of examining the consequences of variation in the initial abundances. There is of course the possibility of varying the ratio of the mixing length to the density or pressure scale height.

One important result that is borne out by more than one group is that mass-loss reduces drastically the occurrence of semi-convection in the core-Hydrogen burning phase of massive stars, the extent of reduction being proportional to the rate of mass-loss (Chiosi and Nasi 1974; Chiosi, Nasi and Sreenivasan 1978*, Sreenivasan and Wilson 1978@, Stothers and Chin 1978, 1979, etc.). This removes one further variation amongst models due to the adoption of one of two specified stability criteria: density (Ledoux) or temperature (Schwarzschild) criterion. It also enables acceptable comparison with results obtained without allowing for semi-convection such as those of de Loore *et al.* As Stothers and Chin (1979) rightly point out, there seem to be too many free parameters in these studies and a reduction or elimination of their number is an important factor to progress.

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*abbreviated as CNS; @abbreviated as SW.

(i) when one plots the evolutionary tracks for different initial masses on the zero age main sequence one is struck by the widening of the main sequence band at lower mass ranges and the shrinking of the band at the higher end, (CNS), if the mass-loss rates are high. This tendency is not seen to the same extent in the computations of CNB†, however. The lowest initial mass for which mass-loss has been taken into account is 15 M_0 because that is (a) the lower limit of detection in the results of Snow and Morton (1976) and (b) a mass at which semi-convection is definitely known to occur in the conservative evolutionary studies. The limit for the occurrence of semi-convection according to Sreenivasan and Ziebarth (1974) is given as 14 M_0 while Barbaro *et al.* (1972) quote 13M_0. A low mass-loss rate simply widens the main sequence band (defined by the locus of the coolest turning point in the core-hydrogen burning phase and the ZAMS line).

(ii) the mass-losing models are over luminous for their masses although the tracks run at lower luminosity compared to the conservative evolution tracks.

(iii) the main sequence lifetimes of these mass-losing models are affected in two ways. In the conservative evolution of massive stars the occurrence of semi-convection increases the hydrogen burning lifetime because more hydrogen is fed into the convective core by the adjoining semi-convective zone through a double-diffusive convection process with helium diffusing outward and hydrogen diffusing inward. The drastic reduction in the semi-convective zone (see e.g. structure diagrams in Sreenivasan and Wilson (1978)) due to mass-loss hence does the reverse due to the added fact that the fractional mass of the convective core is smaller than for the conservative models. There is, therefore, less hydrogen for fusion. On the other hand less massive objects evolve more slowly and have lesser energy to radiate so that the hydrogen burning lifetime is increased. However, Stothers and Chin (1979) reach a different conclusion, that the hydrogen burning lifetime is, on balance, decreased. It should be pointed out that when rotation is taken into account fully and properly in the evolutionary code (as done e.g. by Bodenheimer (1971) and Sofia and Endal (1976)) the main sequence or hydrogen burning lifetime is increased and luminosity reduced for a mass-conserving model. I shall return to this point later on.

(iv) depending on the amount of mass-loss and the time-scale over which it occurs the spectral features of the models would reveal changed abundance ratios of heavy elements to hydrogen. Depending on the formulation used the mass-loss rate will either maintain a functional dependence with luminosity or go through a maximum for the form given by Lamers *et al.* (1976). In most of the work of various groups the mass-loss rate is taken as steady.

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†Chiosi, Nasi & Bertelli: (1979) AA 74, 62.

Inclusion of the effect of rotation and the loss of angular momentum due to mass-loss changes the steady character of assumed

Inclusion of the effect of rotation and the loss of angular momentum due to mass-loss changes the steady character of assumed mass-loss rates and introduces an additional variable contribution. (Sreenivasan and Wilson 1978 b). Dearborn and Eggleton (1977)* suggested that CNO processed material could be revealed with sufficiently high mass-loss. This result has subsequently been confirmed by others (CNS, CNB, DBHS, SW 1979, etc.) Thus yellow supergiants should reveal the changed abundance ratios due to mass-loss if high rates are present.

