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Radiation driven winds of hot luminous stars

II. Wind models for O-stars in the Magellanic Clouds

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Summary. Wind models are calculated for O-stars in the Magellanic Clouds using the modified radiation driven wind theory developed by Pauldrach et al. (1986). For the calculation of the radiative line forces a lower metallicity is adopted: $Z_{\rm LMC} = 0.28 * Z_{\rm Galaxy}$; $Z_{\rm SMC} = 0.1 * Z_{\rm Galaxy}$. As a result, significantly weaker winds are obtained in the Clouds than in the Galaxy, which show smaller mass-loss rates $\dot{M}$ *and* terminal velocities v_∞. Our calculations, in which wind models computed along evolutionary tracks for each of the three galaxies are used, confirm quantitatively the observations of Garmany and Conti (1985) who found generally lower terminal velocities in the Clouds.

Key words: galaxies: Magellanic Clouds – stars: atmospheres of – early-type stars – stars: mass loss.

1. Introduction

The winds of hot luminous stars in the Magellanic Clouds are subject to intense observational study. The major objective is the investigation of the influence of metallicity on the strength of the stellar winds. As the analysis of H II region emission line spectra (see for instance Dufour, 1984) indicates a significant underabundance of metals in the LMC as well as in the SMC (here even more pronounced), the clouds are ideal for a comparative study of stellar winds relative to our galaxy. In this way Hutchings (1982) and Bruhweiler et al. (1982) found first the evidence that the luminous stars in the Clouds show winds that are weaker than those of their galactic counterparts. Since these results were based on IUE spectroscopy of either every luminous super-giants (which show even in our own galaxy severe pecularities) or on objects with mainly photometric spectral types (for discussion of this uncertainty see Garmany and Conti, 1985), it was not completely clear whether this would hold in general for the massive stars in the Magellanic Clouds.

Consequently Garmany and Conti (1985) carried out a new comprehensive study based on a sample of "normal" OB-stars with well defined spectral types. The main result that they found was a characteristic difference between the galactic and the Magellanic Clouds stellar winds with respect to their velocities. For O stars of luminosity classes between III and *V* the terminal wind velocities v_∞ in the LMC and the SMC are about 600 km s^{-1} and 1000 km s^{-1} lower than in the galaxy (see Fig. 1). Since v_∞ is a well defined quantity which can be measured with high precision ($\pm 10\%$), this is a very significant result and merits a quantitative interpretation on the basis of stellar wind theory.

The most promising way to explain the correlation of v_∞ with metallicity is the theory of radiation driven winds, where the accelerative force is obtained from the radiative momentum absorbed by UV metal lines. This theory was introduced by Lucy and Solomon (1970), was first formulated in a self-consistent form by Castor, Abbott and Klein (1975, "CAK") and was later modified by Abbott (1982), who used a realistic line force based on an extensive tabulation of metal lines. Pauldrach et al. (1986, Paper I) improved the theory further by relaxing the so-called radial streaming approximation and investigated the validity of the Sobolev approximation for the calculation of the line force. With their modified theory they calculated self-consistent radiation driven wind model atmospheres for individual OB-stars in the galaxy. A comparison between theory and observation showed reasonable agreement for v_∞ *and* mass-loss rate $\dot{M}$ not only for O-stars but also for B-supergiants such as the extreme object P-Cygni. Thus the theory is obviously in a very reliable state, at

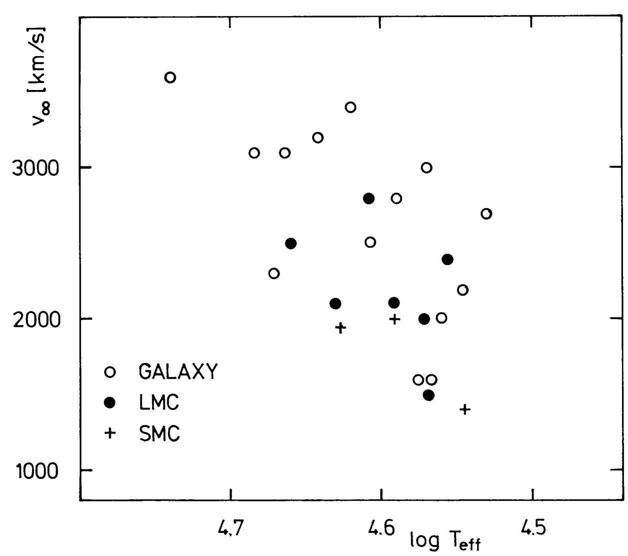

Fig. 1. Observed terminal velocities v_∞ as a function of effective temperature for O-stars in the Galaxy(O), LMC(●), SMC(+). The data are taken from Garmany and Conti (1985)

Send offprint requests to: R.P. Kudritzki least for luminous stars with galactic metal content.

