THE DEPENDENCE OF MASS LOSS ON THE BASIC STELLAR PARAMETERS.

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I. INTRODUCTION

We determined the dependence of mass loss on the stellar parameters for O and B stars of various luminosities. We used four homogenous sets of mass loss rates derived by different authors from the radioflux, the infrared excess, the UV lines and Hα emission. As the rates derived from the radio flux are the least dependent on model assumptions for the stellar wind, these will be adopted as our standards. The others sets of mass loss rates will be corrected for the differences in the adopted wind model, especially in the velocity law, by scaling the rates to those derived from radio data, using the stars which the different sets have in common.

II. STELLAR PARAMETERS AND MASS LOSS RATES

We used the new effective temperatures derived by Underhill et al. (1979) and Remie and Lamers (1981). The radius was derived from the angular diameter (same references), or from T_{eff} and M_{bol}. The masses were derived from the evolutionary tracks by de Loore et al. (1978) with a mass loss rate of $\dot{M} = 100\,L/c^2$. The adopted masses are not sensitive to this assumption. The gravity was derived from M and R, corrected for radiation pressure.

The sources for the mass loss rates are listed in Table 1.

TABLE 1.

THE SOURCES FOR MASS LOSS RATES

Method	Nr stars	Spectral type	Luminosity class	Scaling $\Delta \log \dot{M}$	Reference
Radio	4	O4 - B1	Ia, Of	0.00	Abbott et al. (1980)
Infrared	30	O4 - B9	Ia^+,Ib,Of	+ 0.34	Barlow & Cohen (1977)
UV	25	O4 - B1	Ia - V	0.00	Gathier et al. (1981)
Hα	13	O3 - O9.5	III - f	- 0.27	Conti & Frost (1977) Klein & Castor (1978)
Total	53	O3 - B9	V - Ia^+		

C. Chiosi and R. Stalio (eds.), Effects of Mass Loss on Stellar Evolution, 19–25.

The scaling factor, $\Delta \log \dot{M}$, indicates the correction to be made to the mass loss rates given in the literature, in order to normalize the rates to the radio results. In total, we obtained a homogeneous sample of mass loss rates for 53 OB stars of all luminosity classes, covering a range of $\log \dot{M} = -4.68$ to -7.25 and $M_{bol} = -11.2$ to -6.0. The mass loss rates are plotted versus M_{bol} in Figure 1. Notice the large spread in $\dot{M}$ for any value of $M_{bol} < -8$. In this range, the supergiants and Of stars have a considerably larger mass loss rate than the giants and main sequence stars.