(v) the core of helium left in these models at the end of hydrogen burning is smaller in mass compared to the conservative models. On the other hand since the models have lost a considerable amount of mass which can vary from under 10% to 50% depending upon the initial mass of models and mass-loss rates the fractionary mass of the He core is larger than for the conservative evolution. This result can have profound consequences for the subsequent evolution of the star. For one thing, if this fraction $q_{He} = (M_{Hec}/M)$ is greater than about 60% the models return to higher effective temperature as first pointed out by Giannone (1967). Here M_{Hec} is the mass of the Helium core. This results in an upper limit for the luminosity of supergiants, for the mass of cepheids as well as controlling the occurrence of types of supernovae (Renzini 1978).

(vi) it is also evident that the mass-luminosity relation as well as the ages of models are affected by mass-loss. It is possible that a long standing discrepancy between kinematic expansion ages and the nuclear evolutionary ages as inferred for stars in clusters can be reconciled since high mass-loss implies a lower age for a given absolute magnitude. (CNS). However, van der Hucht (1978) disagrees with our conclusions.

Similarly the determination of masses from evolutionary tracks becomes a more complicated task with mass-loss. Lines of constant mass are not only steeper than for the conservative case, they can also overlap at high luminosities. This factor might influence considerably estimates of the mass of single stars. Errors of up to 40% in the masses could be present especially for very luminous and evolved stars.

4. LATE TYPE STARS: Population I

In this section we shall recall the main results from groups which have discussed the helium burning stages to the exhaustion of helium in the core. This restricts any comparison to those of a couple of groups, namely those of Stothers and Chin and us in Calgary.

It is well known that in the conservative evolution, models computed using the Schwarzschild criterion burn helium as blue supergiants

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*abbreviated as DE

whereas those computed using the density or Ledoux criterion do so as red supergiants. It appears that the effect of mass-loss is to transform the evolutionary pattern to mimic the conservative evolution of a model with the Ledoux criterion adopted. This behaviour is clearly seen in the work of Sreenivasan and Wilson as well as CNS at lower masses. (15-40 $M_\odot$). One sees the occurrence of a blue loop that did not exist in a conservative evolutionary model obeying the Schwarzschild criterion. The occurrence of mass-loss also widens and reddens the blue supergiant area. However, the inclusion of additional mass due to a non-thermal hot wind resulting in a 10% mass-loss suppresses the blue loop. (SW 1978a).

This non-thermal (hot) wind induced mass-loss has many interesting consequences. At higher masses the models do not have an extended red supergiant phase. They return to higher effective temperatures once $q_{Hec} \gtrsim 0.6$. This factor alters considerably the ratio of the number of blue/red supergiants and as pointed out by Humphreys and Davidson (1979) one should only use this ratio below a certain mass limit for the purposes of studying chemical gradients in galaxies. It should also be pointed out that when additional mass-loss due to rotational effects is considered in models of massive stars (30 $M_\odot$) in the early spectral stages and a non-thermal (hot) wind included mass-loss in the late stages (F,G), the models developed an overshooting helium burning core. This phenomenon similar to what is seen in conservative evolution of lower mass (5 $M_\odot$) models of Robertson and Faulkner (1972) as well as in the horizontal branch star models of Pop II stars (Castellani *et al.* 1970) is sometimes referred to as induced semi-convection. We prefer to call it overshoot because the energy transport in this region is by convection rather than essentially by radiation as in an ordinary hydrogen semi-convective region and also because the overshoot is never larger than a scale-height. As in Hydrogen semi-convection, the helium burning lifetime of the model is increased because the overshot region contains more helium than the core which is carbon rich and has a greater opacity as a result. Unfortunately, however, it is <u>not</u> possible to compute the enhancement of the He burning time of the model since one cannot obtain convergent solutions if the overshoot is not taken into account unlike in the hydrogen semi-convection treatment. But although the He burning lifetime is increased, the 30 $M_\odot$ model did not have a blue loop, quite analogous to the 15 $M_\odot$ model which suffered an extra 10% mass loss in the red giant branch (SW 1979). We shall see later on that this result may have interesting implications to the cepheid problem as well as the problem of WR stars. This model had a mass of about 16 $M_\odot$ at core He exhaustion.