In this paper we wish to investigate whether the improved theory can also reproduce the observed wind properties of luminous stars in the Magellanic Clouds, when the metal abundance is reduced according to the values quoted for the Clouds. In particular, we will concentrate on the observed terminal velocities as displayed in Fig. 1, but mass loss rates $\dot{M}$ will also be discussed. Section 2 describes calculations of line forces analogous to those of Abbott (1982) but for reduced metal abundance. In Sect. 3, wind models are calculated for a typical O5 main sequence star with $T_{\rm eff} = 45{,}000$ K, $\log g = 4.0$, $R/R_\odot = 12$ and three different metal abundances ($Z_{\rm Gal}$, $Z_{\rm LMC}$, $Z_{\rm SMC}$). It will be shown that not only $\dot{M}$ but also v_∞ is significantly reduced by lowering Z. Section 4 contains the quantitative interpretation of the Garmany and Conti results (as displayed in Fig. 1) on the basis of evolutionary tracks by Pylyser et al. (1985) for LMC, SMC and the galaxy and wind models calculated along the tracks. A discussion of the ($\log \dot{M} - \log L$) relation for the different galaxies is also given.

2. Calculations of the line force for low metal abundances

For the set of solar abundances Abbott (1982) has calculated line forces as function of depth in the atmosphere using the Sobolev approximation and a list of more than 250,000 lines that is essentially complete for the first to sixth stages of ionization from H to Zn. In these calculations a simple approximation for the treatment of the ionization in non-LTE was used (Eq. (8) in Abbott's paper) and LTE was assumed for the population of excited levels. (Both assumptions need to be critically assessed in the future, but, for reasons of simplicity, are kept for the moment in this differential study). The line force for a given model (characterized by $T_{\rm eff}$, $\log g$, Z, $R/R_\odot$) is then parametrized by the force multiplier

$$M_A(t) = k t^{-\alpha} (n_E/W)^\delta . \tag{1}$$

Here k, α, δ are fit constants for an individual model and are determined iteratively (see Paper I). They will be discussed below. The atmospheric depth parameter t is defined as

$$t = \sigma_{\rm Th} \rho v_{\rm th} (dv/dr)^{-1} . \tag{2}$$

ρ is the mass density, $v_{\rm th}$ the thermal velocity of hydrogen, $\sigma_{\rm Th}$ the electron scattering coefficient, v the velocity and r the radial coordinate. In addition n_E is the electron density (in units of $10^{11}\,{\rm cm}^{-3}$) and W is the dilution factor. Relaxing the radial streaming approximation (see Paper I) the acceleration $g^L_{\rm rad}$ due to the line force is related to $M_A(t)$ by

$$g^L_{\rm rad} = \frac{1}{c\rho(r)} \sigma_{\rm Th}(r) \sigma_B T^4_{\rm eff} M_A(t) (2/(1-\mu_*^2)) \times \int_{\mu_*}^{1} \left(\left((1-\mu^2)\frac{v}{r} + \mu^2 \frac{dv}{dr} \right) \Big/ \frac{dv}{dr} \right)^\alpha \mu \, d\mu . \tag{3}$$

Here c is the light speed, σ_B the Stefan-Boltzmann constant, μ the usual cosine of the angle between the ray direction and the outward normal on the spherical surface element and μ_* is defined by

$$\mu_* = (1 - (R_*/r)^2)^{1/2} . \tag{4}$$

It gives the cosine of the angular extent of the photospheric disk (with radius R_*) as seen from r.

The meaning of the fit constants is as follows (see also Abbott, 1980 and 1982): k is related to the number of all lines contributing effectively to the line force in all depths; δ and α describe the depth dependence of the line force. The change of the line force due to changes in the ionization balance through the atmosphere is parameterized by δ and is based on the radiation ionization model mentioned above (see Abbott, 1982), while α is related to the ratio of weak to strong lines, $\alpha = 1, (0)$ implies that only strong (weak) lines accelerate the wind. If in a simplified model n_w, n_s are the numbers of weak and strong lines, respectively, that contribute to the line force, then α is given approximately by

$$\alpha = \frac{1 - (d \ln n_s / d \ln t)(1 - \langle \tau_W \rangle)}{1 + n_W \langle \tau_W \rangle / n_s} . \tag{5}$$

(see Abbott (1980)) where $\langle \tau_W \rangle$ is the average optical depth of the weak lines.