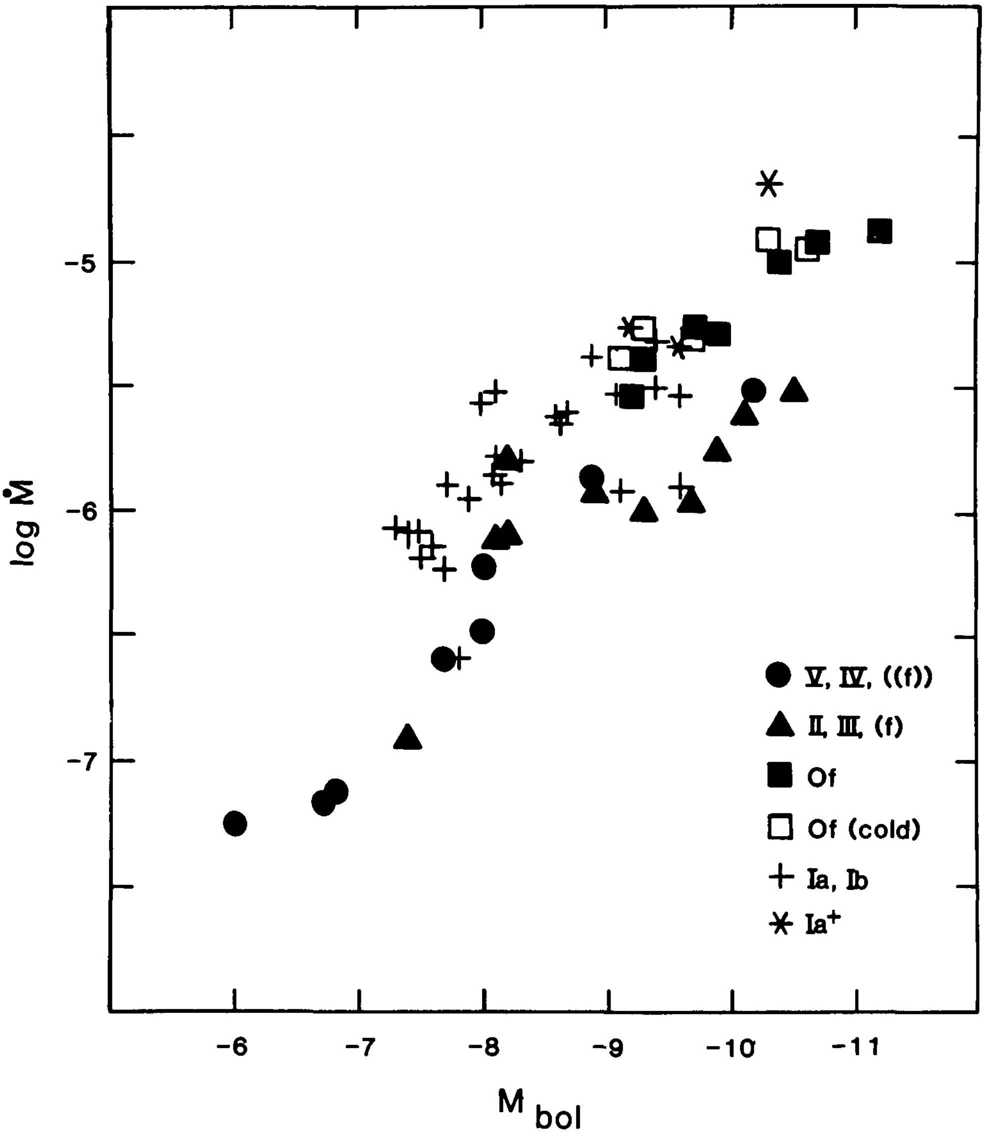

Figure 1. The mass loss rates as a function of M_{bol}. Notice the general trend and the dispersion in $\dot{M}$ for stars of different luminosity classes.

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III. THE DEPENDENCE OF MASS LOSS ON THE STELLAR PARAMETERS

We found, by means of the standard multiple least-square regression technique, that the mass flux can be described by the relation:

$$\text{(1)} \quad \log F_m = -5.23\ (\pm\ 0.06) + 4.60\ (\pm\ 0.45) \log(T_{eff}/3.10^4) \\ -0.48\ (\pm\ 0.11) \log(g_{eff}/10^3)$$

where F_m is in g/cm^2 s; or that the mass loss rate can be described by the relation

$$\text{(2)} \quad \log \dot{M} = -4.83\ (\pm\ 0.28) + 1.42\ (\pm\ 0.40) \log(L/10^6) \\ -0.99\ (\pm\ 0.97) \log(M/30) + 0.61\ (\pm\ 0.13) \log(R/30)$$

where $\dot{M}$ is in $M_\odot$/yr and L, M, R in solar units. Both fits have a correlation coefficient of 0.95, a chi-square value of 0.72, and a root mean square difference between observations and theory of $\Delta \log \dot{M} = \Delta \log F_m = 0.17$. The difference between the predicted and observed rates are plotted in Figure 2. We notice that most of the stars fit the predictions within about $\Delta \log \dot{M} = 0.2$, except the Of stars with rates derived from Hα. These rates, however, are the most uncertain ones in our sample, as their determination involves corrections of the observed profile for rather uncertain photospheric profiles.

