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Mass loss rates in the Hertzsprung-Russell diagram

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Summary. — From the literature we collected values for the rate of mass loss for 271 stars, nearly all of population I, and of spectral types O through M. Rates of stellar mass loss determined according to six different methods were compared and appear to yield the same result per star within the limits of errors ; this is true regardless of the star's position in the HR-diagram. Thus average rates of mass loss $-\dot{M}$ were determined, and weights were allocated to the $\dot{M}$-determinations for each star. The $\dot{M}$-data can well be represented by one empirical interpolation formula, as a function of the effective temperature $T_{\rm eff}$ and luminosity L. An individual determination of log $(-\dot{M})$ has an intrinsic accuracy (one sigma) of ± 0.37, while the adaptation to the interpolation formula has a sigma value of ± 0.45. Hence, part of this larger spreading must be due to other causes than $T_{\rm eff}$ or L. An interesting discontinuity in the mass flux $\dot{M}/4\pi R^2$ is observed to occur near log $(L/L_\odot) = 6$ and $T_{\rm eff}$ in a broad range around 10^4 K ; it agrees roughly with the Humphreys-Davidson limit. In addition we studied some groups of other stars : *fast rotators* (22 Be-type stars), and *chemically evolved stars* (31 Wolf-Rayet stars ; 11 C- and 4 S-type stars and 15 nuclei of planetary nebulae). The chemically evolved stars have rates of mass loss which are larger than those of « normal » stars occupying the same positions in the Hertzsprung-Russell diagram, by factors : 160 for Wolf-Rayet stars ; 11 for C-type stars, and by estimated factors of 10^3 to 10^4 for the nuclei of planetary nebulae. The exess factor is 26 for the *disc areas* of Be stars, while their *high-latitude parts* behave as « normal » B stars with the same $T_{\rm eff}$ and L.

Key words : planetary nebulae — stars : Be — stars : carbon — stars : Hertzsprung-Russell diagram — stars : mass loss — stars : Wolf-Rayet.

1. Introduction.

The description of the rate of mass loss $-\dot{M}$ of a star as a function of its position in the Hertzsprung-Russell diagram is important for two reasons. Firstly, since the evolution of a star is described in terms of its tracks through the HR-diagram, the description of $-\dot{M}$ as a function of $T_{\rm eff}$ and L automatically shows the way in which the stellar mass M varies during the evolution. Secondly, the dependence of $\dot{M}$ on $T_{\rm eff}$ and L may give insight into the process(es) which are responsible for the mass loss.

Various attempts have been made to describe the mass loss rates of stars as a function of their basic parameters such as L, $T_{\rm eff}$, M, R and the surface acceleration of gravity g. For the hot stars ($T_{\rm eff} \gtrsim 10000$ K) such studies were made e.g. by Barlow and Cohen (1977), Lamers (1981), Abbott *et al.* (1981), Garmany and Conti (1984), Vardya (1984), Peppel (1984), Wilson and Dopita (1985), and Van Buren (1985). The mass loss rates of the cool stars have been described as a function of the basic parameters by Reimers (1978) ; Dupree (1986) demonstrated that this relation breaks down for luminosity I class stars. Vardya (1984) and Chiosi and Maeder (1986) listed a good dozen of such interpolation relations published by various authors. These investigations were made to compare the observed rates with predicted ones, which depend on the mass, gravity, luminosity etc. So these descriptions depend on parameters which in general cannot be directly observed (M, g, R). The knowledge of these parameters may be essential for understanding the *mechanisms* which produce the mass loss, but one drawback is that these values are not known for all stars ; hence the result depends on a small number. A second, more fundamental criticism was published by Vardya (1987). On the basis of dimensional analysis he showed that, although some of these relations are seemingly based on fundamental stellar parameters, they have no physical significance and must be considered as no more than just interpolation formulae.

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In this paper we will describe how $\dot{M}$ depends on the two most directly observable quantities : T_{eff} and L. This approach has the disadvantage that it may not give direct information on the origin of the mass loss. However it has the important advantage that it describes how $\dot{M}$ varies in the HR-diagram. If the position of a star in the HR-diagram is a unique function of its evolution, our description can give the variation of $\dot{M}$, and hence of M, over the lifetime of a star.

A first attempt to describe the variation of $\dot{M}$ in the whole HR diagram was made by one of us (de Jager, 1983). The mass loss rates were assumed to depend on T_{eff} and L only. The resulting diagram showed that most of the stars fit a general trend through the HR-diagram, but that there are groups of stars with deviating mass loss rates. These were the Wolf-Rayet stars, (strongly evolved helium-rich stars) and the Be-stars (rapidly rotating stars), and there was some suspicion with regard to Of and P Cyg stars.

The data used by De Jager (1983) were mainly based on a compilation by De Jager (1980) and are therefore at present some 8 years old. In addition the number of stars was small : the diagram contained some forty stars. Much new information has been published since, and the amount of material available presently is larger than the earlier number by at least a factor eight.

The use of the new material will enable us, first, to establish the $\dot{M}(T, L)$ relation with more certainty than before, and next to find out quantitatively to what extent chemically evolved stars, that occur at the same position of the HR-diagram as not or moderately evolved stars, deviate from the general $\dot{M}(L, T)$ relation. The available material can also be used to investigate the dependence of $\dot{M}$ on other parameters. To give an example : the dependence of mass loss on rotation is presently under investigation (Nieuwenhuijzen and De Jager, 1988a). In the same vein as the present investigation the material will easily allow us to express the rate of mass loss for O- through M-type stars as a function of L, R and M, by calculating the radius R from L and T_{eff} and by reading M from calculated evolutionary tracks such as those by Maeder and Meynet (1987). This study is also in progress (Nieuwenhuijzen and De Jager, 1988b). Another parameter is the terminal stellar wind velocity v_{∞}. Underhill (1983) remarked that v_{∞} can be different for stars with the same T_{eff}, L and M, and she remarked that this should not occur if radiation would be the chief driving agent for winds of early-type stars.

The outline of this paper is as follows. Its main part deals with a table with mass loss data of 271 O- through M-type stars of stellar population I and the discussion of this data, the establishment of the $\dot{M}(T_{\text{eff}}, L/L_{\odot})$ relation, and a discussion of the accuracy of the fitting procedure. In subsequent sections we give compilations of $\dot{M}$ data for (a) chemically evolved stars : 31 Wolf-Rayet stars, 11 C- and 4 S-stars, and 15 nuclei of planetary nebulae ; and for (b) a group of rapidly rotating stars : 22 Be stars. The compilation requires knowledge of the statistical relations between the spectral type, T_{eff} and $L/L_{\odot}$ for Mira stars and for C- and S-type stars. Such relations are established and are given in tabular form. We compare these $\dot{M}$-results with those derived for the « normal » O- through M-type stars.

Finally we give a graphical representation of the variation over the Hertzsprung-Russel diagram of the mass fluxes : $-\dot{M}/4\pi R^2$. This leads to an interesting conclusion on the location of the area of stellar atmospheric instability in the hypergiants region.

A first, preliminary version of this paper was published in the proceedings of the Porto Heli IAU symposium No. 116 (De Jager *et al.*, 1986). That paper was based on 189 stars, nearly 170 less than in the present paper. The remarks, reprints and preprints received from many colleagues after the circulation of a preprint of the Porto Heli paper greatly helped us to identify omissions in our material, and are very thankfully acknowledged.

2. Compilation of rate of mass loss for O- through M-type stars ; accuracy ; a few best studied stars.

Table I lists data for 271 stars of spectral types O through M and of population I, for which rates of mass loss have been collected from the literature. The table consists of two parts. The left-hand part gives for each star its HD designation, name, spectral type and luminosity class, effective temperature, bolometric log $(L/L_{\odot})$-value, the average (logarithmic) rate of mass loss, the squared weight of the mass loss determination and the differences between the observed and the interpolated log $(-\dot{M})$-values (see Sect. 3). The righthand part of the table gives $-\log(-\dot{M})$-values from determinations according to six different methods. In that part of the table the designations mean :

- U : from ultraviolet spectra, mainly from far UV resonance line profiles ;
- V : from spectral lines in the visual and near ultraviolet spectral ranges, mainly subordinate lines such as H_{α}, but in some cases also from other lines, including the H and K lines ;
- I : from broad-band infrared photometric data, assuming the flux to be due to free-free emission ;
- C : from infrared data on C-molecular compounds ;
- M : from maser lines in the microwave range ;
- R : from radio continuum data : radiofluxes due to free-free emission, i.e. excluding data of stars for which the radio emission is assumed to be synchrotron radiation (cf. e.g. Underhill, 1984a).

In certain cases the same observational data have been discussed by various authors using basically the same method but with other choices of certain parameters. For example, the rate of mass loss derived from infrared (I) or radio (R) observations depends on the assumed value for the asymptotic velocity v_{∞} of the stellar wind. Initial values for $\dot{M}$ based on a first assumption of v_{∞} are sometimes superseded by more modern $\dot{M}$-values when new v_{∞}-values became known. In such cases we took the latest value ; for these data our list of references (numbers, referring to the reference list) only shows the latest reference. A similar problem arises with the analysis of optical spectra of cool non-binary stars, where a value for the inner shell radius has to be assumed to derive mass loss rates from circumstellar lines. Such values, though apparently not independent, have yet been included in table I (cf. Refs [46], [51] and [116] — with thanks to D. Reimers for this point). Some of the older $\dot{M}$-values have been published in reviewing compilations where average values have been taken over a number of earlier determinations. In such cases we have referred to these reviews and not to the earlier studies. In practice this has only been done for observations from before IUE ($\lesssim 1979$), a spacecraft that contributed so much to modern $\dot{M}$-determinations.

If more than one publication gives log $(-\dot{M})$-values derived independently by different authors according the the *same* method (cf. our above grouping in six methods) but using other observational data, the straight average of such log $(-\dot{M})$ determinations is given in the relevant column of the table, together with references to the various individual determinations (numbers).

The determination of effective temperature and luminosity was done as follows. There are two sources : first the T_{eff} and L values as communicated for the relevant stars in the various individual publications — we call these the *individual determinations* ; next, a recently determined *statistical relation* between on the one hand spectral type and luminosity class, and on the other hand T_{eff} and $L/L_{\odot}$ (De Jager and Nieuwenhuijzen, 1987). References to the « individual determinations » are given in the columns REFS. In order to obtain the final T_{eff} and $L/L_{\odot}$-values we took in all cases the mean of all individual determinations of T_{eff}, resp. log $(L/L_{\odot})$ (each being given unit weight), *and* of the values derived from the statistical relation of De Jager and Nieuwenhuijzen. The data from that latter relation got as a rule also weight unity. An exception is made for the late spectral types for which the statistical relations are less well known in certain specified spectral ranges (indicated in the mentioned paper). In the averaging process *these* log T_{eff} and log L values got weight one-half. The mean values of log T_{eff} and log $(L/L_{\odot})$ thus determined are given in columns 5 and 7 of the table. For those stars for which data on spectral type or luminosity class did not exist and for stars with peculiar (p) spectral designation, no use could be made of the De Jager-Nieuwenhuijzen relation ; hence in these cases only the individual determinations of T_{eff} and log $(L/L_{\odot})$ were used, and, as described above, they were averaged if more than one determination was available.

The Mira stars require some more attention. For these objects a relation between average spectral type (M1 through M8) and average effective temperature and bolometric luminosity was derived on the basis of data published by Scalo (1976) and those from other authors, summarized by De Jager (1980, Table XXV). The relations thus derived, are given in table II.

The mass loss data collected in table I allow us firstly to determine the *intrinsic accuracy* of the mass loss-values. Such a determination should be based on a number of comparisons of rates of mass loss obtained for one and the same star by *different methods*. A comparison of data obtained for the same star by the *same methods* or by using the same kind of data (e.g. by only using ultra-violet resonance line profiles) but made by *different authors* cannot be considered as truly independent and such determinations are therefore not suitable for this goal for two possible reasons : the basic material may be the same, or the technique for determining $\dot{M}$ from the observations is the same or analogous.

In order to obtain a reliable measure for the intrinsic accuracy of the various $\dot{M}$-determinations we selected all stars for which $\dot{M}$ determinations are available from at least three *different* methods (cf. the right-hand part of Tab. I). For each of these stars we determined the average rate of mass loss, $\langle \log(-\dot{M}) \rangle$, as well as the deviations Δ from the average :

$$\Delta = \log(-\dot{M}) - \langle \log(-\dot{M}) \rangle$$

for the data derived according to the $\geqslant 3$ various methods. We thus obtained 106 Δ-values, from which a one sigma value

$$\sigma_{\Delta} = 0.37 \pm 0.03$$

was derived. This value is hence the average intrinsic sigma-value *per determination*. This result also means that a value for the rate of mass loss based on determinations by three different methods has an average sigma value of 0.26 ($= \sigma_{\Delta}/\sqrt{2}$), by four methods of 0.21 and by five methods of 0.18.

Here we wish to draw attention to a few very well studied stars, for which $\dot{M}$ has been determined on the basis of good data, by various authors, and by at least four different methods. For these few « prime objects » the differences between the $\dot{M}$-values according to the various methods appear to be small, and the intrinsic accuracy of the resulting average $\dot{M}$-value is therefore good, of the order of ± 0.04 to ± 0.08 (logarithmically) for four of the five objects. We have listed these stars in table III.

The determination of the average rate of mass loss for each of the various stars thereupon proceeded in several steps. The first four steps (A, B, C and D in the following) are devoted to a search for systematic differences between the results for different methods, and to a determination of their relative accuracies.