In Paper I we have used Abbott's (1982) Table 2 to determine k, δ, α for individual wind model atmospheres of hot luminous stars with solar abundances. The data are given in Table 1.

For the Magellanic Cloud O-stars we had to calculate new line forces for reduced metal content in analogy to Table 2 of Abbott (1982). For this purpose we used the identical line list (which was carefully debugged with respect to data errors). As the calculations were made with a new program independently developed in Munich, we first recalculated Abbott's data for solar abundance to test the code. Almost exact agreement was found. We then started the calculations for the LMC and SMC. For simplicity, we did not adopt the individual abundance pattern quoted for the Clouds, for instance by Dufour (1984). Instead, we simply scaled down all abundances by a constant factor assuming

$$Z_{\rm LMC} = 0.28 Z_{\rm Gal} , \quad Z_{\rm SMC} = 0.1 Z_{\rm Gal} . \tag{6}$$

This procedure is consistent with the evolutionary calculations by Pylyser et al. (1986), which will be used in Sect. 4. (Calculations with individual abundance patterns will be useful as soon as individual stellar abundances for Magellanic O-stars become available by means of modern ground based and HST-observations together with quantitative non-LTE spectroscopy (see Kudritzki and Hummer, 1986; Gehren et al., 1986; Kudritzki, 1985)).

Table 1 contains the fit constants k, δ, α as obtained from these calculations. They allow a first discussion of the relative values in $\dot{M}$ and v_∞ to be expected from the detailed wind calculations.

For the relevant domain in the wind, characterized by $-6 \le \log t \le -2$ and $-2 \le \log n_E/W \le +2$, we find for the line force multiplier the expected inequality

$$M_A^{\rm Gal}(t) > M_A^{\rm LMC}(t) > M_A^{\rm SMC}(t) . \tag{7}$$

This means that a corresponding inequality will hold for the mass-loss rates in the galaxy, LMC and SMC. The velocity field is mainly determined by the parameter α which gives the depth dependence of the line force. We find

$$\alpha^{\rm Gal} > \alpha^{\rm LMC} > \alpha^{\rm SMC} , \tag{8}$$

which can be easily understood in terms of the metallicity. As the metal abundance decreases from the galaxy to LMC and SMC, the ratio of strong to weak lines must decrease accordingly. This means, however, that the acceleration due to the line force in the outer layers is strongest in the galaxy and weaker in the LMC

Table 1. Line force multiplier parameters k, α, δ

	$Z = Z_{Gal}$		
	k	α	δ
$30{,}000\,K \le T_{eff} \le 40{,}000\,K$	0.17	0.590	0.09
$40{,}000\,K \le T_{eff}$	0.124	0.640	0.07
	$Z_{LMC} = 0.28 Z_{Gal}$		
	k	α	δ
$30{,}000\,K \le T_{eff} \le 37{,}500\,K$	0.164	0.557	0.088
$37{,}000\,K \le T_{eff} \le 42{,}500\,K$	0.127	0.589	0.062
$42{,}000\,K \le T_{eff}$	0.089	0.627	0.100
	$Z_{SMC} = 0.1 Z_{Gal}$		
	k	α	δ
$30{,}000\,K \le T_{eff} \le 40{,}000\,K$	0.128	0.552	0.138
$40{,}000\,K \le T_{eff}$	0.097	0.580	0.104

and SMC. Consequently, we expect smaller terminal velocities in the Clouds than in the galaxy. The effect will be enhanced due to the increase in δ, in particular in the SMC, which causes a stronger decrease in the line force with decreasing density. A quantitative discussion will be given in the next two sections.

3. Wind models for a typical O5 V-star

Using the line forces of the previous section we now calculate wind models for a typical O5 V star with $T_{eff} = 45{,}000\,K$, $\log g = 4.0$ and $R/R_{\odot} = 12$. To investigate the effect of metallicity we compute three models with Z_{Gal}, Z_{LMC}, Z_{SMC}. The results are summarized in Table 2, in which $\dot{M}$ and v_{∞} are given together with the location of the critical point r_c (in units of the stellar radius R_*) and the wind efficiency $\dot{M} v_{\infty} c/L$. As was to be expected the mass-loss rates decrease from Z_{Gal} to Z_{SMC}. However, compared with present day observational accuracy the effect is only moderate showing $\dot{M} \sim Z^{+0.47}$ between the two extreme metallicities.