Our relation (2) differs from the empirical relation derived by Chiosi (1981), who found that $\dot{M} \propto (R/M)^{2.25}$ whereas we find $\dot{M} \propto (R/M)^{0.6}$. The difference is due to the fact that the mass loss rates from main sequence stars is higher in our sample than adopted by Chiosi, because we allowed for differences in the ionization balance in the winds of different stars (Lamers et al. 1980).

IV. COMPARISON WITH PREDICTIONS

The radiation driven wind models by Castor et al. (1975) predict a specific dependence of the mass loss rate on the stellar parameters and on the force multiplier parameters k and α. This theory predicts $\dot{M} \propto L^{1/\alpha} \propto L^{1.43}$ for $\alpha \simeq 0.70$, but a very small gravity dependence. The observed gravity dependence might be explained by assuming that the constant k is density dependent.

The fluctuation theory of mass loss by Andriesse (1979) predicts

$$\text{(3)} \quad \dot{M} = 5.78 \times 10^{-5}\ (L/10^6)^{1.5}\ (R/M)^{2.25}$$

The R/M dependence is much stronger than the observed $(R/M)^{0.6}$ dependence. In particular, the theory predicts about 30 times too large rates for late-B supergiants and 3 times too small rates for OB main sequence stars.

V. DISCUSSION

The large scatter in the $\dot{M}$, M_{bol} diagram of Figure 1 is largely due to differences in the stellar gravity or in M/R. We found a well defined correlation between either the mass flux and T_{eff}, g_{eff} or between $\dot{M}$ and L, R, M. The scatter in the residuals $\log \dot{M}_{obs}/\dot{M}_{pred}$ is only about $\pm$ 0.20 except for rates derived from Hα. The uncertainty in the observed mass loss rates is estimated to be of this order (see

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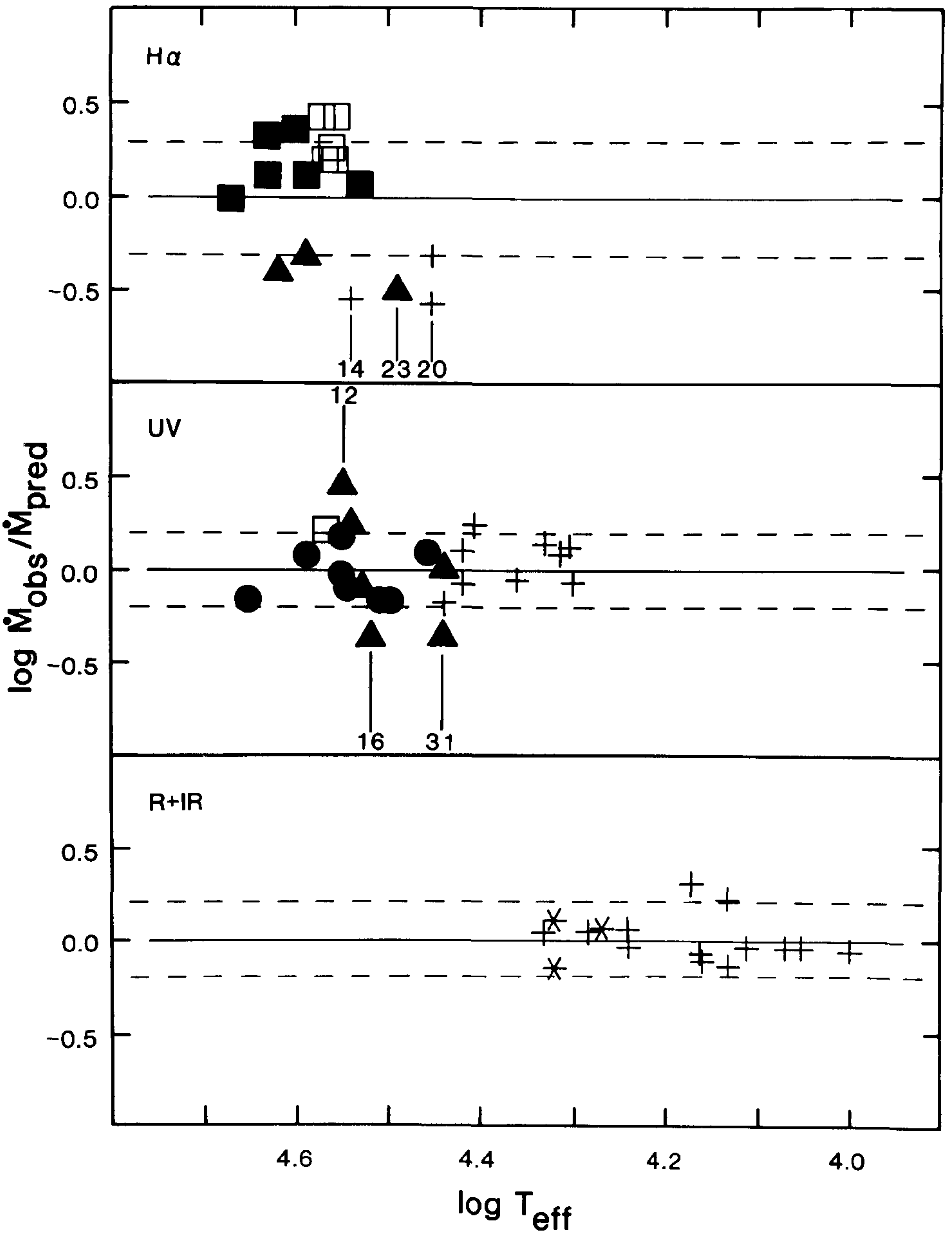