A. For each star we determined the straight mean of $-\log(-\dot{M})$ from the available data in the right-hand part of the table. These straight means are given in column 9 of table I. A different procedure was followed for a few stars for which we either felt that the values in the second part of table I are not reliable enough, or for which an average well-determined rate of mass loss does already exist in literature data, as a result of a thorough discussion of the material available for that particular star. These stars are objects numbered in table I : 109 : η Car, 111 : AF And and 145 : P Cyg. For these three stars these values of $-\log(-\dot{M})$ and references to the determination of $\log(-\dot{M})$ are given in the column « average $-\log(-\dot{M})$» (the numbers refer to the list of references at the end of this paper).

B. Since the average value of $\log(-\dot{M})$ (cf. column 9) is in all other cases assumed to be the straight mean of the values obtained from the different methods of determination, it makes sense to verify that assumption. This was done by examining if there are systematic differences between the results obtained by the various methods. To that end we first established a numerical interpolation model of the whole data set by representing them by an analytical expression. In a first discussion of part of the material (De Jager *et al.*, 1986) we took for the analytical expression a sum of power polynomials and their cross-products. Since that time we experienced that a better representation, without risk for large deviations at the ends of the ranges, is obtained by writing $\dot{M}(T_{\mathrm{eff}}, L)$ as a sum of Chebychev polynomials $T_n(x)$ of the first kind, and of their cross products :

$$-\log(-\dot{M}) = \sum_{n=0}^{N} \sum_{\substack{i=0 \\ j=n-i}}^{i=n} a_{ij}\, T_i(\log T_{\mathrm{eff}}) \times \times T_j\left(\log\left(\frac{L}{L_\odot}\right)\right). \quad (1)$$

C. The whole available material on mass loss rates was thus written in the form (1). It appeared that a 10-term representation, with $N = 3$ was sufficient for *this first* approximation.

Thereupon we considered again the mass loss rates determined according to the six different methods, as listes in the second part of table I. For these values we determined the residuals

$$D = -\log(-\dot{M})_{\mathrm{obs}} + \log(-\dot{M})_{\mathrm{mod}} \quad (2)$$

where the suffixes *obs* and *mod* refer to the observed average data (column 9 of Tab. I) and the numerical model of equation (1), respectively. We did this to find out if systematic differences exist between the average D values as determined by the up to six different methods. To that end we first determined for each of the six methods their average D values and their corresponding one-sigma-values. The results are given in the upper part of table IV. In this table n is the number of D-values used ; $\langle D \rangle$ the average value, s the sigma-value per communicated D-value, and σ the sigma-value of $\langle D \rangle$. Note that a positive value of D means that the observed mass loss is smaller than the value according to the interpolation model. From this table we learn that the average D-values are zero within the 3 sigma range for five of the six methods, the exception being the values derived from maser lines (M).

Since we have the feeling that the R-values are the easiest to interprete and suffer perhaps least from systematic errors, our preliminary conclusion is that the U, V, I, C and R determinations are free from systematic errors within the accuracy of measurements. For the M-determinations $\langle D \rangle = -0.69 \pm 0.20$, hence $\langle D \rangle$ just exceeds the (fairly arbitrary) 3 sigma limit. The question then arises if it would be allowable or advisable to « correct » the M-determinations for an apparent scale-deviation of 0.69. Before we decide on this matter we have to investigate if and how D varies over the Hertzsprung-Russel diagram, and particularly : what is the reason for the deviating result from Maser (M) observations.

D. To obtain a better insight in the question whether systematic differences exist between results of the various methods, and also in order to examine if the interpolation formula (1) fits the observations over the *whole* ($\log T_{\mathrm{eff}}$; $\log(L/L_\odot)$)-range we split the ($\log T_{\mathrm{eff}}$; $\log(L/L_\odot)$)-area in six sub-areas, viz. three temperature ranges : $\log T_{\mathrm{eff}} \geqslant 4.5$; $4.5 > \log T_{\mathrm{eff}} \geqslant 4.0$; $\log T_{\mathrm{eff}} < 4.0$, and two brightness ranges, namely, for $\log T_{\mathrm{eff}} \geqslant 4.5$: luminosity classes I$^+$, I, II, II-III ; and luminosity classes III, IV, V, and VI ; for $\log T_{\mathrm{eff}} < 4.5$: $\log(L/L_\odot)$ either $\geqslant 5.0$ or <5.0. For each of these six sub-areas and for each of the six methods (hence : 36 subgroups) we determined the average deviation (according to formule (2)), and the sigma value of that average. These results are shown in the second part of table IV. For those of the 36 subgroups for which the result was based on less than 5 stars no data are communicated. In the second part of table IV we write T for T_{eff}, and the notation $b \geqslant 3$ means luminosity class III, IV, V or VI (for the b-notation cf. De Jager and Nieuwenhuijzen, 1987). Inspection of table IV.B shows that deviations that are apparently significant occur only for the I and R measurements in the high T, high L group. In all other subdomains no method yields significant non-zero D-values. Also the maser (M) determinations do not really behave differently : the larger scatter shown in table IV.A appears to be due to only three stars in various subdomains. This result, combined with that for the material as a whole (Tab. IV.A) and interpreted with a conservative attitude leads us to *conclude* that there are, at least in the present material, no significant non-zero D-values for *any* of the six methods in the various subgroups. We therefore have decided not to apply systematic scale corrections to any of the data sets. Since, furthermore, none of the methods used, not even the Carbon compound (C)-method, (for which s was initially found to be larger than that of the other methods) shows sigma values that are significantly deviating from the average, we also decided to give the same weight to rates of mass loss determined according to any of the six various methods ; a remarkable and *a priori* unexpected result !

In this process we found a few stars with D-values larger than 2.0, hence with rates of mass loss deviating from the mathematical model values by more than 4 sigma. Since there is a very small statistical probability for the occurrence of such large deviations in our relatively small data set, this was a reason to re-examine these stars, and if but only if we found that there were causes for their exceptional behaviour, we excluded them from the further discussions, because for the present study we are interested in the average, statistical behaviour. The same was done for stars for which we knew *a priori* that they were deviating. In three cases we did not exclude *all* data for certain stars, but we excluded certain measurements : there are a few early-type stars for which the radio-emission is assumed to be due to the synchrotron mechanism, while yet the observational data have been interpreted with the theory of the bremsstrahlung mechanism. Such specific data were excluded.

The stars for which data have been fully or partly excluded from the present discussion are listed in table V. In addition we excluded a few super- and hypergiants discussed by Hagen *et al.* (Ref. [51]) because we are not sure of their accuracy.

3. Mathematical representation of the mass-loss data.

After the preliminary explorations described in section 2 it is now possible to use the data of table I for establishing the functional relation between log $(-\dot{M})$, log (T_{eff}) and log $(L/L_{\odot})$. Before doing so, *weights w* were allocated to each of the log $(-\dot{M})$ data, cf. the tenth column of table I. We choose w^2 equal to the number of methods used in deriving the average value, as can be read from the second part of table I. Hence $1 \leqslant w^2 \leqslant 6$, from that point of view. For the « well studied stars » listed in table III we choose $w = 0.37/\sigma$, where σ is the value given in the last column of table III, and 0.37 is the average sigma-value per log $(-\dot{M})$-determination, as derived in the previous section.

In addition there are a few stars with lesser weight : η Car (star no. 109), for which we feel that $\dot{M}$ is only known to a factor of ten, thus got a weight $w = 0.37$; hence $w^2 = 0.15$. The same small weight was given to α Cyg (star no. 197), a well-studied star, for which, however, individual authors publish rates of mass loss spreading over a few factors of ten.

In a first phase of the analysis, the material, first still with unit weight for all data, was subjected to an analysis according to equation (1) in which it was attempted to minimize chi-squared with respect to the searched model. We obtained for the sigma-value for a determination of weight unity :

for a 20-terms representation : $\sigma = 0.496$;
for 40-terms : $\sigma = 0.480$;
for 60-terms : $\sigma = 0.463$.

From this we learn that there is no substantial improvement reached by increasing the number of terms beyond about 20. This result also suggests (by extrapolation) that the σ-value for a « large » number of terms (e.g. 80 or 100) will be smaller than that for a 20-terms representation by an estimated amount of about 0.05.

We wish to stress at this point that this sigma-value, derived for stars in the *whole* upper part of the Hertzsprung-Russell diagram is fully comparable to the values derived by others using material from *subdomains* of the HR-diagram : e.g. Peppel (1984) finds from a study of 22 OB stars : $\Delta \log (-\dot{M}) = \pm 0.5$.

In the final phase of our research the material was therefore subjected to a 20-terms analysis with the weights included, as described above, and given in the tenth column of table I. For this representation we found a sigma value per unit weight of 0.499. Following again the previous result we estimate that for a representation with a « large » number of terms the sigma value per unit weight will be about 0.45.

This value should subsequently be compared with the intrinsic sigma-value per observational determination (hence per unit weight), the being 0.37 (cf. Sect. 2). This shows the satisfactory result that the $\dot{M}(T, L)$-representation accounts for the major part of the $\dot{M}$-dependence, but that a certain fraction of the deviations, with sigma approximately 0.26 $(= (0.45^2 - 0.37^2)^{1/2})$ must be due to other causes, such as discussed in section 1. We reserve a discussion of these secondary causes to later investigations.

The constants a_{ij} for the 20-terms case are given in table VI, and the representation of mass-loss data is given in figure 1. The data have been normalized to the intervals : $\log T_{\mathrm{eff}} = 3.3$ to 4.8, and $\log (L/L_{\odot}) =$ 2.5 to 6.7. Hence the constant term a_{00} corresponds to the interpolated value of $-\log(-\dot{M})$ at $\log T_{\mathrm{eff}} = 4.05$ and $\log(L/L_{\odot}) = 4.6$.

For practical applications the expression (1) should therefore read :

$$-\log(-\dot{M}) = \sum_{n=0}^{N} \sum_{\substack{i=0 \\ j=n-i}}^{i=n} a_{ij}\, T_i\left[\frac{\log T_{\mathrm{eff}} - 4.05}{0.75}\right] \times T_j\left[\frac{\log(L/L) - 4.6}{2.1}\right]$$

with the customary definition :

$$T_j(x) = \cos(j \arccos x) .$$

At this stage we have to judge the quality of the analytical numerical adaption. To that end we give in figures 2 (*A*, *B*, *C*, *D*) plots of *D*-values, derived according to equation (2), against $\log T_{\mathrm{eff}}$, for the whole material as well as for three subsets of the data : those with $-\log(-\dot{M})$ between 4.5 and 5.5, between 5.5 and 6.5, and those between 6.5 and 7.5. For values outside this range the number of *D*-values available is too small for a useful subset representation. This figure shows again the gratifying result that in all ranges the scatter of the data points around the zero line is random without clear systematic effects. Finally, figure 3 gives histograms of *D*-values for the four $\dot{M}$-ranges of figure 2.

The representation in figures 2 and 3 show that our adaption of rates of mass loss by Chebychev polynomia of the first kind is useful and satisfactory.

We refrain from a detailed comparison of our relation with the various interpolation formulae derived by different authors for subdomains of the HR diagram, such as the relations for OB stars, those for cool stars, etc., referred to in the 2nd paragraph of the introduction of this paper. A few remarks may suffice :

1. As stated before, the accuracy of our adaption ($\sigma \approx 0.45$ to 0.50 over the whole HR diagram) is about equal to the accuracy (≈ 0.5) derived by others for the subdomain relations.

2. Many of the interpolation relations so far published for OB stars give $\dot{M}$ as a function of only L. But figure 1 shows that there is also a T_{eff}-dependence (which is equivalent to a radius (R)-dependence).

3. Waldron (1984) is the only author who also derived a relation for the whole HR-diagram : $\log(-\dot{M}) = 1.07 \log(L/L_{\odot}) + 1.77 \log(R/R_{\odot}) - 14.3$, which transforms into :

$$\log(-\dot{M}) = 1.955 \log(L/L_{\odot}) - 3.54 \log(T_{\mathrm{eff}}) - 0.99 ,$$

which is a linear relation in $\log L$ and $\log T_{\mathrm{eff}}$.

Our relation (1), reduced to the linear approximation, would read (cf. Tab. VI) :

$$\log(-\dot{M}) = 1.769 \log(L/L_{\odot}) - 1.676 \log(T_{\mathrm{eff}}) - 8.158 .$$

To show the differences : at our « central point » $\log T_{\mathrm{eff}} = 4.05$, $\log(L/L_{\odot}) = 4.6$, Waldron gives $\log(-\dot{M}) = -6.33$, while we find -6.81. The $\log(-\dot{M})$-value of the linear terms of the Chebychef approximation gives here -6.14. These differences are noticable. Waldron's expression, applied to our whole set of observation's yields a sigma-value per unit weight, roughly 2.4 times our value. This reflects only in part the influence of the higher order terms, neglected in Waldron's approach ; for the larger part the difference is due to the greater extension of our material as compared to Waldron's.

4. Despite the fact that different mass-loss mechanisms may be operative in different parts of the HR-diagram (e.g. radiation-driven for hot stars, shock-driven for Mira stars, ... etc.) one single $\dot{M}(T_{\mathrm{eff}}, L)$ relation appears to be sufficient for a description of mass loss over the whole upper HR-diagram.

5. We draw attention to the region of the coolest stars, where the $\dot{M}$-value is virtually independent of luminosity in the $\log(L/L_{\odot})$-range of 3.5 to 5.0.

4. Mass fluxes.

With the data from figure 1 it is an easy matter to calculate the mass fluxes $\dot{m}/4\pi R^2$, in actual practice $\dot{m}/R^2$. This can only be done if one assumes spherically symmetric winds. This is not true for all stars — a clear case being the Be-type stars, which we did not include in the present discussion. Figure 4 shows such data, where R is expressed in solar units. Physically, this diagram is more interesting than figure 1 because it is closer linked to the explanation of the process of mass loss.