On the other hand, the reduction of the terminal velocity for Z_{SMC} by $900\,km\,s^{-1}$ is a clearly observable effect. It can be discussed on the basis of the scaling relation given in paper I which reads

$$v_{\infty}^{es} = v_c^{es}(1 - R_*/r_c)^{-\beta}$$

$$v_c^{es} = 1/2 \left(\frac{1}{1 - (1+\alpha)(1 - (R_*/r_c)^2)^{\alpha}} \right)^{1/2} (\alpha\delta/\alpha - 1)^{1/2} v_{esc} \qquad (9)$$

$$\beta = 0.95\alpha + 0.032 v_{esc}/500\,km\,s^{-1} + 0.008/\delta,$$

where v_c^{es} is the estimated velocity at the critical point and is proportional to v_{esc}, the escape velocity from the photospheric surface

$$v_{esc}^2 = 2GM(1 - \Gamma)/R_*. \qquad (10)$$

According to Paper I, the exponent β is also useful for an analytical description of the velocity field outward of the critical point ($r \ge r_c$)

$$v(r) = v_{\infty}(1 - R_*/r)^{\beta}. \qquad (11)$$

In Table 3 the values for v_{∞}^{es}, v_c^{es}, β for the three O5 V star models are given. They reveal that the main influence of α in the exponent β is to lead to smaller terminal velocities for the LMC and SMC. Thus, the change of the ratio of strong to weak lines due to the decreasing metallicity is the most important effect. (In addition the slight shift of the critical point r_c towards outer layers causes an additional decrease of v_{∞}^{es} on the basis of Eq. (9)). The effect of increasing δ on the exponent β, on the other hand, is compensated by its influence on v_c^{es}, which is larger in the Clouds than in the galaxy.

A comparison of the three velocity fields is shown in Fig. 2. It is evident that, from the critical point throughout the wind the velocity is significantly lower for the Magellanic Cloud metallicities. Such a difference in the velocity fields will be clearly observable on the basis of future UV-spectra with sufficient resolution and detailed line formation synthesis.

The efficiency of the radiation driven winds is reduced by a factor of 4 in the SMC relative to the galaxy. This means that for a given stellar luminosity, the stellar wind momentum for the interstellar medium is reduced by a factor of four. This might be of importance for the dynamical evolution of surrounding H II regions and scenarios of sequential star formation.

A detailed comparison of the results of our calculations with observations for a typical O5 V star with fixed parameters for all three galaxies is of course not possible. From stellar interior theory it is evident that because of the different metallicity, main sequence stars of the same mass will have different T_{eff} and R. We have therefore chosen an alternative way to compare Fig. 1 with the theory. This will be described in the following section.

Table 2. Stellar wind properties of a typical O5 V star $T_{eff} = 45{,}000\,K$, $\log g = 4.0$, $R/R_{\odot} = 12$) for galactic and Magellanic Cloud metallicity

	$\dot{M}$ ($10^{-6} M_{\odot}$/yr)	v_{∞} ($km\,s^{-1}$)	r_c/R_*	$\dot{M} v_{\infty} c/L$
Z_{Gal}	2.12	3350	1.036	0.66
Z_{LMC}	1.35	2900	1.047	0.36
Z_{SMC}	0.72	2435	1.052	0.16

Table 3. Estimated velocity field properties of a typical O5 V star according to the Equations (9) and (11)

	v_c^{es} ($km\,s^{-1}$)	β	v_{∞}^{es} ($km\,s^{-1}$)
Z_{Gal}	233	0.793	3343
Z_{LMC}	283	0.747	2871
Z_{SMC}	273	0.699	2232