Another category of stars with considerably high mass-loss rates that have been studied are M supergiants. The very high rates quoted (10^{-4} $M_\odot$ yr^{-1}) for objects whose mass is believed to be in the 15-20 $M_\odot$ range (Bernat 1977) and subsequently corroborated independently by van der Hucht *et al.* (1979) suggest that we do not have a very clear understanding of the mechanisms responsible in these stars. It would either imply that there is a very intense acoustic energy flux causing a non-thermal wind that leads to such high mass-loss rates or that these M supergiants dissipate a much larger fraction of the non-thermal energy flux. Typically we have used an efficiency factor $\varepsilon = 10^{-4}$ to 10^{-2} in the expression: $\dot{M} = \varepsilon . L_{ac}/V_s . V_{escape}$ for calculating mass-loss rates due to non-thermal winds. A high mass-loss rate would mean that either ε is high or L_{ac} is high. Here L_{ac} is the acoustic or non-thermal luminosity of the star, V_s is the local speed of sound waves and V_{escape} is the escape velocity from the star. Alternatively, there is possibly a different mechanism for such high mass-loss, if the observations indicate the reality.

Still another kind of wind has been suggested to clarify the well-known discrepancy between pulsational and evolutionary masses by Cox *et al.* (1978). It is the so-called cepheid wind which results in a He enriched envelope and thus removing the mass discrepancy in pulsational calculations. However, the mass-loss in the cepheid due to the cepheid wind is not large. It is of the order of 10^{-10} - 10^{-11} M_0 yr^{-1}.

Sreenivasan and Wilson (1978a) have shown that a 15 M_0 Pop I model essentially arrives at this stage with a mass of about 75% of the initial mass, if mass-loss in both the early and later spectral stages are taken into account. It appears that at present there are three alternate explanations for the discrepancy. Revised distance and/or temperature scales (Iben and Tuggle 1972, 1975); mass-loss for $M \gtrsim 15$ M_0 stars in the blue and red phases or the cepheid wind enhancement of He (Cox *et al.* 1978). It is clear, however, that a single mechanism cannot explain the anomaly for all cepheids.

4b. LATE TYPE STARS: Population II

Mass-loss is known to be of importance for models of population II composition. The problem has recently been reviewed by Renzini (1979) so I shall not enter into any detailed discussion here. Mass-loss rates are calculated essentially using an equation of the form given by McCrea and elaborated by Fussi-Pecci and Renzini (1975 a, b) and Reimers (1975). Renzini concludes by saying that considerable improvement ensues when mass-loss is taken into account for stars of mass $\gtrsim 8$ M_0.

Mass-loss is also an important factor in the understanding of the phenomena of long period variables such as the Miras. This problem has recently been discussed by Wood (1979) as well as at another of these Joint Discussions. I shall not go into any details here except to point out that mass-loss rates vary between 10^{-12} M_0 yr^{-1} to as high as 10^{-2}! Again, shock waves are thought to propagate in the atmosphere of these objects.

5. EFFECTS OF ROTATION

It is well known from the work of Bodenheimer (1971) that the inclusion of rotation affects not only the luminosity (rotating models of stars have a lower luminosity as compared to the non-rotating ones) but that their main sequence lifetimes are enhanced (see also Endal and Sofia 1976, 1978). It can be shown that the loss of angular momentum due to mass-loss can be studied without explicitly using a code which incorporates rotation. Starting with reasonable values of V sin i it can be shown that the star models spin down to zero spin well before hydrogen is fully converted into helium in the core (Sreenivasan and Wilson 1978; Packet *et al.* 1979). It is also possible to model the effects of differential rotation and to show that as the star loses mass the surface layers spin down, the shrinking core spins up and that soon an instability analogous to that in Couette flow has to occur. This generates shear turbulence and a consequent non-thermal energy flux, which in turn when dissipated in the outer layers results in a corona (Sreenivasan and Wilson 1979b). If the instability is strong enough it might lift off a thick shell from the star and a planetary nebula like structure might result.