There are two interesting regions in this diagram. One is situated near $\log(L/L_{\odot}) = 6$ and at temperatures around 10^4 K. In a later paper we wish to deal with the physical consequences of this result. We note that this region coincides with the Humphreys-Davidson upper limit of stellar luminosity (see the lines drawn in Figs. 1 and 4). The other region occurs at $\log T_{\mathrm{eff}} \approx 3.5$ and $\log(L/L_{\odot})$ 3 to 5 ; there the lines of constant mass flux can hardly be drawn or not at all in the existing material ; the numerical model seems to show an instability in that region or we have to conclude that in a large part of that area the mass flux is indeed independent of luminosity.

In general, the diagram shows that the mass flux increases with increasing L, as well as with increasing T_{eff}. (The total rate of mass loss, though, decreases with increasing T_{eff}, because of the decreasing stellar radius).

It is also noted that the hot subdwarfs fit well in this general pattern.

5. Chemically evolved stars ; the Wolf-Rayet stars.

For certain groups of (mostly evolved) stars we know, already for a long time, that their rates of mass loss deviate from the average. Among these are the Wolf-Rayet stars. We are now in a position to give quantitative data for the deviations.

The 31 Wolf-Rayet stars for which rates of mass loss are known are given in table VII. Here the various columns have the following meaning : column 2-4 : number in the Catalogue of Van der Hucht *et al.* (1981), HD number, and spectral type ; column 6 gives the logarithmic rate of mass loss $-\log(-\dot{M})$ based on radio data and velocity data from Abbott *et al.* (1986), the distances given by Hidayat *et al.* (1986), and ionisation calculations by Van der Hucht *et al.* (1986). The values between parentheses are based on the 6 cm flux estimates as compiled by Willis (1982).

The stellar luminosities (column 7) are observed values taken from Barlow *et al.* (1981), if necessary corrected for the distances (Hidayat *et al.*, 1986).

The effective temperature T_{eff} is the most uncertain factor. Tentatively we adopted the values given in the fifth column, on the basis of the relation between spectral type and T_{eff} given by Schmutz (1982). We note that some authors (e.g. Pauldrach *et al.*, 1985) argue that T_{eff} and L may be well higher than these values, but arguments for the validity of the lower temperatures adopted by us are given by Van der Hucht *et al.* (1986)

and Schmutz and Haman (1986). Underhill (1986) argues for even lower temperatures than those adopted here.

Figure 5 gives the positions and rates of mass loss of the WR stars in the Hertzsprung-Russell diagram (along with those of other deviating groups of objects, to be discussed in the subsequent Sections of this paper). A comparison of the $\dot{M}$-values with the interpolation lines confirms the well-known fact that Wolf-Rayet stars have a larger rate of mass loss than the normal O-type stars of similar effective temperatures and luminosities. This fact is shown quantitatively by producing a histogram (Fig. 6A) of D-values (defined in Eq. (2)).

From the histogram it appears that the WR stars group together. For the stars listed in table VII we find :

— for the average :

$$-D = \log(-\dot{M})_{\mathrm{obs}} - \log(-\dot{M})_{\mathrm{calc}} = 2.20 \pm 0.11 ;$$

— for the individual determinations :

$$\sigma = 0.45 .$$

6. Chemically evolved stars : the C- and S-type stars.

In order to be able to discuss these two groups of stars one needs to have a relation between spectral type, absolute luminosity and temperature for them. Such a relation is not known for the S-type stars, but we derived one for the C-stars. This was done on the basis of work by Mikami (1975), Scalo (1976), a compilation by De Jager (1980, Fig. 40, tables XXII and XXIII), and a paper by Lucy *et al.* (1985). The resulting relations are given in table VIII.

For the few S stars we assumed — for lack of better data — the relation for Mira's, table II.

The rates of mass loss for 11 C- and 4 S-type stars are given in table IX. To compare these rates of mass loss with those for the « normal » stars, for which the values are given in table I and figure 1, we have plotted the rates of mass loss of these two groups of stars in figure 5. Figure 6B gives the histogram of deviations D (according to Eq. (2)), only for the C-stars. One star could not be used because its luminosity was outside the region of validity of the interpolation formula. It appears that the scattering of the D-values is considerable ; yet the average deviation can be defined, and is -1.04 ± 0.22, meaning that the mass loss rate for C stars is about ten times the value for « normal » late type stars of the same luminosity and effective temperature. The one-sigma-value of an individual determination is 0.71. The large spread of the D-values is remarkable in view of the fact that the C-stars form a very homogeneous population (Knapp, 1985), all having progenitor masses of about $2\, M_{\odot}$.

From the S-type stars one could not be used, because the L-value is outside the region of validity of the interpolation formula. For the three remaining S type stars, $D = -0.54 \pm 0.81$, which is not significant. The large standard deviation, being 1.41, may for a part be due to the uncertainty in the temperatures adopted.

7. Rapid rotators : the Be- and shell-stars.

It is not always evident if a star belongs to this category : many authors believe that the Be characteristics may be transient. Stars without clear conventional Be characteristics (H emission lines) but with shells may be « quiescent Be stars ». Our final choice of stars included in the list has been influenced by remarks from colleagues on the basis of preprints of this paper. The present results therefore deviate somewhat from those given in the preprints and in De Jager *et al.* (1986).

The rates of mass loss for Be- and shell-type stars are given in table X, which has the same lay-out as table I. This table shows the interesting observation, noted earlier by Lamers and Waters (1986), that the rates of mass loss derived from ultraviolet resonance lines are by factors between 10 and 100 smaller than those derived from the infrared continuum intensities. Lamers and Waters (1987) explain this difference by the disc model initially proposed by Marlborough *et al.* (1978) and by Poeckert (1982). In that model the UV lines are formed in the high-latitude and polar regions of the star, and the infrared continua in a dense equatorial disc with strong mass loss.

Whatever the explanation be, it is clear that the two groups of data have to be dealt with separately. Therefore we calculated D values for $\log(-\dot{M})$, as defined in equation (2), both for the $\dot{M}$-values from the UV observations (U) as well as for those derived from the infrared continuum (I). Not all data from table X can be used for this comparison because for some stars the L-values are outside the region of validity of the interpolation formula (1). The resulting histograms for the remaining 16 (U) and 9 (I) stars are shown in figures 6C and 6D respectively. From this we see that the rate of mass loss derived from the ultraviolet observations is somewhat smaller than the rate for normal B-type stars. Actually, we found for the UV data the average value

$$-D = -0.61 \pm 0.16 ,$$

with an individual sigma value of 0.64. In contrast, the $\dot{M}$-values derived from infrared continuum observations (ascribed to the disc) are much larger than those for normal B-type stars :

$$-D = +1.42 \pm 0.25$$

with an individual sigma-value of 0.74.

Hence the essential difference between a Be (or shell-type) star and a normal B-type stars is the presence of the disc, with its excessive infrared radiation and corresponding large rate of mass loss. The data derived from the UV resonance lines, and attributed in Lamers and Waters's model to the high latitude parts of the stars, do only deviate by a factor four from those valid for non-Be stars with the same T_{eff}- and L-values. It should be noted that, since we were not able to use all stars from the available material, the given average D-values are to be taken with caution.

8. Chemically evolved stars : the nuclei of planetary nebulae.

For the sake of completeness we give in table XI a compilation of rates of mass loss for the nuclei of planetery nebulae, while the log $(-\dot{M})$-values are also shown in figure 5. A comparison with the interpolated values for normal Population I stars (the lines in Fig. 5) is hardly possible, or not all, because the nuclei of planetary nebulae fall outside the range of validity of the interpolation model.

Yet it is clear that the $\dot{M}$-values for the PN-nuclei tend to be much larger, by factors of the order 10^3 to 10^4 than the values that would be expected from extrapolation of the data for normal stars. Hence the conclusion seems justified that nuclei of planetary nebulae have rates of mass loss, much larger than those one would expect for Population I stars of similar T_{eff}- and L-values. This effect was mentioned already by Cerruti-Sola and Perinotto (1985), who remarked that an extrapolation of Abbott's one-parameter relationship $\dot{M} \sim L^{1.77}$ would result in underestimating mass loss rates for nuclei of planetary nebulae. The physical causes underlying the mass loss mechanisms for PNN must therefore be very different from those of Population I stars.

9. Conclusions.

We find that it is possible to represent the rate of mass loss of Population I O- through M-type stars by a function depending only on T_{eff} and L of the stars. The adaptation has a logarithmic sigma value of ± 0.45 to ± 0.50, while individual determinations of the logarithmic rate of mass loss have a sigma-value of ± 0.37 which is hence slightly smaller. This shows that $\dot{M}$ depends for the larger part on T_{eff} and L, but that there are small additional effects influencing the rate of mass loss.

For stars of the same luminosity $\dot{M}$ generally increases with decreasing T_{eff}, but the opposite is true for the mass flux $\dot{M}/R^2$.

Certain groups of stars do not comply with this general behaviour. These are the chemically evolved stars ; they have all a rate of mass loss far exceeding the $\dot{M}$-value for « normal » population I type stars of the same T_{eff} and L. We find for the differences

$$-D = \log(-\dot{M})_{\text{observed}} - \log(-\dot{M})_{\text{pop I stars}}$$

the following values :

— for the Wolf-Rayet stars : 2.20 ± 0.11,
— for the C-type stars : 1.04 ± 0.22,
— for the nuclei of planetary nebulae : 3 to 4 (estimated, by extrapolation).

The Be and shell-stars show an interesting feature : the $\dot{M}$-values derived from ultraviolet observations, and attributed — in a certain model — to gas originating from the high-latitude area of the star, are by a factor four smaller than the values for « normal » stars of the same T_{eff} and L, whereas the $\dot{M}$-values from the infrared continuum observations (ascribed to an equatorial disc) are logarithmically larger by 1.42 ± 0.25. Apparently, what makes a Be star differ from a normal star, is the presence of its disc, with its large local rate of mass loss.

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TABLE I. — *Rates of mass-loss from O- through M-type stars. The left-hand part of the table summarizes, while the right-hand part gives values of* $-\log(-\dot{M})$ *from six different methods. Column 9 gives the average negative logarithmic rate of mass loss (see also text), column 10 the squared weights of these values, and column 11 gives observed minus calculated values of* $-\log(-\dot{M})$. *Hence when O-C is positive the observed rate of mass loss is smaller than the calculated one. The REFS refer to the list of references at the end of the paper (1 through 153) ; underlined numbers between brackets (1 through 15) refer to notes at the end of this table.*

NR	HD	NAME	SPECTR	T_{eff}	REFS	log $L/L_\odot$	REFS	AVERAGE $-\log(-\dot{M})$	w^2	O-C
1		Cyg OB2; 7	O3 If	49100	1,25,143	6.27	1,25,87,135, 143	4.90	3	- 0.13
2	93129 A		O3 f	48500	25,123	6.37	25,65,123,139	4.84	2	+ 0.16
3	93250		O3 V((f))	52300	25,123,139	6.27	25,123,139	5.90	1	+ 0.62
4	49798		sdO	47500	143	3.95	143	8.65	1	+ 0.41
5	66811	ζ Pup	O4 Ief	40900	25,41,77,101 144,153	5.96	25,41,49,65 139,144	5.325	70	- 0.03
6	15570		O4 If$^+$	43200	3,90,103,106	6.15	90,103,139	4.925	19	- 0.09
7	190429A		O4 f	40700	106,139	5.95	139	5.58	2	+ 0.21
8		NGC 6530; 7	O4	39000	10	6.02	10	6.02	1	+ 0.89
9	242908		O4 V(n)	46000	39,103	5.81	39,103	5.91	2	- 0.14
10	164794	9 Sgr	O4 V((f))	45300	1,3,41,139, 144	6.03	1,41,144	5.52	1	+ 0.07
11	168076		O4 ((f))	45300		5.90		5.22	1	- 0.56
12	128220 B		sdO	45000	49	3.34	49	9.70	1	- 0.11
13	46223		O4.5 V(f)	43500		5.85	65	7.00	1	+ 1.23
14	16691		O5 If	40200	106,139	5.84	106	4.98	3	- 0.61
15	14947		O5 If$^+$	39300	103,106,139	5.95	65,103,139	5.26	2	- 0.04
16		Cyg OB2; 9	O5 If	43100	1,3,87,106, 144	6.34	1,66,87,106, 144	4.94	2	+ 0.44
17		Cyg OB2; 11	O5 If	40600	66,144	6.12	1,66,87,144	5.10	2	+ 0.14
18	15629		O5 f	41000	90	6.06	90	5.78	1	+ 0.65
19		Cyg OB2; 8C	O5 IIIf	43800	87	5.98	87	5.40	2	- 0.08
20	15558		O5 III(f)	41700	3,90,103,106 139	6.02	1,90,103,139	5.43	3	+ 0.17
21		Cyg OB2; 8D	O9 (1)	32700	143	5.02	87,143	---- (1)	-	- 1.65
22	193682		O5 V((f))	42600	103	5.75	103	5.64	1	- 0.29
23		Cyg OB2; 22	O5:	42000	66,144	6.09	66,87,144	5.41	2	+ 0.31
24	228766		O5.5 f	39700		6.03		5.00	1	- 0.14
25	46150(2)		O5.5 ((f))	42600		5.65		5.96	2	- 0.18
26	150958		O6 Iaf	37800		5.93	65	5.19	1	- 0.09
27	210839	λ Cep	O6 Ief	38400	3,106,144	5.97	1,65,87,106 144	5.39	3	+ 0.17
28		Cyg OB2; 8A	O6 Iab(f)	38900	1,3,87,106,144	6.11	1,66,87,106, 144	4.98	2	+ 0.06
29		Cyg OB2; E	O6 f	38800	66,144	6.02	66,87,144	5.47	2	+ 0.35
30	153919		O6 f	38500		6.07	65	4.82	1	- 0.18
31	152233		O6 III(f)	37500	139	5.74	139	5.49	2	- 0.18
32	199579		O6 Ve((f))	38800	41,139,144	5.41	41,139,144	5.87	1	- 0.49
33	101190		O6 V((f))	40600	139	5.54	65,139	6.55	2	+ 0.32
34		- 59.2600	O6 V((f))	38300	139	5.63	139	5.60	1	- 0.33
35		+ 24.3881	O6 V((f))	39200	103	5.50	103	5.74	1	- 0.48
36		+ 60.0497	O6 Vn	39200	90	5.54	90	6.19	1	+ 0.04
37	163758		O6.5 Iaf	36400	139	5.95	139	5.49	1	+ 0.30
38	191612		O6.5 Ifpe	37700	103	5.78	103	5.51	1	- 0.08

TABLE I (*continued*).