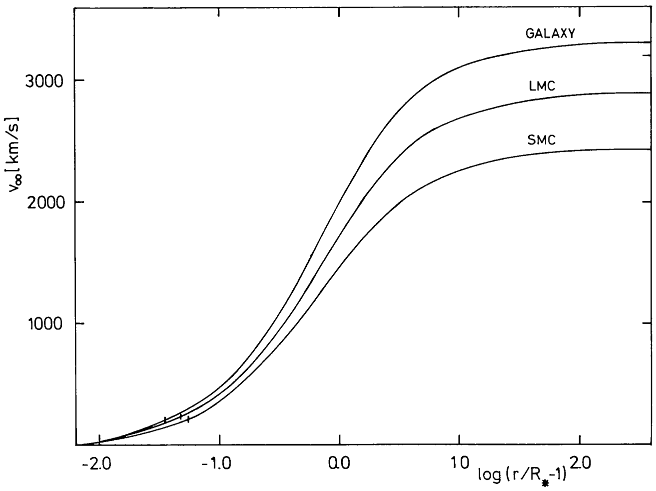

Fig. 2. The theoretical velocity field for a typical O5 V star in the Galaxy, LMC and SMC. For discussion see text. (The tick marks indicate the location of the critical point)

4. Comparison with observations

According to Eq. (9) the terminal wind velocity v_∞ depends on the wind parameter α, which is in turn determined by the number of strong and weak accelerating lines (see Eq. (1)). As shown in Sect. 2 α depends on the metal content. However, v_∞ also depends on the escape velocity v_{esc}. Since v_{esc} shows strong changes during the evolution of massive stars, a detailed quantitative comparison between theory and observation is not possible in principle without the accurate determination of stellar gravities by means of detailed NLTE spectral analysis. Such work is underway and results will be forthcoming soon (see Kudritzki and Hummer, 1986; Gehren et al., 1986; Kudritzki, 1985) but are not yet available at the moment. Therefore, we carry only out a general comparison of the Garmany and Conti (1985) observations given in Fig. 1 with our calculations. For this purpose we use the evolutionary tracks for the Galaxy, LMC and SMC that have been published very recently by Pylyser et al. (1985) and in which the same values for Z_{Gal}, Z_{LMC}, Z_{SMC} are adopted. In the upper parts of Fig. 3 the change of v_{esc} during the evolution away from the ZAMS is shown. As can be seen, the tracks form a band in the (v_{esc}, $\log T_{eff}$)-plane that is defined by the ZAMS and the $40\,M_\odot$ track. It is very similar in each galaxy. However, since the relation between v_∞ and v_{esc} is different for each galaxy because of the difference in α, we expect the corresponding bands in the (v_∞, $\log T_{eff}$)-plane to be shifted in height. The lower parts of Fig. 3 show that this is indeed true. For the Galaxy we obtain the highest v_∞-values along the tracks, whereas in the SMC v_∞ is significantly smaller at the ZAMS as well as in the supergiant stage. (For the construction of the (v_∞, $\log T_{eff}$)-diagram several wind models have been calculated along the tracks. These are marked by dots in the Figure. For positions between these marked points (crosses) we used a $v_\infty = f(v_{esc})$ relation obtained from the calculations at the neighbouring points). The relative position of the (v_∞, $\log T_{eff}$)-bands of the Galaxy, LMC and