There is also another source of non-thermal energy flux that may be available for early type stars as discussed by Martens (1979). These are line driven sound waves which are amplified until dissipated to form a corona. Martens estimates that the flux in these waves may be of the order of 10^{-3} the flux in radiation for a typical O star like ζ Pup. The ratio of the fluxes in the case of the sun is similar in order of magnitude. Such a possibility might indeed exist if one looks at the recent results from the Einstein satellite (Rosner *et al.* 1979) on X-ray measurements of OB associations. The line drive sound waves are a consequence of a Rayleigh-Taylor instability. It appears that in a rotating star losing mass there also exists a Kelvin Helmholtz instability and this might help explain the kind of variability observed in β Cephei type of stars (Sreenivasan and Wilson 1979a; Papoloizou and Pringle 1978). The estimates of the main sequence lifetimes as well as mass-loss rates would be affected if one considers fully rotating models. The mass-loss rate is proportional to the luminosity and hence would be lower for rotating stars. This would, therefore, enlarge the semi-convection regions and extend thereby the main sequence lifetimes over the non-rotating models. This would in turn increase the total mass that is lost from the star.

On the observational side the presence of macroturbulent velocities in and V sin i's of O and B stars have been studied by Conti and Ebbetts (1978), Ebbets (1979) and Hutchings (1979). The theoretical predictions are in qualitative agreement with these results. All these studies have not considered the role of magnetic fields. As in the case of the sun, it can be argued that a small magnetic field will slow down the spin of early type stars, if they possessed magnetic fields (Mihalas and Conti 1979).

However, it is not clear at the moment whether the observations favour a rigidly rotating star or one that has some form of differential rotation. We may have to await more sophisticated models along the lines of Endal and Sofia (1978) to answer some of these questions.

6. IMPLICATIONS OF MASS-LOSS

a) Wolf-Rayet Stars: Since the results of Copernicus have been clarified, the study of Wolf-Rayet stars has gathered considerable momentum. On the observational side there appears to be considerable argument as to whether they are hydrogen burning objects or helium burning objects. It has been known for some time that the identification of hydrogen lines in the spectra of these objects is problematic (Smith 1973). But for a long time it has been assumed that WR stars are members of binary systems and that they are helium rich, hydrogen poor stars of around 10 M_0. That situation appears to have definitely changed (see e.g., Conti 1978; Conti and de Loore 1979) and it appears that there are definitely single WR stars, that not all of them are around 10 M_0 and that they may well be hydrogen burning objects although with difficult-to-identify hydrogen lines (Underhill 1966, 1978 1979 *et seq.*). Conti (1978) has suggested an evolutionary sequence in which O stars turn into WN7 stars as a result of mass-loss and it is thought that the WC stars are later evolutionary products than WN stars.

On the theoretical side, it is possible to model an evolutionary scenario such as indicated by Conti either by invoking mass-exchange in binary systems (de Loore *et al.* 1977 *et seq.*) or by arguing that WR stars are helium burning single stars whose hydrogen rich outer layers have been peeled off by mass-loss (CNS and CNB). Whatever the mechanism, it is clear that it ought to explain the occurrence of both single as well as binary WR members. Dearborn *et al.* (1978)*, Dearborn and Blake (1979)† and DE have shown that there exists a critical mass-loss rate which controls the formation of WR objects with CNO processed material revealed as a consequence of mass-loss. According to them it is possible to explain OBN stars, WN and WC stars. Sreenivasan and Wilson (1979d) have shown that their initial 30 M_0 model does not return to higher effective temperatures but that it burns up helium in the core being too red. They took enhanced mass-loss due to rotational effects (centrifugal force + differential rotation) and as pointed out earlier, the model did not turn blueward despite an extended He burning lifetime due to convective overshoot. They thus concluded that either Chiosi's scenario is applicable only to models starting off more massive than 30 M_0 on the ZAMS or that there is an alternate explanation for the origin of WR stars. The 30 M_0 model has a deep convective envelope and an overshooting (and hence larger) convective helium burning core. As such the hydrogen shell source is closer to the core and envelope, the star therefore continues to expand in radius consequently keeping the model at lower (effective) temperatures throughout the He burning stage. The star remains red rather than looping back towards blue. This in turn has the consequence of raising the lower limit for the initial mass on the ZAMS for models which evolve into a WR phase, unless an increased mass-loss were to reinstate the blue loop as first suggested by Forbes (1968). To investigate the possibility of understanding WR stars as products during the course of core hydrogen burning evolution, Sreenivasan and Wilson (1979c) showed in another study that in order to have a WR star with the right surface chemical composition due to mass-loss the mass-loss rate has to be critical. If it is too large, the model simply slides down along and close to the ZAMS line, to lower and