	U	REFS	V	REFS	I	REFS	C	REFS	M	REFS	R	REFS
1			5.09	66	4.89	87					4.72	1,2
2	4.80	21	4.89	83								
3	5.90	40										
4	8.65	49										
5	5.32	41,49,83,100	5.22	41,65,101	5.33	41,101					5.43	101
6	5.07	25,90	4.72	25,72,83,103	4.85	106					5.06	3
7	5.03	83	5.26	21	> 6.46	106						
8	6.02	10										
9	6.10	39	5.72	103								
10	5.52	21,41									4.51	1,3
11			5.22	25								
12	9.70	49										
13			7.00	65								
14	5.10	21	5.11	83	4.74	106						
15	5.40	40	5.12	65,72,104								
16			5.17	66,87	4.71	87,106					4.72	2
17			5.40	66	4.80	87						
18	5.78	90										
19			5.39	87	5.40	87						
20	5.58	21,90	6.00	103	> 6.52	106					4.72	3
21			5.10	66 (1)	> 6.00	87						
22			5.64	103								
23			5.70	66	5.12	87						
24			5.00	25								
25	6.10	40	5.82	65								
26			5.19	65								
27	5.40	40	5.52	25,65	5.24	87,106					> 5.30	3
28			5.28	66,87	4.67	87,106					4.49	1,3
29			6.00	66	4.94	87						
30			4.82	25,65								
31	5.55	21,40	5.43	72								
32	5.87	41										
33	6.10	40	7.00	65								
34	5.60	40										
35			5.74	103								
36	6.19	90										
37	5.49	40										
38			5.51	103								

TABLE I (continued).

NR	HD	NAME	SPECTR	T_{eff}	REFS	log $L/L_{\odot}$	REFS	AVERAGE $-\log(-\dot{M})$	w^2	O-C
39	12993		O6.5 V	39200	39	5.28	39	6.60	1	+ 0.00
40	42088		O6.5 V	39200	139	5.26	139	6.90	1	+ 0.27
41	48099		O6.5 V	39100	139,144	5.46	139,144	6.98	2	+ 0.69
42	152723		O6.5 V	39200	39	5.54	39	6.10	1	- 0.05
43		+ 60.0501	O6.5 V	37800	90	5.24	90	6.72	1	+ 0.13
44	108		O7 Ifpe	36200	34,103,106	5.92	34,65,103,106	4.40	2	- 0.84
45		Cyg OB2; 5	O7 If	37600	1,3,87,106	6.13	1,66,87,106	4.69	3	- 0.14
46	148937		O7 f	36200		5.94		5.10	1	- 0.10
47	192639		O7 Ib(f)	35900	103	5.81	103	5.57	1	+ 0.11
48	193514		O7 Ib(f)	35900	103	5.81	103	5.50	1	+ 0.04
49	167659		O7 II	35900		5.79		5.50	1	+ 0.00
50		Cyg OB2; 4	O7 III(f)	36200	66,144	5.47	66,87,144	5.40	2	- 0.72
51	93222		O7 III((f))	36600	139	5.46	139	6.30	1	+ 0.14
52	54662		O7 IV	36200	139,144	5.42	139,144	6.70	1	+ 0.49
53	152623		O7 V((f))	38000	39	5.53	39	6.30	1	+ 0.20
54		- 59.2603	O7 V((f))	37900	139	5.28	139	7.20	1	+ 0.67
55		+ 60.0513	O7 Vn	36900	90	5.24	90	6.56	1	+ 0.01
56	217086		O7 Vn	37500		5.34		6.38	1	- 0.03
57	152590		O7 V	38000	39	5.21	39	7.40	1	+ 0.75
58	159176		O7 V	38200	144	5.30	144	6.70	1	+ 0.19
59	35619		O7 V	38000	39	5.45	39	7.30	1	+ 1.05
60		NGC 6530; 118	O7 V	38200	10	5.51	10	5.70	1	- 0.45
61	13268		O7	38500	39	5.32	39	6.40	1	- 0.10
62		Cyg OB2; 24	O7:	36000	144	5.31	87,144	5.52	1	- 0.87
63	57060	UW (29) CMa	O7.5 Iaf	36900	31,144	5.86	65,144	5.35	2	- 0.04
64	135591		O7.5 III(f)	35400	144	5.46	144	6.81	2	+ 0.70
65	24912	ξ Per	O7.5 III((f))	35000	41,144	5.34	41	5.77	1	- 0.53
66	47839	S (15) Mon	O7.5 IV((f))	35300	41,100,101, 139,144	5.22	41,65,139,144	6.72	2	+ 0.21
67	47129		O7.5 IV f	35000	106,144	5.37	25,106,144	5.07	2	- 1.18
68		Cyg OB2; 8B	O7.5	35700	66,103,144	5.58	66,103,144	5.45	2	- 0.45
69	160641			35000	50	4.00	50	8.10	1	- 0.31
70	151804		O8 Iaf	33900	143	5.98	65,143,144	5.04	3	- 0.01
71	152408		O8 Iaf	33900	139,144	5.98	65,139,144	4.70	3	- 0.35
72	188001	9 Sge	O8 If	34300	106,144	5.90	65,106,144	5.04	2	- 0.18
73		+ 24.3866	O8 If	34000	103	5.79	103	5.32	1	- 0.11
74	167771		O8 I(f)	34700	139,144	5.84	139,144	5.89	-	+ 0.54
75										
76	36861	λ Ori A	O8 III((f))	35000	41,100,101, 139,144	5.26	41,139,144	6.40	2	- 0.03
77	46056		O8 V(e)	36100	139	5.03	139	7.60	1	+ 0.76
78	101413		O8 V	36100	139	5.00	139	6.89	1	+ 0.00
79		+ 34.1038	O8 nn	36500	39	5.42	39	6.10	1	- 0.13
80		Cyg OB2; 23	O8	35000	66,144	4.88	66,144	6.00	1	- 1.03
81		Cyg OB2; 15	O8:	35000	144	5.00	87,144	5.96	1	- 0.89
82										

TABLE I (continued).

	U	REFS	V	REFS	I	REFS	C	REFS	M	REFS	R	REFS
39	6.60	39										
40	6.90	40										
41	6.95	21,40	>7.0	65								
42	6.10	39										
43	6.72	90										
44			4.50	65,103	4.30	34,106						
45			4.91	66,87	4.47	87,106					4.55	1,3
46			5.10	65								
47			5.57	104								
48			5.50	104								
49	5.50	40										
50			5.40	66	5.40	87						
51	6.30	40										
52	6.70	40										
53	6.30	39										
54	7.20	40										
55	6.56	90										
56	6.38	104										
57	7.40	39										
58					6.70	131						
59	7.30	39										
60	5.70	10										
61	6.40	39										
62					5.52	87						
63	5.63	31	5.07	65								
64	7.22	21	6.40	65								
65	5.77	41,83										
66	6.44	41,100	7.00	65								
67			5.30	25	4.84	18,106						
68			5.49	66,87	5.40	87						
69	8.10	50										
70	5.06	21,40	5.00	25,65,72							5.06	2,3
71	5.00	40	4.36	65,72							4.74	1
72			5.12	65							4.96	106
73			5.32	103								
74	5.80	21	5.97	72								
75												
76	6.10	41	6.70	101								
77	7.60	40										
78	6.89	40										
79	6.10	39										
80			6.00	66								
81					5.96	87						
82												

TABLE I *(continued)*.

NR	HD	NAME	SPECTR	T_{eff}	REFS	log $L/L_{\odot}$	REFS	AVERAGE $-\log(-\dot{M})$	w^2	O-C
83	37043	ι Ori	O8.5 III	34100	41,101,139,144	5.46	41,139,144	6.33	3	+ 0.28
84	46149		O8.5 V	35200	139	5.08	139	7.70	1	+ 0.97
85	149404		O9 Iae	32300	144	6.00	65,144	5.46	1	+ 0.48
86	210809		O9 Iab	32200	103	5.71	103	5.49	1	- 0.04
87		Cyg OB2; 10	O9 I	32500	66,144	5.84	66,87,144	4.96	2	- 0.33
88	112244		O9 Ib	32600	144	5.81	65,144	5.30	1	- 0.05
89	57061	τ CMa	O9 Ib-II	32300	41,139,144	5.67	41,139,144	5.99	1	+ 0.39
90	152246		O9 III	34100	39	5.38	39	6.90	1	+ 0.71
91	214680	10 Lac	O9 V	34600	41,133,139,144	4.97	139,144	6.59	1	- 0.29
92		Cyg OB2; 3	O9	35000	66,144	5.87	66,87,144	5.23	2	- 0.07
93	30614	α Cam	O9.5 Iae	28000	41,101,139,144	5.73	41,139,144	5.42	2	+ 0.02
94	154368		O9.5 Ia-Iab	30900	144	5.87	65,144	5.40	1	+ 0.20
95	152249		O9.5 Iab	31900	39,139,144	5.70	39,144	5.93	2	+ 0.39
96	195592		O9.5 I	29000		5.92	65	5.46	1	+ 0.38
97	36486	δ Ori A	O9.5 I-II	29900	41,101,139	5.47	25,41,65,139	6.17	4	+ 0.27
98	152424		O9.5 I-II	30000	39,139	5.70	39,65	5.50	4	+ 0.01
99	16429		O9.5 II((n))	29800	103,139	5.62	103,139	5.71	2	+ 0.08
100	13745		O9.5 II	29500	39,130	5.27	39,103	6.05	2	- 0.19
101	152247		O9.5 II-III	30300		5.28		5.57	1	- 0.67
102	38666	μ Col	O9.5 V	33200	41,101,139,144	4.62	41,139,144	7.35	2	- 0.03
103	37742	ζ Ori A	O9.5-9.7 Ib	29700	25,41,100,101 139,144	5.47	25,65,139 144	5.94	7	+ 0.05
104										
105										
106	226868		O9.7 Iab	27900		5.60	65	5.60	1	- 0.02
107	225146		O9.7 I	28000	103	5.40	103	5.96	1	- 0.01
108	149038	μ Nor	O9.7-BO Ia-Iab	27700	41,139,144	5.68	41,139,144	5.53	1	+ 0.05
109	93308	η Car		29300	25,137,141	6.62	25,137,141	3.0 (3)	0.15	- 1.01
110	38489	S134 (12)		28500	122	6.28	122	4.30	1	- 0.19
111		AF And		25000	84	6.26	84	4.30	1	- 0.27
112		- 9.4395		25000	50	4.30	50	7.70	1	- 0.30
113	37128	ε Ori	BO Iae	26800	25,41,100,101 139,144	5.65	25,41,65,144	5.680	40	+ 0.16
114	152667	V 861 Sco (4)	BO Iae	25000	58,59,144	5.75	58,65,144	5.25	3	- 0.08
115	77581		BO Ia	25900		5.88	65	5.15	1	+ 0.03
116	167264	15 Sgr	BO Ia	26000	144	5.76	65,144	5.70	1	+ 0.38
117	105056		BO Ipe	26200		6.14	65	4.52	1	- 0.20
118	163181		BO I	26200		5.75	65	5.20	1	- 0.14
119	205196		BO Ib	26100	103	5.11	103	6.22	1	- 0.22
120	192660		BO Ib	26100	103	5.61	103	5.57	1	0.00
121	149438	τ Sco	BO V	31300	41,49,139,144	4.57	41,49,139,144	8.02	1	+ 0.57
122		Cyg OB2; 16	BO:	31000	144	4.88	87,144	5.77	1	- 1.16
123		Cyg OB2; 19	BO:	31000	144	5.36	87,144	5.28	1	- 0.84
124		MWC 349 (6)	BO-B5 e+cont	22000	45	5.8	56	4.22	1	- 1.00
125	269445	S30 (12)		23400	122	6.27	122	4.52	1	- 0.06
126		S9 (12)		23400	122	5.82	122	5.00	1	- 0.20
127	93030	θ Car	BO-0.5 Vp	29100	41,139,144	4.34	41,139,144	7.25	1	- 0.62
128		R126 (LMC)	B0.5 Ia^+	22700	153	6.04	153	4.15	1	- 0.73

TABLE I (continued).

	U	REFS	V	REFS	I	REFS	C	REFS	M	REFS	R	REFS
83	5.94	41	6.52	101	6.52	131						
84	7.70	40										
85			5.46	65								
86			5.49	103								
87			5.15	66	4.77	87						
88			5.30	65								
89	5.99	83										
90	6.90	39										
91	6.59	83										
92			5.40	66	5.05	87						
93	5.29	83	5.55	101								
94			5.40	65								
95	6.20	39	5.66	72								
96			5.46	65								
97	5.94	21,83	6.73	65,101	5.98	7					6.03	2
98	5.82	39	5.45	72	5.28	9					5.52	25
99	5.80	25	5.61	72,103								
100	6.10	39	6.00	103								
101			5.57	72								
102	7.17	83	7.52	101								
103	6.05	83,100	6.19	65,101	6.00	83,101					5.54	3,101
104												
105												
106			5.60	65								
107			5.96	103								
108	5.53	83										
109												
110	4.30	122										
111			4.30	71								
112	7.70	50										
113	5.75	41,100	5.75	65,101	5.70	7					5.51	3
114	5.47	58,59,67,149	4.57	65	5.70	131						
115			5.15	65								
116			5.70	65								
117			4.52	65								
118			5.20	65								
119			6.22	103								
120			5.57	103								
121	8.02	49,83 (5)										
122					5.77	87						
123					5.28	87						
124	4.22	122										
125											4.52	32
126	5.00	122										
127	7.25	83										
128	4.15	153										

TABLE I *(continued)*.