Figure 2. The difference between the observed and predicted mass loss rates as a function of T_{eff}. The three panels show results for three different determinations of $\dot{M}$ from Hα, UV, or radio and IR. The symbols are the same as in Figure 1. The most discrepant stars are indicated by their number (see Ap.J. paper).

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e.g. Gathier et al. 1981). Therefore it is quite possible that the residuals are totally due to uncertainties in the observational data. On the other hand, variations in the mass flux from normal (non-Be) stars have been observed (e.g. Snow, 1979). The fact that our mass loss rates derived from snap-shot observations, fit the mean relations within $\Delta \log \dot{M} \simeq 0.20$, indicates that the variablility in the mass loss rate is probably smaller or of the order of $\Delta \log \dot{M} \simeq 0.20$.

Thomas has introduced the concept of stellar individuality in order to account for large differences observed between similar stars (mainly fast rotators or Be-stars). The existence of the mean relations (1) and (2) indicates that the individuals deviate little from the mean party-line, at least as far as the mass loss rates are concerned. It is obvious that many extremists can be found in the camp of the Be-stars, which show both large variations and strong individuality. This clearly indicates that rotation plays a dominant role in the rapid rotating stars; a role which is far from being understood.

Adopting the mass loss rates given by equation (2) we find that from the ZAMS to the first core contraction phase a star of 100 $M_\odot$ loses 15 $\pm$ 2 $M_\odot$, a star of 60 $M_\odot$ loses 7 $M_\odot$, a star of 40 $M_\odot$ loses 3.8 $M_\odot$ and a star of 20 $M_\odot$ loses 1.1 $M_\odot$.

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DISCUSSION

KWOK: Since Dr. Lamers put so much emphasis on the radio data, I would like to point out that we have to be particularly cautious about evaluating radio interferometry data. Careful data reduction is also necessary. P Cygni was observed at 2cm at the VLA by C.R. Pinton and myself in March, 1980. The data reduction can be outlined in 3 steps: (1) removal of instrumental induced bad data by examination of visibility data; (2) correct the measurements by an antenna solution constructed from the calibrations; and (3) cleaning. Three methods were used to obtain the flux values: (1) construction of maps of different resolutions; (2) cleaning over different areas of the map to determine the effect of sidelobes; (3) fitting of elliptical gaussians to cleaned maps and directly to the visibility data. We obtained flux value of 15±3 mJy at λ 2cm. I would like to report that R. Newell of New Mexico Tech. has recently measured P Cygni at the VLA finding 6±1 mJy at λ 6 cm which is lower that the value reported by Abbott et al. (1980).