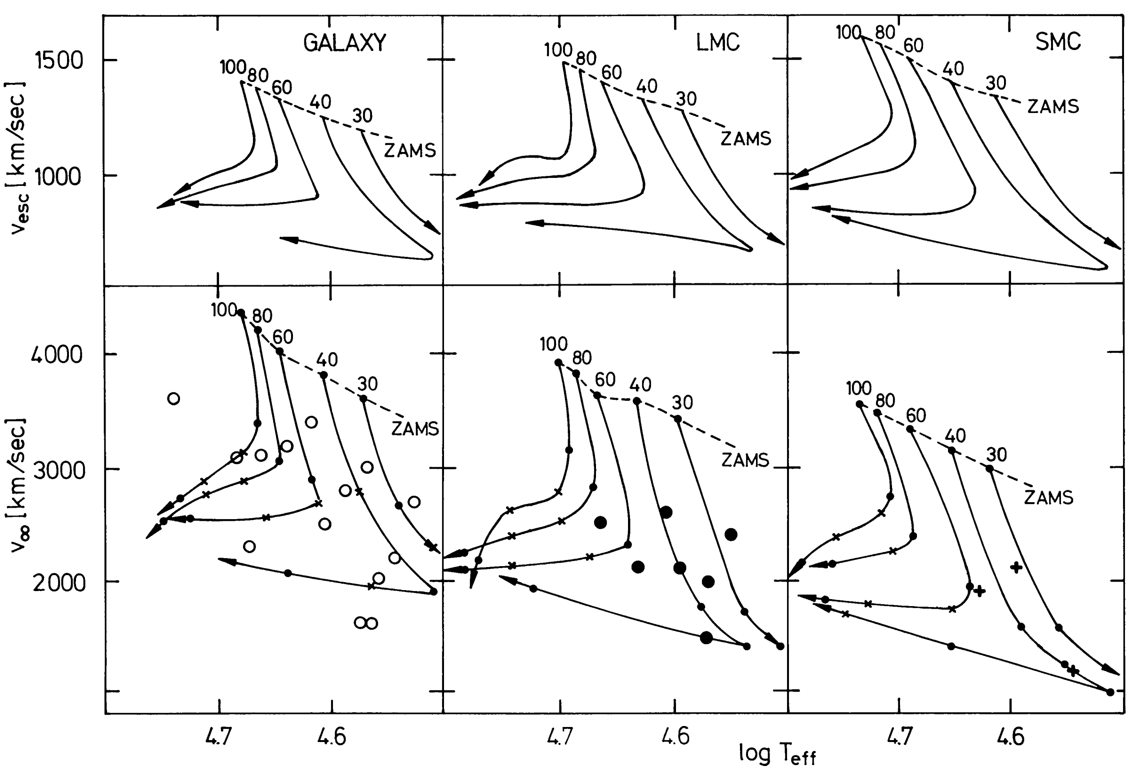

Fig. 3. Upper part: The change of surface escape velocity v_{esc} during the evolution of massive stars for the Galaxy, LMC, SMC. The curves are computed from evolutionary tracks by Pylyser et al. (1985) and are labelled by their initial mass at the ZAMS. Lower part: Terminal velocity v_∞ computed with our theory along the same tracks as in the corresponding upper diagram. Points where wind models have been calculated are marked by (●). At points marked by (x) the scaling relations (see text) have been used. Observed values from Fig. 1 have been added for comparison. For a detailed discussion see text

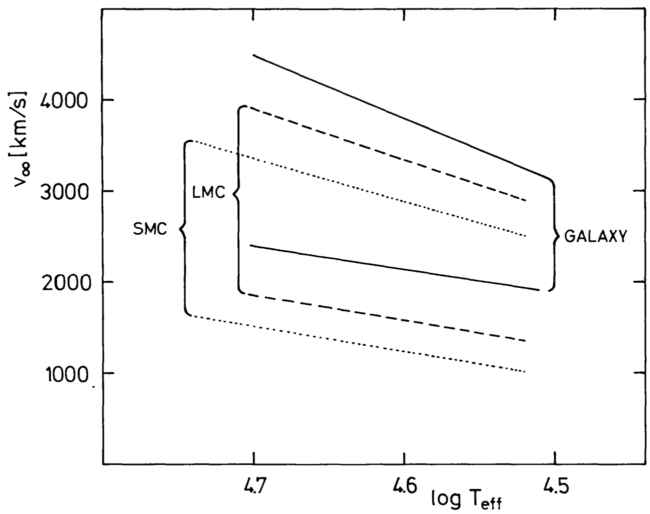

Fig. 4. The v_∞-bands as function of T_{eff} for the Galaxy, LMC, SMC as predicted by our theory