NR	HD	NAME	SPECTR	T_{eff}	REFS	log $L/L_\odot$	REFS	AVERAGE $-\log(-\dot{M})$	w^2	O-C
129	38771	κ Ori	B0.5 Ia	24800	25,41,101,139	5.57	25,41,101,139	5.88	3	+ 0.26
130	152234		B0.5 Ia	23700	144	5.72	65,144	5.22	1	- 0.14
131	185859		B0.5 Ia	23700	144	5.51	65,144	6.22	1	+ 0.52
132	194839		B0.5 Ia	23500	103	5.53	103	5.70	1	+ 0.03
133	228712		B0.5 Ia	23400	103	5.68	103	5.52	1	+ 0.10
134		+ 60.0493	B0.5 Ia	23400	103	5.48	103	5.70	1	- 0.05
135	115842		B0.5 Ia-Iab	23800	144	5.64	65,144	6.15	1	+ 0.66
136	13402		B0.5 Ib	23600	103	5.34	103	6.00	1	+ 0.01
137	192422		B0.5 Ib	23600	103	5.34	103	5.80	1	- 0.19
138	24760	ε Per	B0.5 III	27400	41,139	4.83	41,139	6.90	1	- 0.06
139	143275	δ Sco	B0.5 IV	28500		4.66	134			+ 3.24
140	35411	η Ori	B0.5 Vnn	27700		4.38	124			+ 2.23
141	40111	139 Tau	B0.5-B1 Ib-II	23100	41,139,144	5.16	41,139,144	6.18	1	- 0.12
142		Var A-1 (12)		22000	84	6.30	84	4.82	1	+ 0.25
143		R81[12]		20000	84	5.90	84	4.52	1	- 0.54
144	169454		B1 Ia$^+$	20700	139	5.91	65,139	5.27	3	+ 0.22
145	193237	P Cyg	B1 Ia$^+$e	19700	3,25,84,93, 139,144	5.93	1,25,65,84,93 139,144	4.70	3	- 0.32
146	2905	κ Cas	B1 Iae	20600	25,101,139,144	5.45	139,144	5.94	2	+ 0.19
147	148688		B1 Iae	21100	144	5.69	65,144	5.60	1	+ 0.22
148	269700		B1 Iae	21200		5.58		5.64	1	+ 0.09
149	154090		B1 Ia-Iab	21100	144	5.54	65,144	5.40	1	+ 0.21
150	13854		B1 Iabe	21200	144	5.50	65,144	5.46	1	- 0.22
151	91316	ρ Leo	B1 Iab	20900	25,41,139,144	5.20	25,41,65,139 144	5.94	3	- 0.25
152	96248		B1 Iab	21400		5.46	65	6.70	1	+ 0.95
153		Cyg OB; 2	B1 I	21200	143	5.64	70	5.89	1	+ 0.43
154	24398	ζ Per	B1 Ib	20800	41,139,144	5.07	32,54,107,110	6.22	2	- 0.20
155	157246	γ Ara	B1 Ib	21000	41,139,144	5.06	32,107,110	6.14	1	- 0.30
156	147165	σ Sco	B1 III	24500		4.54	16	8.72	1	+ 1.22
157	152236	ζ^1 Sco	B1-B1.5 Ia$^+$	19200	3,25,144	6.08	19,54,110	4.88	2	+ 0.06
158	190603		B1.5 Ia$^+$	18800		5.68	54,107,110	4.80	2	- 0.56
159	194279		B1.5 Ia	19000	139	5.42	107	5.60	1	- 0.17
160		- 14.5037	B1.5 Ia	19100		5.50		6.40	1	+ 0.76
161	94910	AG Car	B0-A1 Ieq	----(8)	17,84,150	----	17,84,150	----	1	- 1.76
162	148379		B1.5-B2 Ia	18600	144	5.71	65,144	5.22	1	- 0.09
163	41117	χ^2 Ori	B2 Iae	17500	139,144	5.51	65,139,144	5.24	2	- 0.34
164	14143		B2 Ia	17400	139	5.50	65,139	5.37	2	- 0.23
165	14818	10 Per	B2 Ia	17500	144	5.41	65,144	5.19	1	- 0.55
166	199140	BW Vul	B2 III	22100	15	4.17	15	8.85	1	+ 0.51
167									1	+ 1.05
168										
169	42087	3 Gem	B2.5 Ib	16400	144	4.99	65,144	5.60	1	- 0.86
170										
171		R 127 (12)		17000	84	6.14	84	4.22	1	- 0.49
172		+ 10.2179		16800	50	3.70	50	9.95	1	+ 0.25
173	92964		B3 Iae	16000	144	5.58	65,144	5.82	1	+ 0.39
174	198478	55 Cyg	B3 Iae	14900	139,144	5.24	65,139,144	5.54	2	- 0.40

TABLE I (continued).

	U	REFS	V	REFS	I	REFS	C	REFS	M	REFS	R	REFS
129	5.53	83	6.12	101	6.00	7						
130			5.22	65								
131			6.22	65								
132			5.70	103								
133			5.52	103								
134			5.70	103								
135			6.15	65								
136			6.00	103								
137			5.80	103								
138	6.90	83										
139	10.52	124										
140	10.03	124										
141	6.18	83										
142			4.82	71								
143	4.52	151										
144			5.37	65,128	5.41	7,83					5.04	3
145			4.27	65,79,134	4.54	7,97,121					4.79	1,3
146			6.15	101	5.73	7,83						
147			5.60	65								
148			5.64	129								
149			5.40	65								
150			5.46	65								
151	5.96	83	5.82	65	6.05	7						
152			6.70	65								
153					5.89	87						
154	6.23	83	6.22	65								
155	6.14	83										
156	8.72	8										
157			4.65	94,129							5.10	2,3
158			4.30	65	5.29	1,83						
159					5.60	7						
160			6.40	129								
161			4.52	150							3.96	17
162			5.22	65								
163			5.12	65	5.36	83						
164			5.10	65	5.64	83						
165			5.19	65								
166	8.85	8										
167												
168												
169			5.60	65								
170												
171			4.22	128								
172	9.95	50										
173			5.82	65								
174			5.30	65	5.77	83						

TABLE I (continued).

NR	HD	NAME	SPECTR	T_{eff}	REFS	log $L/L_{\odot}$	REFS	AVERAGE $-\log(-\dot{M})$	w^2	O-C
175	14134		B3 Ia	15200	139	5.30	65,139	5.71	2	− 0.14
176	178129		B3 Ia	15900		5.24	65	5.40	1	− 0.58
177	53138	o^2 CMa	B3 Ia-Iab	15100(9)	25,101,139, 144	5.30	25,65,139,144	5.93	2	+ 0.09
178	43384	9 Gem	B3 Iab	15200	144	5.03	65,144	7.00	1	+ 0.66
179										
180		Cyg OB2; 12	B5 Ia^+ (10)	12500	3,87,144	6.14	1,64,66,87, 144	4.64	3	+ 0.25
181	58350	η CMa	B5 Ia	13400	25,139,144	5.07	25,65,139,144	5.91	2	− 0.26
182	36371	χ Aur	B5 Iab	13500	139,144	5.06	139,144	5.85	1	− 0.35
183	164353	67 Oph	B5 Ib	13400	25,139,144	4.64	25,139,144	6.92	1	− 0.14
184										
185		AO 538-66	B III	13000	61	4.06	61	8.40	1	− 0.11
186		R 66 (12)		12000	84	5.46	84	4.52	1	− 0.88
187		R 71 (12)		12000	84	6.14	84	4.30	1	− 0.02
188	15497		B6 Ia	12800	139	5.15	139	6.14	1	+ 0.15
189	166937	μ Sgr	B8 Iape	11200	139,144	5.13	65,139,144	5.77	2	− 0.14
190	34085	β Ori	B8 Iae	11400	25,139,144	5.09	25,139,144	6.41	1	+ 0.41
191	21291	2 Cam	B9 Ia	10200	139,144	4.90	139,144	6.40	1	+ 0.13
192	193426		B9 Ia	10600		4.98	65	5.30	1	− 0.84
193	164865		B9 Iab	10500		4.70	65	5.52	1	− 1.19
194	21389		AO Iae	10100	25,80,144	4.87	25,80,144	7.16	3	+ 0.84
195	87737	η Leo	AO Ib	9700	144	4.06	25,144	8.43	2	+ 0.23
196	12953		A1 Iae	9400	144	5.06	25,144	6.10	1	+ 0.22
197	197345	α Cyg	A2 Iae	9400	25,28,144	5.12	25,144	7.89	0.15	+ 2.13
198	14489	9 Per	A2 Ia	9200	103	5.01	25,144	6.28	1	+ 0.33
199	35343	S Dor (12)	A2-A5 Ia eq	8870	84,127	6.14	84	4.23	2	+ 0.58
200	17378		A5 Ia	8530	144	5.02	25,144	6.49	1	+ 0.63
201	59612		A5 Ib	8380	144	3.83	144	8.52	1	− 0.12
202	163506	89 Her	F2 Ibe	7210		4.00		8.00	−	+ 0.12
203		CRL 2688	F5 Ia^+	5821		5.54		3.84	1	− 0.65
204	224014	ρ Cas	F8 Ia^+	5130	25	5.38	25	5.50	2	+ 0.69
205		IRC + 10420	F8 Ia^+	5270		5.58	63	3.61	2	− 0.70
206	192713	22 Vul	G3 Ib-II	5070		3.40		8.22	1	− 0.45
207	217476		G4 Ia^+	5050	37	5.30	25	4.92	2	− 0.07
208	48329		G8 Ib	4630		3.92		7.40	1	+ 0.03
209	208606		G8 Ib	4630		3.92		7.40	1	+ 0.03
210	17506		K3 Ib	4140		3.98		6.70	1	− 0.37
211	32068	ζ Aur	K4 Ib	3810	20,25,89	3.62	20,25,89	7.36	2	− 0.06
212	13554 A	31 Cyg	K4 Ib	3900	20	3.94	20	7.40	1	+ 0.39
213	192909	32 Cyg	K5 Iab	3890	20	4.08	20	7.55	1	+ 0.73
214	216946		K5 Ib	3950		4.02		6.70	1	− 0.22
215	44537	ψ^1 Aur	K5-M0 Iab-Ib	3800		4.36		6.30	1	− 0.15
216	42475	TV Gem	M0-M1 Iab	3560		4.75		5.92	1	− 0.11
217		Boss 1985	M1 Iab	3490		4.78				
218	42543	BU(6) Gem	M1-M2 Ia-Iab	3440		5.15		5.68	2	+ 0.16
219	39801	α Ori	M1.5 Iab	3500	25	4.87	25	6.02	4	+ 0.11

TABLE I *(continued)*.

	U	REFS	V	REFS	I	REFS	C	REFS	M	REFS	R	REFS
175			5.22	65	6.19	83						
176			5.40	65								
177			5.96	65,101	5.90	83						
178			7.00	65								
179												
180			4.93	66,87	4.48	87					4.52	2,3,146
181			5.40	65	6.42	7						
182					5.85	83						
183					6.92	83						
184												
185	8.40	61										
186			4.52	128								
187	4.30	152										
188					6.14	83						
189			5.30	65	6.23	83						
190					6.41	83						
191					6.40	83						
192			5.30	65								
193			5.52	65								
194	8.0	109	7.10	80	6.38	7						
195			9.52	76	7.33	7						
196					6.10	7						
197	8.10(5)	53,109	7.67(5)	78								
198					6.28	7						
199	4.15	151	4.30	127								
200			6.49	85								
201	8.52	109										
202			8.00	117								
203					3.84	74,75						
204			5.50	14,25	2.40	46 (15)						
205							3.52	75	3.70	12		
206			8.22	115b								
207			4.84	106b,113	2.40	46 (15)					5.00	82
208			7.40	111								
209			7.40	111								
210			6.70	110								
211	8.20	20	6.52	25								
212	7.40	20										
213	7.55	20										
214			6.70	111								
215					6.30	42						
216					5.92	42						
217	< 7.00	20a										
218			5.68	116	5.68	42						
219			5.77	25,44,51,96 130	6.22	42,123b	6.44	73,74	5.66	13b		

TABLE I (continued).