HACK: You have assumed that v(r) is the same for all stars. Actually there is observational evidence that this law is not the same for all stars. Have you guessed how different velocity laws effect $\dot{M}$ determinations?

LAMERS: The mass loss rate from the radio excess is not sensitive to the velocity law. The rate from the UV line is sensitive to the velocity law, but not terribly: a drastic change in v (r) does change the column density by less than a factor 2. The mass loss rates from the infrared are sensitive to the velocity law very close to the star. Panagia (in Tanzi, Tarenghi and Panagia; these proceedings) has shown that if the velocity changes from $v(r) \propto r^1$ to $v(r) \propto r^4$ the mass loss rate increases by a factor 2. So the mass loss rate determinations are dependent on the adopted velocity law, but I think that possible errors are about a factor two at worse.

ANDRIESSE: I was pleased to hear that Lamers' analysis arrives at a dependence of mass loss with luminosity close to the one predicted by the fluctuation theory. He stressed, though, that the dependence with radius and mass is different from the one predicted by this theory. But how does he get masses from observational data?

LAMERS: The effective temperatures are from the most reliable scales from integrated flux measurements (Underhill et al., 1979, MNRAS, 189, 601; and Remie and Lamers, 1980, in press). The radii are

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from the angular diameters, derived by the same authors, and the distances. The temperature and radius gives the location in the HR-diagram. This was compared with evolutionary tracks with moderate mass loss by de Loore et al., (1978, Astron. Astrophys. Suppl. 34, 363, N = 100).

STALIO: How do conciliate variability in mass loss, which is shown to be quite large from the UV lines, with the $\dot{M}$ vs M_{bol} diagrammes?

LAMERS: The variability in mass loss rate for normal (non-Be) stars is of the order of 50 percent. This will show up as a scatter in the relations between $\dot{M}$ and the stellar parameters. The r.m.s. scatter in my fits is about 0.17 in $\Delta \log \dot{M}$, part of this may be due to variability.

CHIOSI: There is a similar analysis by myself based on Conti and Garmany (1980) data which showed much larger dispersion in the $\dot{M}$ - M_b plane than presented here. In performing this analysis the major uncertainty was related to the determination of the mass of these stars which rests on the luminosity, effective temperature, and underlying evolutionary stage. Owing to the many uncertainties affecting this type of analysis one might perhaps infer that the $\dot{M} = \dot{M}$ (L, R, M) relationship that you have obtained coincides with the simple law $\dot{M}$ = (const) LR/M. Finally the much smaller dispersion existing in your data may account for the fact that your relations quantitatively differ from the one I found.

LAMERS: The smaller scatter in $\dot{M}$ - M_{bol} plane for our data compared to the data by Conti and Garmany (who used our data, except for a small numbers of stars observed by IUE) is mainly due to the assumed rates for the main sequence stars. In calculating the rates, Conti and Garmany assumed the same degree of ionization in the wind as in ζ Pup (Lamers and Morton, 1976) or in τ Sco (BoV; Lamers and Rogerson, 1978). However, a study of the UV profiles in a large number of stars by Gathier, Lamers and Snow (1980, Ap J, in press) has shown that the ionization in the winds varies drastically from star to star. Taking into account this effect, we found that the rates of the main sequence stars go up by a factor about 10. This reduced the scatter in the $\dot{M}$ - M_{bol} plane drastically. Consequently, I found in my analysis that the dependence of $\dot{M}$ on gravity or on M/L is less steep than from the Conti and Garmany sample, and indeed may fit with the standard $\dot{M} \propto$ LR/M law. I do not think that the masses are the most uncertain factor. I derived the masses from evolutionary tracks with $\dot{M}$ = 100 L/c^2. After having derived the relation $\dot{M}$ = f (L, M, R), I checked the effect of $\dot{M}$ on the evolutionary tracks and ound that the values of M are reasonably accurase.