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*abbreviated to DBHS; †abbreviated to DB.

lower masses as in the Hartwick sequence. If it is too low it might simply follow the 30 M_0 model's pattern. This confirms the picture that follows from the computation of DB. In any event, it appears that one can produce models of WR stars as representing either a hydrogen burning phase (as de Loore *et al* or DB suggested) of single stars or binary system members by a suitable combination of a number of parameters, or as helium burning objects with the hydrogen rich surface layers removed due to mass-loss (CNS, CNB). Clear cut observations of the status of WR stars are urgently needed which will provide guidance regarding masses, ages, mass-loss rates, and chemical compositions at the surface. There appear to be too many parameters available for the model makers and a deeper understanding of the physics of WR stars is needed before theoretical models of these objects can be constructed properly.

b) O and B Stars: O_3 stars can be reached in the HR diagram by models with a very high rate of mass-loss as shown by CNS. The variability associated with these objects can be understood either as a manifestation of Kelvin Helmholtz instabilities as discussed earlier or as manifestations of pulsations. The distribution of rotational velocities: V sin i can be understood as a consequence of mass-loss but fully rotating models are required before any definitive statements can be made. Similarly the β Cephei stars and the shell stars again could be manifestations of the instability associated with Couette flow before and after the ejection of a shell. The removal of a shell from a B star could reveal its faster spinning interiors. The stellar coronae associated with OB stars could be the result of dissipation of non-thermal energy associated either with shear turbulence or line driven sound waves. More work on the physics and hydrodynamics of these phenomena is clearly required.

c) Yellow Supergiants: If mass-loss is the mechanism operative in yellow supergiants spectral peculiarities must be present, the presence or absence of which might afford a check on the hypothesis of mass-loss.

d) Cepheids: The presence of mass-loss might account both for the upper mass-limit for cepheids (periods of 0 (100) days) (Gascoigne 1969) as well as for the discrepancy noted earlier between pulsational and evolutionary masses.

e) Supernovae: The size of the core that remains at the end of hydrogen fusion might account critically for the elimination of the electron pair instability in supernovae which requires massive oxygen cores (DBHS). It will also increase the frequency of type I supernovae (Renzini 1978).

f) The Interstellar Medium: The chemical enrichment of the interstellar medium as well as the amount of gas returned to the interstellar medium are drastically going to be affected if mass-loss from stars occurs at the currently accepted rates and if the phenomenon is as common as appears to be the case. This will have a considerable impact on the evolution of a galaxy. The dynamics of the interstellar medium will equally be changed as the mass balance and the energetics of the mass-loss process are included in the physical considerations that determine it.

7. FUTURE WORK

It must be emphasized, as Renzini (1979) and Stothers and Chin (1979) have done earlier, that the subject of stellar evolution including mass and angular momentum loss contains a large number of free parameters and includes uncertainties in the critical phenomena such as convection, turbulence, etc. Added to this, the star's atmosphere is assumed to be in hydrostatic equilibrium in the face of low effective gravity caused by radiation pressure, rotation, etc. The presence of winds at terminal speeds of the order of 1000 km/s requires that the boundary conditions implied by static atmospheres are untenable. The rates of mass-loss are those given by the presence of steady winds, and considering only partially the physics involved. Humphreys and her associates in their recent series of papers on luminous stars in other galaxies (1979 *et seq.*) argue that mass-loss rates are not only to be increased but suggest that the assumption of steady rates are unrealistic. That winds in O and B stars are commonly variable and do not show a simple dependence of mass-loss rates on luminosity has been reiterated also by Snow (1979). It is unlikely that winds are spherically symmetric (no longer true even for the Sun) and represent steady, stable flow patterns. I have already indicated some of a number of instabilities that must be present, and whose consequences remain to be explored especially in view of the IUE observations by Conti and Garmany (1979) that mass-loss rates can differ by orders of magnitude amongst stars which are otherwise similar. The basic physics of stellar winds and the associated consequences therefore require more careful and complete consideration. The question of which specific mechanisms operate and in which section of the HR diagram and how, are some of the fascinating problems in astrophysical fluid dynamics which require urgent attention.