NR	HD	NAME	SPECTR	T_{eff}	REFS	log $L/L_\odot$	REFS	AVERAGE $-\log(-\dot{M})$	w^2	O-C
220	148478	α Sco	M1.5 Iab	3540	25	4.74	25	6.08	4	+ 0.04
221		RW Cyg	M2 Ia-Iab	3365		5.20		5.30	1	- 0.15
222	208816	VV Cep	M2 Iab	3175	25	5.13	25	6.89	1	+ 1.23
223	36389	119 Tau	M2 Iab-Ib	3400		4.55		6.62	1	+ 0.39
224	206939	μ Cep	M2 Iab-Ib	3400		4.55		5.78	2	- 0.45
225	187076	δ Sge	M2 II	3640		3.47	44	7.70	1	+ 0.22
226		BC Cyg	M3.5 Ia	3155		5.54	63	5.15	1	+ 0.54
227		BI Cyg	M3 Ia-Iab	3155		5.38	63	5.15	1	+ 0.02
228		VY CMa	M3-M5 Iae	2840	25	5.76	25,63	3.620	60	- 0.10
229	128609	R Boo	M3e-M6e	2950	(13)	3.50	(13)	7.00	1	+ 0.39
230		OH 26.5 + 0.6	M	2745	55	4.00	55	4.47	0	- 1.75
231	89845	EV Car	M4 Ia	2930		5.74	63	6.00	1	+ 2.21
232	14528	S Per	M4 Ia	2810	25	5.66	63	4.57	1	+ 0.29
233		UY Sct	M4 Ia-Iab	3000		5.44		5.22	1	+ 0.18
234	175588	δ^2 Lyr	M4 II	3515		3.70		7.30	1	+ 0.23
235	19058	ρ Per	M4 II-III	3475		3.31		7.92	1	+ 0.42
236	175865	R Lyr	M4-5 III	3410		2.98		7.85	1	+ 0.12
237	155161	AH Sco	M5 Ia-Iab	2800		5.62	63	6.00	1	+ 1.52
238	156014	α^1 Her	M5 Ib-II	3335	25	4.13		6.32	2	- 0.21
239	58521	Y Lyn	M5 Ib-II	3275		4.13		6.53	2	+ 0.02
240		L2 Pup	M5e-M6e	2750	(13)	3.87	(13)	7.13	1	+ 0.91
241	172171	X Oph	M5e-M7e	2670	(13)	4.05	(13)	6.05	1	- 0.11
242	149880	R Dra	M5e-M7e	2670	(13)	4.05	(13)	5.54	1	- 0.62
243	14386	o Ceti	M5e-M9e	2365	25 (13)	4.17	25	6.87	3	+ 0.90
244		NML Cyg	M6 Ia	2485		5.80	63,98	4.18	3	+ 0.50
245	78712	RS Cnc	M6 Ib-III	3240	25	3.95		6.22	3	- 0.40
246	144205	X Her	M6e	2670	(13)	4.05	(13)	6.55	2	+ 0.39
247	188915	RR Agl	M6e-7e	2520	(13)	4.20	(13)	6.33	2	+ 0.23
248	209598	TW Peg	M6-M7	2510	(13)	4.20	(13)	6.70	1	+ 0.60
249	59950	S CMi	M6e-M8e	2365	(13)	4.34	(13)	5.20	1	- 0.93
250	39816	U Ori	M6e-M8e	2365	(13)	4.34	(13)	5.92	2	- 0.21
251	69243	R Cnc	M6e-M8e	2365	(13)	4.34	(13)	6.22	1	+ 0.09
252	136753	S CrB	M6e-M8e	2365	(13)	4.34	(13)	5.40	1	- 0.73
253		OH 231.8+4.2	M6I-M9III	2980		4.64		----	-	- 2.32
254		IK Tau	M6e-M10e	2230	(13)	4.65	(13)	5.30	1	- 1.11
255	148206	U Her	M6.5e-M8e	2365	(13)	4.34	(13)	5.59	1	- 0.54
256	177940	R Aql	M6.5e-M9e	2230	(13)	4.65	(13)	6.03	3	- 0.38
257	224090	R Cas	M7 IIIe	2365	(13)	4.34	(13)	6.21	2	+ 0.08
258	222800	R Aqr	M7 III+pecV	2365	(13)	4.34	(13)	7.43	2	+ 1.30
259	126327	RX Boo	M7 IIIe	2365	(13)	4.34	(13)	6.72	2	+ 0.59
260	29712	R Dor	M7 III	3265		3.32		7.16	1	- 0.05
261	207076		M7 III	3265		3.32		6.70	1	- 0.51
262	84346	R LMi	M7e-M8e	2300	(13)	4.50	(13)	6.08	2	- 0.18
263	34019	R Aur	M7e-M9e	2230	(13)	4.65	(13)	6.28	1	- 0.13
264	84748		M8 IIIe	2230	(13)	4.65	(13)	6.62	3	+ 0.21
265		IRC + 10011(14)	M8	2540	55	4.34	55 (13)	4.65	2	- 1.54
266	113285	RT Vir	M8	2230	(13)	4.65	(13)	5.82	1	- 0.59
267	120285	W Hya	M8e-M9e	2160	(13)	4.90	(13)	6.83	2	+ 0.22
268		H 1-36	M	2500	6	3.70	6	4.52	1	- 1.32
269	269953		Go Ia^+	4940		5.16	58	2.40 (15)		
270	269723		G4 Ia^+	4630		5.38	58	2.40 (15)		
271	271182		F8 Ia^+	5270		5.09	58	2.40 (15)		
272	150884		F8 Ia	5930		4.84	58	2.40 (15)		
273		AX Sgr	G8 Ia	4880		4.72	58	2.40 (15)		
274		Var A (M33)		5000	64b	5.70	64b	3.70	1	- 0.20

TABLE I (continued).

	U	REFS	V	REFS	I	REFS	C	REFS	M	REFS	R	REFS
220	6.00	50b	6.17	25	6.44	25,46			5.70	57b		
221					5.30	42						
222					6.89	42						
223			6.62	116								
224			6.05	25,44	5.50	42,46						
225			7.70	114								
226					5.15	42						
227					5.15	42						
228	3.52	59	3.70	25	3.50	42	3.72	75	3.67	12,13,68		
229					7.00	42						
230					4.59	145	3.68	73	5.15	12,13		
231			6.00	51								
232					4.57	42						
233					5.22	42						
234			7.30	116								
235			7.92	116								
236	7.85	20										
237			6.00	51								
238			6.59	25,44,51	6.05	42						
239					6.64	42	6.42	142b (11)				
240					7.13	46						
241					6.05	42						
242					5.54	42						
243			6.85	115,152b			7.07	74,75			6.70	126
244							4.55	73,74 (5)	3.80	13,68	4.19	98
245					6.40	42	6.79	73,75			5.47	74
246					7.05	46	6.05	142b (11)				
247							6.70	73	5.95	12,13		
248					6.70	46						
249							5.20	74				
250					5.92	42			5.92	12,13		
251					6.22	42						
252					5.40	42						
253							3.89	75				
254									5.30	68		
255					5.59	42						
256					6.10	42	5.90	73,142b(11)	6.10	13		
257							6.42	73,75	6.00	13		
258							7.85	73			7.00	126
259					7.00	46	6.45	73,75				
260					7.16	46						
261					6.70	46						
262							6.41	73,74	5.74	13		
263							6.28	75				
264					6.52	46	7.37	73,75	5.96	13		
265							4.58	73,75	4.72	12,13,68		
266							5.82	75				
267					6.37	42,46	7.29	142b (11)				
268											4.52	132
269			2.40	58								
270			2.40	58								
271			2.40	58								
272			2.40	58								
273			2.40	58								
274			3.70	64b								

Remarks to table I:

1. Hutchings (1981) apparently confused no. 8C and 8D (pers. comm. E. Leitherer, 1986) ; therefore this value is not used in our work.
2. Binary ; the other component is O7 (See De Jager, 1980, p. 32).
3. Mass Loss rate indirectly determined from mass of homunculus ; uncertainty 1 dex.
4. Binary ; data for primary component.
5. Large differences between individual determinations of mass loss rate.
6. T and log L variable (1600-2800 K ; 5.54-6.1).
7. Waters and Lamers (1986) give log $(L/L_{\odot}) = 4.57$.
8. Individual T-values range from 9000 to 16500 K.
9. Van Helden (1972) gives a much higher temperature (20000 K).
10. Spectral types in literature range from B3 Ia^{+} to B8 Ia.
11. Largest shell radius assumed in reference [142b].
12. LMC star.
13. T and L derived from Mira-table (Tab. II).
14. WX Pse.
15. Doubtful values ; not included in interpolation model calculation.

TABLE II. — *Adopted effective temperatures and luminosities for Mira stars.*

Spectral type	T_{eff}	$\log(L/L_{\odot})$
M1	3540	2.81
M2	3435	2.89
M3	3265	3.04
M4	3075	3.30
M5	2825	3.68
M6	2670	4.05
M7	2365	4.34
M8	(2230)	(4.65)

Sources: De Jager, 1980, Table XXV
Scalo, 1976

TABLE III. — *Some well studied stars with accurate values for the rate of mass loss.*

HD	Name	Spectrum	$\log(-\dot{M})$	$\pm\sigma$
66811	Zeta Pup	O4 Ief	− 5.325	0.043
15570	−	O4 If^{+}	− 4.925	0.085
37742	Zeta Ori A	O9.5-9.7 Ib	− 5.945	0.141
37128	Eps Ori	B0 Iae	− 5.680	0.057
−	VY CMa	M3-5 Iae	− 3.620	0.047

TABLE IV. — *A search for systematic differences between methods for determining rates of mass loss.*

A. For the full material

Method	U	V	I	C	M	R
n	99	144	87	18	11	21
$\langle D \rangle$	+ 0.139	+ 0.014	− 0.167	− 0.101	− 0.689	− 0.028
± s	0.57	0.56	0.64	0.96	0.64	0.48
± σ	0.058	0.047	0.070	0.23	0.20	0.010

B. Material split in smaller groups: search for variation of systematic differences over the Hertzsprung-Russell diagram. Results are only communicated for subgroups of more than four stars.

group	Method	U	V	I	C	M	R
log $T \geq 4.5$	n	17	36	15	−	−	7
$b < 3$	$\langle D \rangle$	+ 0.02	− 0.08	− 0.39	−	−	− 0.22
	± σ	0.06	0.06	0.07	−	−	0.08
log $T \geq 4.5$	n	40	19	7	−	−	−
$b \geq 3$	$\langle D \rangle$	+ 0.20	+ 0.02	− 0.42	−	−	−
	± σ	0.08	0.16	0.29	−	−	−
$4.0 \leq \log T < 4.5$	n	20	25	25	−	−	9
$\log(L/L_{\odot}) \geq 5.0$	$\langle D \rangle$	− 0.11	− 0.01	+ 0.02	−	−	+ 0.18
	± σ	0.07	0.06	0.09	−	−	0.12
$4.0 \leq \log T < 4.5$	n	15	−	−	−	−	−
$\log(L/L_{\odot}) < 5.0$	$\langle D \rangle$	+ 0.31	−	−	−	−	−
	± σ	0.22	−	−	−	−	−
log $T < 4.0$	n	−	8	12	−	−	−
$\log(L/L_{\odot}) \geq 5.0$	$\langle D \rangle$	−	+ 0.52	− 0.44	−	−	−
	± σ	−	0.37	0.38	−	−	−
log $T < 4.0$	n	−	17	25	14	8	−
$\log(l/L_{\odot}) < 5.0$	$\langle D \rangle$	−	+ 0.24	− 0.13	+ 0.16	− 0.45	−
	± σ	−	0.14	0.10	0.25	0.21	−

TABLE V. — *Excluded stars.*

Nr.	Name or HD	Reason for exclusion
10	9 Sgr	Radio data excluded: synchroton radiation
16	Cyg OB2; 9	Ibid
21	Cyg OB2; 8D	Object misidentified by Hutchings (1981) therefore mass loss data uncertain
28	Cyg OB2; 8A	Radio data excluded; synchroton radiation
74	HD 167971	Eclipsing binary with narrow components
139	Del Sco	Quadruple object with excessive infrared deficiency; Be or shell star?
140	Eta Ori	Binary with Be component
161	AG Car	Strongly variable P Cyg star with variable T and dubious luminosity
202	89 Her	Pop. II star; luminosity estimated
217	Boss 1985	Lower limit of mass loss
230	OH 26.5+0.5	T and L badly known
253	OH 231.8+4.2	Ibid

TABLE VI. — *Coefficients a_{ij} is in the Chebychev adaption with Equation (1).*

j =	0	1	2	3	4
i = 0	6.34916	- 5.04240	- 0.83426	- 1.13925	- 0.12202
1	3.41678	0.15629	2.96244	0.33659	0.57576
2	- 1.08683	0.41952	- 1.37272	- 1.07493	
3	0.13095	- 0.09825	0.13025		
4	0.22427	0.46591			
5	0.11968				

TABLE VII. — *Wolf-Rayet stars.*

NR	WR	HD or other	Sp.type	T_{eff}	$-\log(-\dot{M})$	$\log(L/L_\odot)$
1	1	4004	WN5	40000	4.31	5.25
2	6	50896	WN5 (SB1)	"	4.42	5.08
3	139	193576	WN5 + O6	"	4.86	4.93
4	110	165688	WN6	36000	3.93	5.45
5	115	IC14-19	WN6	"	4.58	----
6	134	191765	WN6 (SB1)	"	4.09	5.47
7	136	192163	WN6 (SB1)	"	3.92	5.84
8	138	193077	WN6 + a(SB1)	"	4.41	4.72
9	141	193928	WN6 (SB1)	"	4.41	----
10	22	92740	WN7 + a(SB1)	30000	(3.96)	5.65
11	24	93131	WN7 + a	"	(3.99)	5.65
12	25	93162	WN7 + a	"	(4.00)	5.65
13	78	151932	WN7	"	3.97	5.61
14	87	LSS4064	WN7	"	(4.16)	----
15	89		WN7	"	4.03	----
16	146	HM 19-3	WC4	50000	(4.48)	5.45
17	111	165763	WC5	40000	4.60	4.99
18	14	76536	WC6	36000	(4.18)	----
19	15	77573	WC6	"	(4.21)	----

TABLE VII *(continued).*

NR	WR	HD or other	Sp.type	T_{eff}	$-\log(-\dot{M})$	$\log(L/L_\odot)$
20	23	92809	WC6	36000	(4.10)	----
21	48	113904	WC6 + O9.5I	"	(4.08)	5.35
22	42	97152	WC7 + O7 V	30000	(4.58)	----
23	79	152270	WC7 + O6	30000	3.81	5.14
24	86	156327	WC7 + a	"	4.13	----
25	93	157504	WC7 + a	"	3.97	----
26	137	192641	WC7 + a	"	4.29	----
27	140	193793	WC7 + O4.5	"	4.01	----
28	11	68273	WC8 + O9 I	26000	3.93	5.09
29	113	168206	WC8 + O8 V	"	4.18*	----
30	135	192103	WC8	"	4.18	4.93
31	81	He3-1316	WC9	19000	4.53	----

*) WR 113: -value from Howard et al. (1982)

TABLE VIII. — *Adopted effective temperatures and luminosities for C-type stars.*