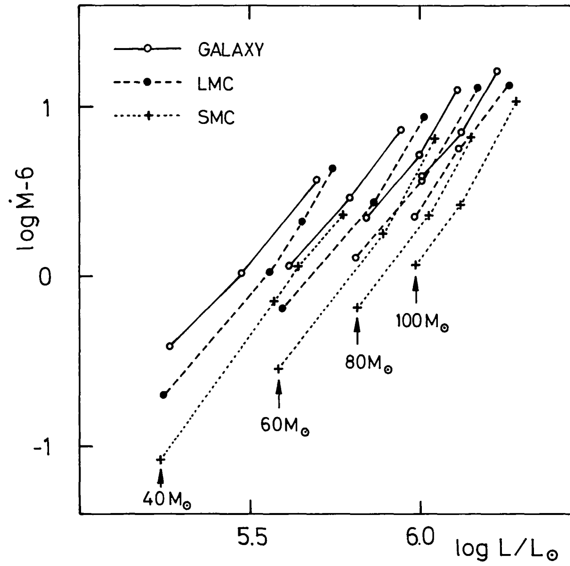

Fig. 5. The (log $\dot{M}$, Log L)-relation along the same tracks as in Fig. 3

SMC, as obtained from Fig. 3 taking the ZAMS as the upper and the 40 $M_\odot$ track as the lower limit are displayed in Fig. 4. Obviously the bands for the LMC and SMC are shifted downward relative to those of the Galaxy. This nicely explains the observations by Garmany and Conti (1985) (see Fig. 1), which indicate that on the average the terminal velocities are lower in the Magellanic Clouds. To demonstrate that the agreement is also satisfactory in a quantitative sense we have added to Fig. 3 the individual objects of each galaxy from Fig. 1. We conclude that the observed v_∞-values are well represented by our calculations. On the other hand, a slight selection effect is obviously present, in particular for the SMC, where observed data were available only for somewhat evolved objects of luminosity class III. Future observations of additional objects supplemented by spectral analysis for the determination of T_{eff} and $\log g$ will however help to put stronger observational constraints.

Selection effects of the same kind might also be responsible for the fact that Garmany and Conti (1985) could find no significant difference between the mass-loss rates in the three galaxies. How the mass-loss rates develop along the tracks according to our calculations is displayed in Fig. 5. The stellar parameter to which $\dot{M}$ is normally correlated is the luminosity L. As we see from Fig. 5, $\dot{M}$ is well correlated with L along each individual track. In addition, for tracks of same initial mass on the ZAMS the mass-loss rates are clearly smaller in the Magellanic Clouds. However, the diagram shows that, if evolved objects of lower mass in the SMC are compared with more massive but less evolved objects in the Galaxy because of a selection effect, then very similar mass-loss rates can be obtained. This again implies that an accurate determination of the stellar parameters is needed for such a comparison.

Another uncertainty for the comparison of mass-loss rates derived from UV-line spectra (besides the ionization calculation) is that the individual abundance of the ion showing the P-Cygni profile must be known. Up to now, mostly solar abundances have been adopted for galactic O-stars. The recent work on the brightest galactic O-star, namely ζ Puppis shows however that this is not always true. The atmosphere of ζ Puppis consists most probably of CNO burnt material. Apart from an increase in helium and nitrogen this implies a depletion of carbon as well (Kudritzki et al.,1983, Kudritzki, 1985; Butler and Simon, 1985; Bohannan et al., 1986). Thus, before using the C IV lines in IUE-spectra for estimates of mass-loss rates as usual, one has to determine the individual stellar carbon abundances. In view of these uncertainties the comparison of mass-loss rates has to be postponed.

5. Conclusions and future work

Our calculations, which are based on the modified radiation driven wind theory developed in Paper I show that the winds of luminous O-stars become significantly weaker in velocity and density if the metal abundance is reduced to values suggested for the LMC and the SMC. In particular the decrease of the terminal velocity v_∞ observed by Garmany and Conti (1985) can be well reproduced by the calculations. This means that the theory of radiative driven winds generally appears to function correctly also at low metallicities as well. On the other hand, the results can also be interpreted as an indirect proof of the overall low metallicity in the LMC and SMC if one is willing to accept the wind theory as a priori correct.

With regard to the agreement with the observations our results are based on a statistical comparison using only spectral classification for the determination of the stellar parameters and average abundances for each object in the galaxy. In this way, the observed scatter in terminal velocity for a given T_{eff} (see Fig. 3) is attributed only to the change of escape velocity during the evolution. This scatter could, of course, also partially be induced by either chemical inhomogeneities or systematic abundance gradients in the individual galaxies. The recent study of galactic early main sequence B-stars by Gehren et al. (1985) indicates that chemical inhomogeneity is probably non-negligible, while the abundance gradient turns out to be surprisingly small. In addition, also the change of stellar surface composition of the O-stars during their evolution with mass-loss might be of importance.

Therefore the next step (besides improving the theory of radiation driven winds as outlined in Paper I) is to determine the precise parameters of O-stars in the Galaxy *and* in the Magellanic Clouds (T_{eff}, $\log g$, L *and* metal abundances) by the use of detailed NLTE model atmosphere techniques (for a description see Kudritzki, 1985 or Kudritzki and Hummer, 1986). This will allow an individual, star by star comparison between theory and observation and thus provide a crucial test of the quantitative reliability of the theory of radiation driven winds. It will also place severe observational constraints on the present theory of the evolution of massive stars where the treatment of mass-loss, convective overshooting and mixing is under debate.

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