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REFERENCES

Bodenheimer, P. (1971) Ap. J. 167, p. 153
Casinelli, J.P. (1979) Ann. Rev. Astr. Ap. 17 (in press)
Castellani *et al.* (1971) Ap. Space Sci. 10, p.355
Chiosi, C. (1978) *The H. R. Diagram*, p.357. Ed. A.G.D. Phillips (D. Reidel: Dordrecht)
Chiosi, Nasi and Sreenivasan (1978) Astr. Ap. 63, p.103 (CNS)

Conti, P.S. (1978) Ann. Rev. Astr. Ap. 16, p.371

Conti and Garmany (1979) Ap. J. submitted

Conti and de Loore (1979) *Mass-loss and O type stars*, IAU Symp. No. 83, (D. Reidel Publ. Co., Dordrecht)

Cox, J.P. (1979) *Stellar Pulsation Instabilities* NASA-SP, in press

Cox, A.N. *et al.* (1978) Ap. J. 222, p.621

Dearborn and Blake (1979) Ap. J. 231, p.193 (DB)

Endal and Sofia (1978) Ap. J. 220, p.279

Forbes, J.E. (1968) Ap. J. 153, p.495

Hucht, van der (1978) thesis, Utrecht

Hucht, van der *et al.* (1979) preprint

Humphreys, R. (1978) Ap. J. Suppl. 38, p.309

Humphreys, R. (1979) Ap. J. Suppl. 39

Humphreys and Davidson (1979) Ap. J. Suppl. (in press)

Hutchings *et al.* (1979) preprint

de Loore, C. (1979) *Mass-loss and O type stars*, IAU Symp. No. 83, Eds. Conti and de Loore (D. Reidel Publ. Co., Dordrecht), pp.313.

de Loore *et al.* (1977) Astr. Ap. 61, p.251

de Loore *et al.* (1978) Astr. Ap. 67, p.373

Martens (1979) Astr. Ap. 75, p. L7

Mazurek (1979) Ap. Space Sci. (in press)

Mihalas and Conti (1979) preprint

Packet, W. *et al.* (1979) Astr. Ap. (in press)

Renzini, A. (1978) *Supernovae and Supernovae Remnants*, Mem. Soc. Astr. Ital. (in press)

Renzini, A. (1979) *Stars and star systems*, ed. B. Westerlund, p. 155 (D. Reidel: Dordrecht)

Robertson and Faulkner (1972) Ap. J. 171, p. 309

Rosner *et al.* (1979) BAAS 11, p.446

Snow, T.P. (1980) *Highlights of Astronomy*, 5. These proceedings, pp. 525.

Sreenivasan and Wilson (1978a) Ap. Space Sci. 53, p.193

Sreenivasan and Wilson (1978b) Astr. Ap. 70, p.755

Sreenivasan and Wilson (1979a) *Stellar Pulsation Instabilities*, NASA-SP, (in press)

Sreenivasan and Wilson (1979b) *Mass-loss and O type stars*, IAU Symp. No. 83, (D. Reidel Publ. Co., Dordrecht), pp. 367.

Sreenivasan and Wilson (1979c) BAAS 11, p.417

Sreenivasan and Wilson (1979d) Astr. Ap. (to be published)

Stothers and Chin (1979) Ap. J. (in press)

Tanaka (1966a) PASJ 18, p.47

Tanaka (1966b) Prog. Theor. Phys. 36, p.844

Underhill, A.B. (1978a) Bull. Astr. Soc. India (in press)

Underhill, A.B. *et al.* (1978b) M.N. (in press)

Wood, P.R. (1979) *Stellar pulsation instabilities*, NASA-SP (in press)