Spectral type	T_{eff}	$\log(L/L_\odot)$
C2	3700	2.73
C3	3415	3.06
C4	3180	3.35
C5	2980	3.58
C6	2825	3.78
C7	2700	3.98
C8	2600	4.15
C9	2520	4.33

TABLE IX. — *Rates of mass loss from C- and S-type stars.*

Object	Spectr.type	T_{eff}*	Ref	$\log(L/L_\odot)$*	Ref	$-\log(-\dot{M})$	Ref
RU Vir	Cep (R3)	4170	118	1.90	118	5.02	75
CIT 6	C4,3	3180		3.80		5.36	73,74,75
Y CVn	C5,4	2980		3.61		7.04	73,75
V Hya	C6,3e	2825		3.80		5.28	73,74,75
R Scl	C6 II	2825		3.80		4.73	73,74,75
R Lep	C6 IIe	2825		3.80		5.71	73,75
T Dra	C6,2e - 8,3e	2700		3.98		5.78	73,75
V Cyg	C7e	2700		3.98		5.18	73,74,75
IRC + 20370	C7,3e	2700		3.98		4.88	73,74,75
IRC + 40540	C8	2600		4.15		4.50	73,74,75
IRC + 10216**	C9,5	2500	126	4.44	45,66	4.24	74,75
R Cyg	S3,9	3370		3.17		6.64	73
W Agl	S3,9 - 4,9e	3275		3.48		4.91	74,107
R And	S4,6 - 8,8e	2825		3.80		6.40	73,74,75
Y Cyg	S7-10 Ie	2560		4.24		6.59	73,74,75

*) Ref. for T and L: see Table VIII; for S stars: table II

**) = CW Leo

TABLE X. — *Rates of mass loss from Be stars. Note : Infrared rates of mass loss with a reference W are from a forthcoming paper by Waters, Coté and Lamers, (1987), which we obtained after having nearly finalized the paper.*

NR	HD	NAME	SPECTR	T_{eff}	REFS	$\log(L/L_\odot)$	REFS	U	REFS		V	REFS	I	REFS
1	149757	ζ Oph	O9.5 V(e)	32500	41,62,139,144	5.01	41,139,144	6.55	52,67					
2	5394	γ Cas	B0.5 IV e	28500		4.64	124	9.10	43,97	(5)			6.9	W
3	212571	π Aqr	B1 III-IVe	24500	139	4.33	124	8.59	97					
4	35439	25 Ori	B1 Ve	22500	139	4.17	125	8.66	98				7.3	W
5	28497		B1.5 Ve	20700	139	3.98	124	9.11	97				7.6	W
6	127972	η Cen	B1.5 Ve	20700	139	3.97	139	9.55	98					
7	200120	59 Cyg	B1.5 Ve	20700	139	3.98	125	9.82	98					
8	138690	γ Lup	B2 IV	21900	139	3.93	139	10.02	125					
9	106490	δ Cru	B2 IV	21900	139	3.93	139	10.39	125					
10	10516	ϕ Per	B2 IVep	21100	139,143,144	3.78	125,144	9.59	98				7.48	109;W
11	105435	δ Cen	B2 IVne	22000	139,143	4.02	125	10.13	98				7.88	109;W
12	148184	χ Oph	B2 IVpe	22500	143	3.84:							7.80	109;W
13	56139	ω CMa	B2 IV-Ve	19300	139	3.80	125	9.85	98				8.0	W
14	202904	ν Cyg	B2 Ve	18300	139	3.71	125	10.22	98					
15	10144	α Eri	B2 Vpe	14400	139	3.13	125	9.89	98					
16	121263	ζ Cen	B2.5 IV	19000	139	3.65	139	10.40	125					
17	25940	48 Per	B3 Ve	14200	139	3.14	125	9.77	98				7.9	W
18	37202	ζ Tau	B4 IIIp	16600		3.90	124	9.63	124				7.6	W
19	91465	ρ Car	B4 Ve	16900:		2.94:					9.52	17	8.2	W
20	142983	48 Lib	B5 IIIp	15100		3.18	124	10.17	124				7.8	W
21	22192	ψ Per	B5 Ve	17200	139	3.34	125							
22	217675	o And	B6 pe	11400	139	2.53	125	10.12 9.92	98 98				7.9	

TABLE XI. — *Rates of mass loss from nuclei of planetary nebulae.*

Object	T_{eff}	Ref	$\log(L/L_\odot)$	Ref	$-\log(-\dot{M})$	Ref
NGC 40	33000	19	2.80	19	7.52	19
1535	66000	19	3.55	19	9.00	19
2371	80000	70	2.77	70	7.30	19
5189	65000	19	2.40	19	8.22	19
6210	74000	19	3.20	19	9.22	19
6826	40000	70	3.11	70	7.70	19
6891	39000	70	2.37	70	9.22	19
7009	65000	70	2.88	70	9.52	19
IC 418	33000	70	3.26	70	8.40	19
2149	31000	70	2.80	70	7.00	19
3568	51000	70	3.15	70	8.30	19
4593	28000	70	2.35	70	8.00	19
Abell 30	80000	70	2.69	70	9.52	19
Hn 2 - 1	51000	19	3.15	19	8.05	19
SwSt 1	33000	19	2.40	19	7.30	19

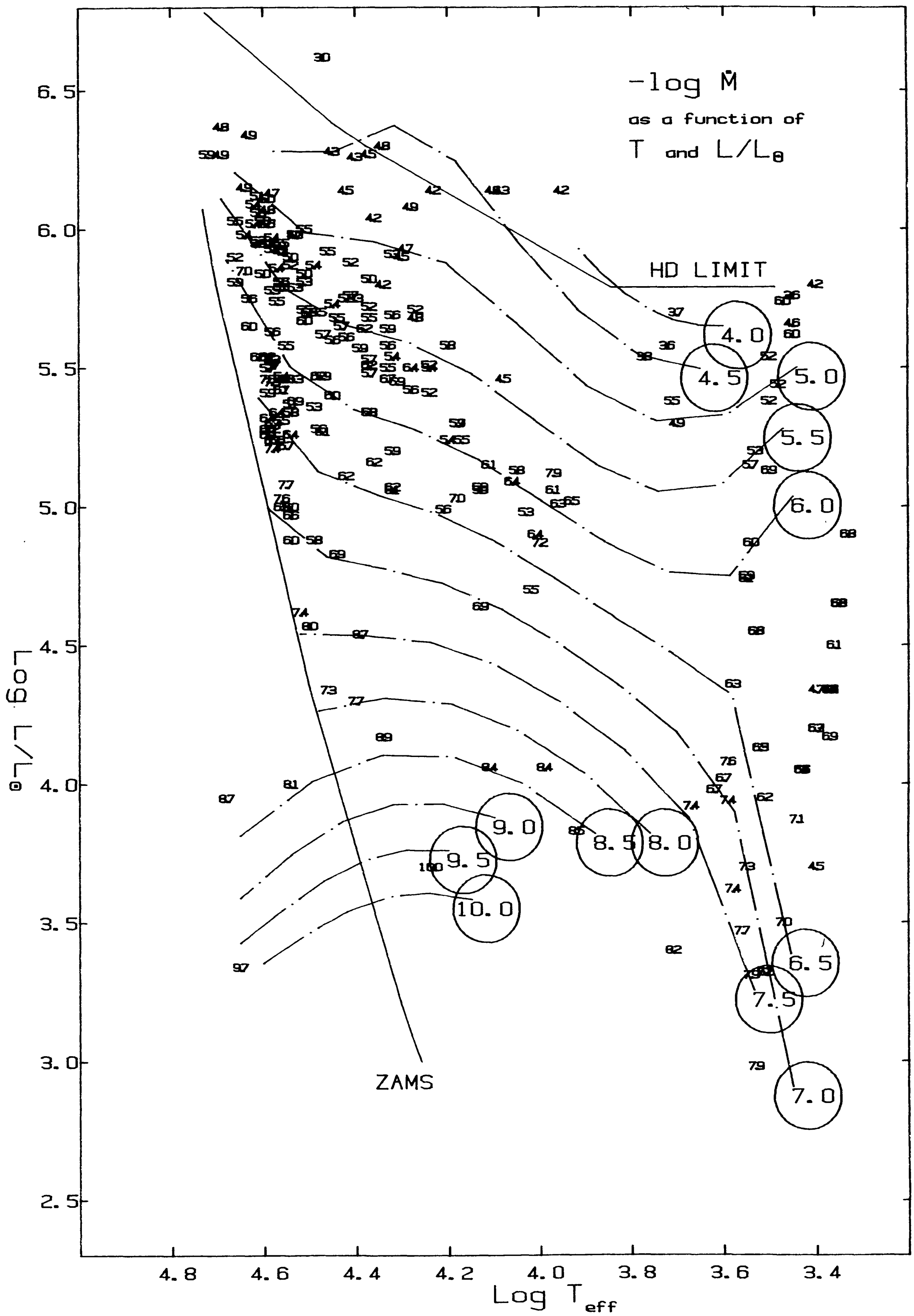

FIGURE 1. — Hertzsprung-Russell diagram with lines of constant rate of mass loss, according to Eq. (1) and using the constants a_{ij} of table VI. Lines are labeled with $-\log(-\dot{M})$, with $\dot{M}$ in $M_{\odot}$ yr^{-1}. Each number represents the $-\log(-\dot{M})$-value for an individual star, to one decimal. The drawn line is the Humphreys-Davidson limit.

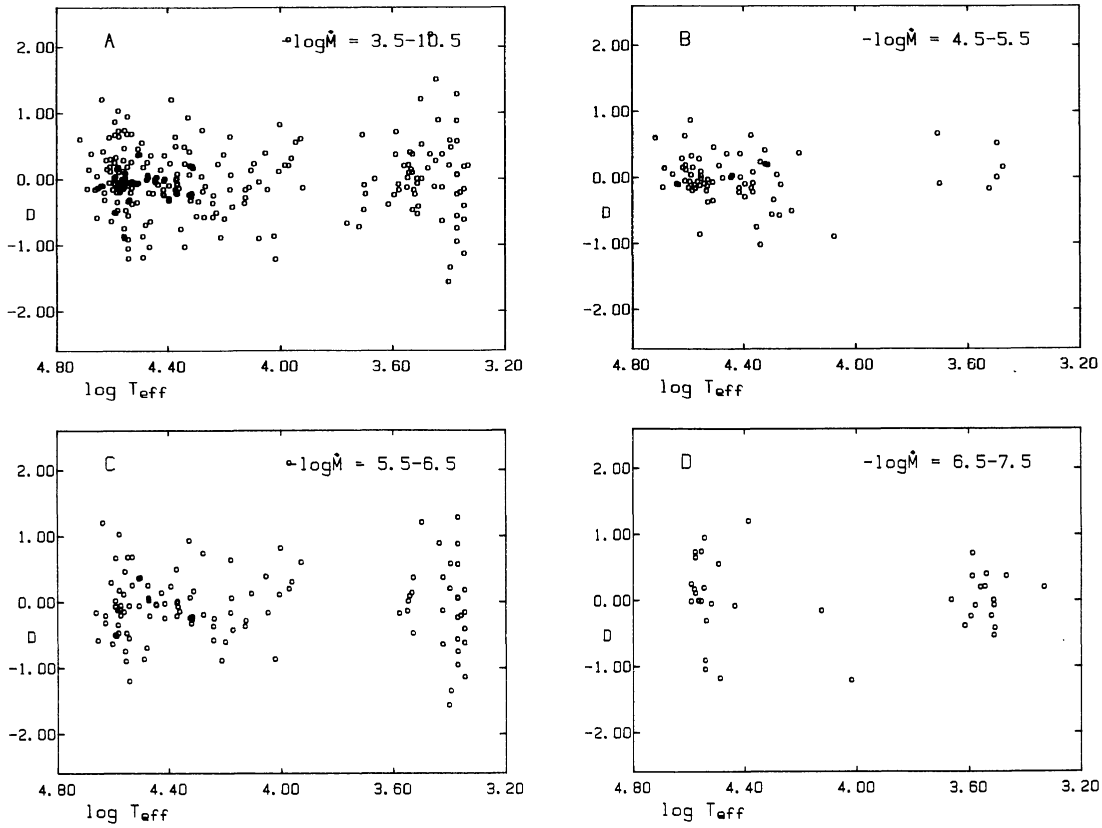

FIGURE 2. — Residuals D (defined in Eq. (2)) of the observed log $(-\dot{M})$ values as compared to those calculated with equation (1) and table VI. A : for the whole material ; B : $-$ log $(-\dot{M})$ between 4.5 and 5.5 ; C : between 5.5 and 6.5 ; D : between 6.5 and 7.5.

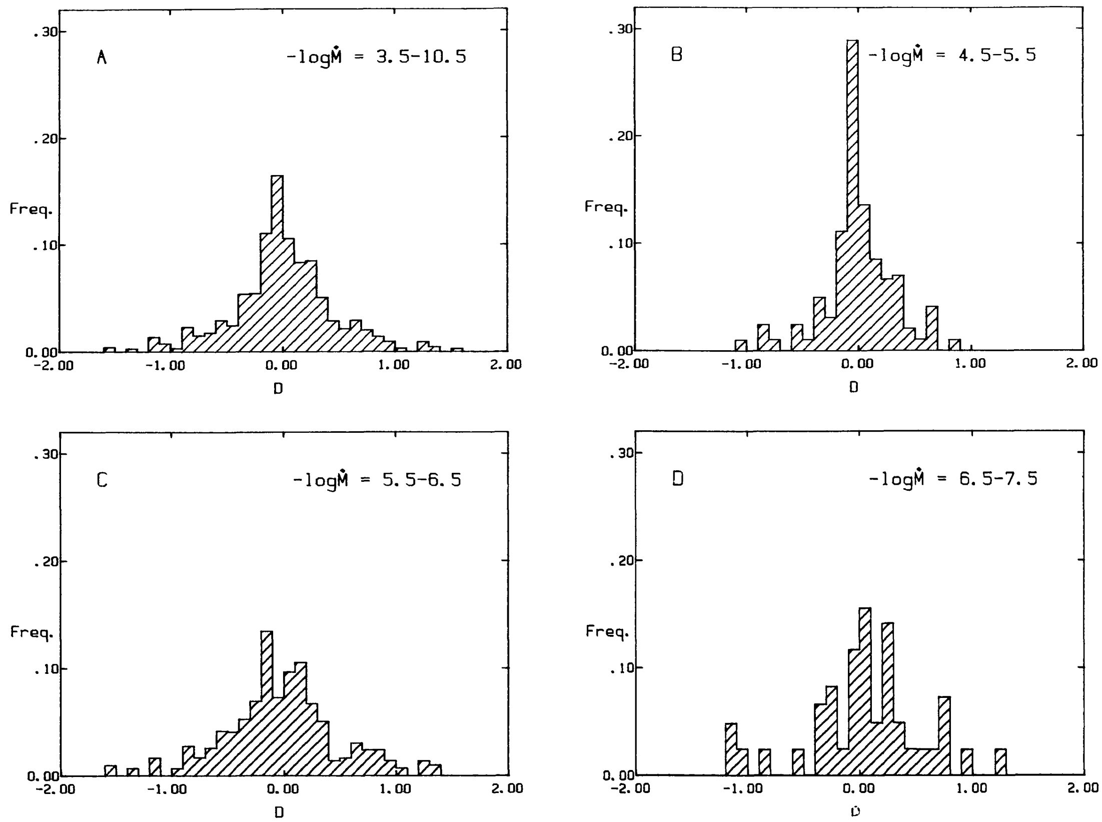

FIGURE 3. — Histogram of residuals D between the actual rate of mass loss of O through M-type stars and the values derived from the interpolation formula (1), for the same four ranges of $\dot{M}$-values as in figure 2. Note : a negative D-value means that the observed mass loss rate is larger than the calculated one.

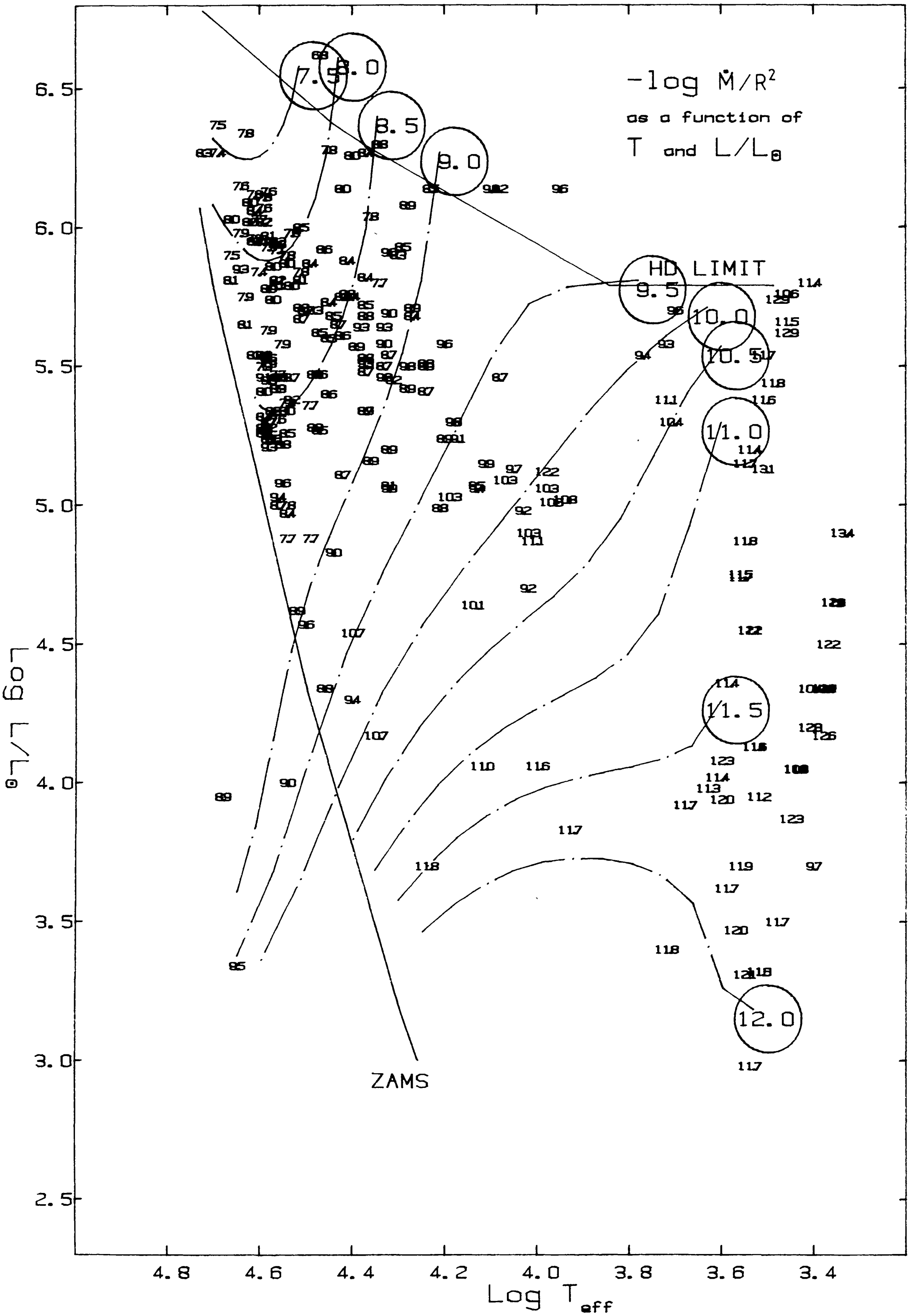

FIGURE 4. — Rate of mass fluxes $-\dot{M}/R^2$ in $M_\odot$ yr^{-1} $R_\odot^{-2}$ over the Hertzsprung-Russell diagram.

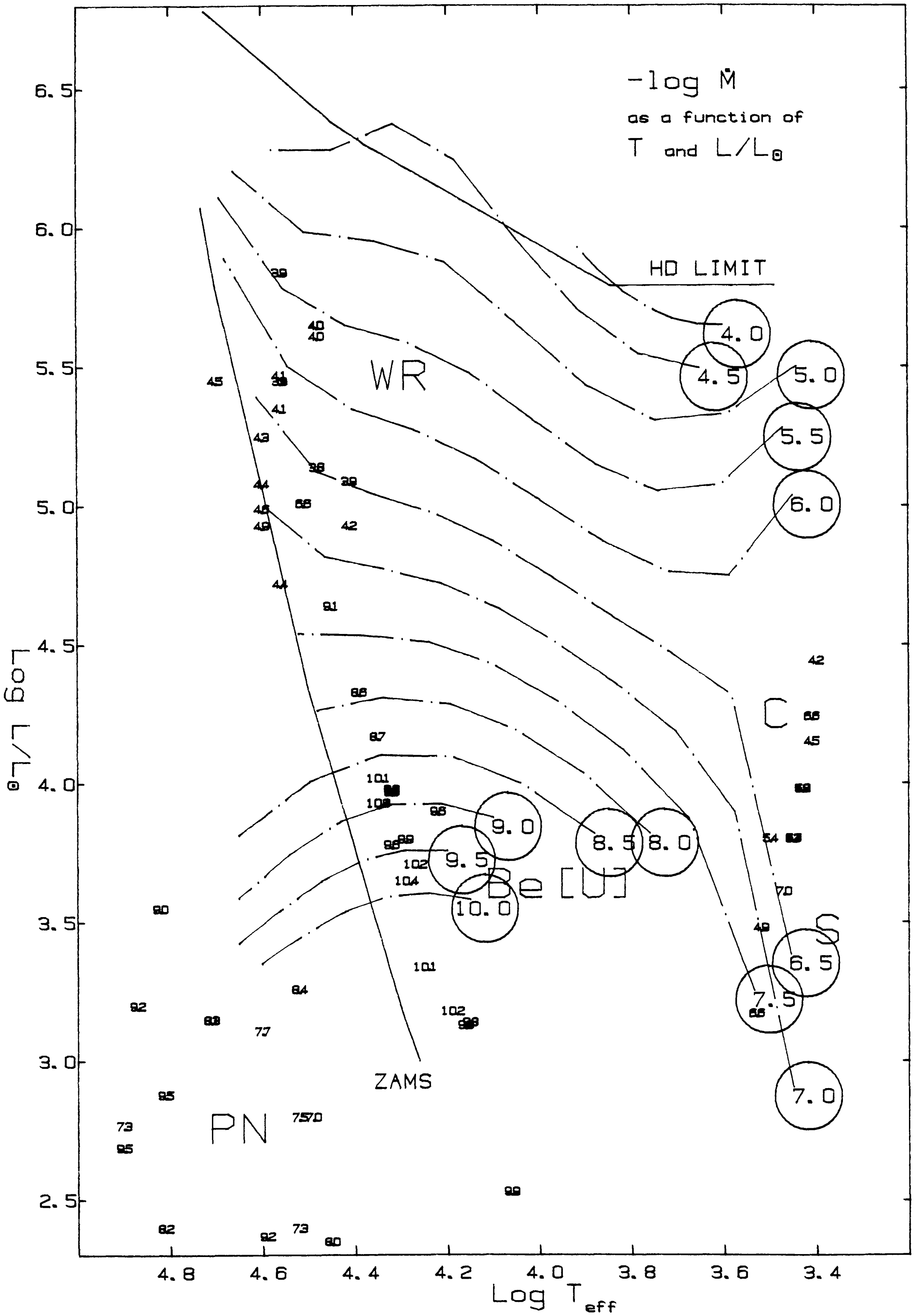

FIGURE 5. — The Hertzsprung-Russell diagram with the lines of equal rates of mass loss (taken from Fig. 1). The rates of mass loss of special groups of stars are given at their relevant (T ; L) position. The numbers give – log (– $\dot{M}$) in solar masses per year to the first decimal. WR : Wolf-Rayet stars (Tab. VII) ; C, S : C and S stars (Tab. IX), Be : Be-type stars, the $\dot{M}$-values derived from UV measurements, (Tab. X) ; PN : nuclei of planetary nebulae (Tab. XI).

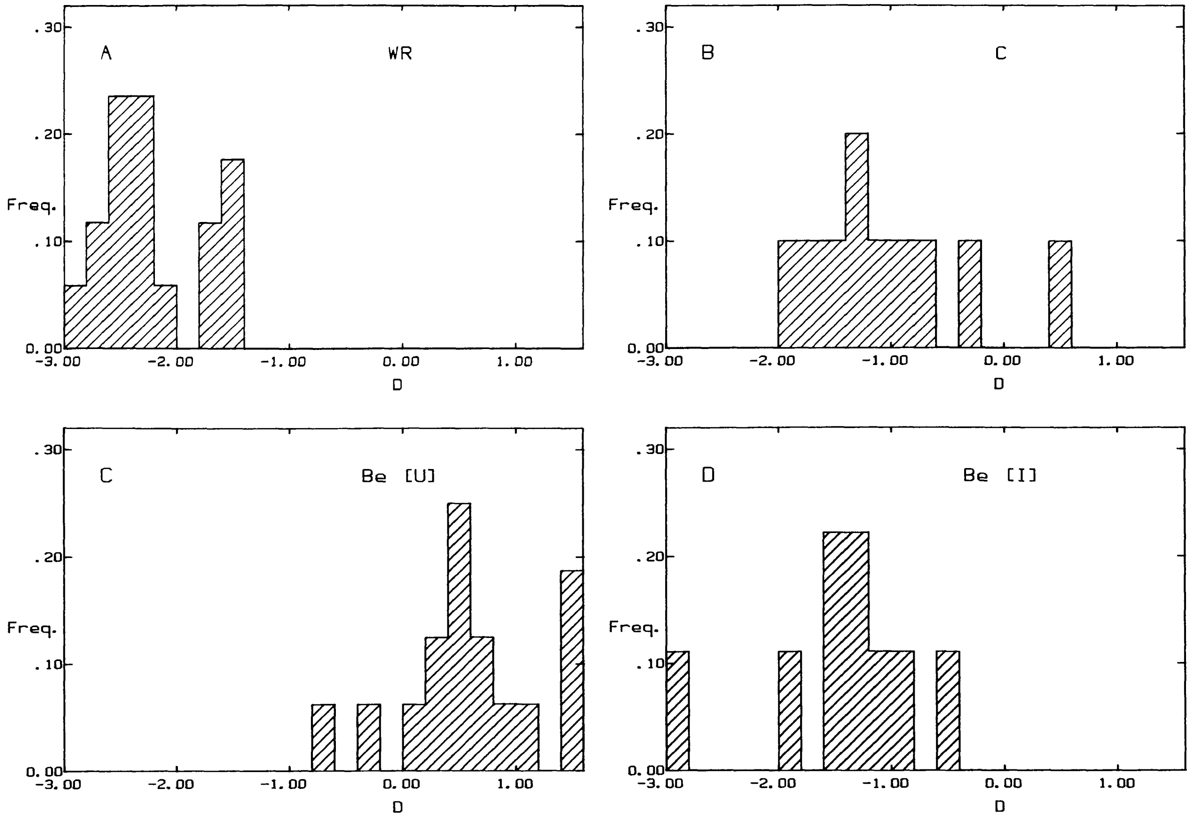

FIGURE 6. — Histogram of the differences D between the actual rates of mass loss and the values calculated with Eq. (1). A negative D-value means that the observed mass loss rate is larger than the calculated one. A : Wolf-Rayet stars ; B : C stars ; C : Be stars with $\dot{M}$ determined from ultraviolet resonance lines ; D : the same but from infrared continuum measurements.