WINDS OF HOT STARS IN THE MAGELLANIC CLOUDS

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1. Introduction

The Magellanic Clouds provide a unique laboratory in which to study the metallicity dependence of stellar winds. If proved by observations, such a dependence would have important consequences for stellar evolution, nucleosynthesis, energy balance of the ISM, star formation and so on. In addition, the diagnostics of emitting gaseous nebulae in metal-poor galaxies would be affected, since the photospheric ionizing radiation of massive hot stars is modified by metal absorption in the surrounding stellar winds (see recent review by Kudritzki *et al.* 1990). Moreover, the method of using mass-loss rates $\dot{M}$ and terminal velocities v_∞ to determine stellar distances, radii and masses (Kudritzki & Hummer 1990) would need further modification.

2. Winds in the Galaxy: theory and observations

Three basic observational facts characterize the winds from massive hot stars in the Galaxy:
- all stars with $M(ZAMS) \geq 15 M_\odot$ show winds (Snow & Morton 1976, Abbott 1979);
- the mass-loss rate is correlated with luminosity: $\dot{M} \sim L^{1.6}$ (Garmany & Conti 1985, Howarth & Prinja 1989);
- the terminal velocity is correlated with the photospheric escape velocity (Abbott 1982).

All three can, in principle, be explained nicely by the theory of radiation-driven winds, as developed by Castor *et al.* (1975) and Abbott (1982) and modified and improved by Pauldrach *et al.* (1986), Pauldrach (1987) and Puls (1987). The improved theory and its various applications to observations have been reviewed recently by Kudritzki and Hummer (1990), Kudritzki *et al.* (1990), Pauldrach and Puls (1990a,b). It is a full radiation-hydrodynamic treatment of spherically expanding atmospheres, where the radiative force is calculated completely in NLTE by solving simultaneously the detailed multi-level rate equations of 26 elements in 133 ionization stages, together with the radiative transfer and the hydrodynamic equations. In total, the absorption of more than 100000 lines is taken into account, including the "multi-line-effects" due to line overlaps. These extensive calculations reproduce not only (at least qualitatively) the hydrodynamical properties of hot star winds, but also the observed spectral characteristics.

R. Haynes and D. Milne (eds.), The Magellanic Clouds, 279–284.

3. The Magellanic Clouds: winds at low metallicity?

If it is true that the extremely young population of stars in the LMC and SMC has a significantly lower metallicity, then one would expect the winds in the Clouds to be weaker than in the Galaxy. Many observations were carried out to investigate this effect (for a summary, see Leitherer 1990). Generally, however, the results obtained suffered from the moderate quality of the data that was achievable. Most of the UV spectra were obtained in IUE in low resolution (or are very noisy if in high resolution); the optical spectra of H_α or HE II 4686 (to investigate mass-loss rates) taken so far were also of moderate resolution and quite noisy, or were limited to the very brightest objects with uncertain galactic counterparts. On the other hand, the data allow some very interesting first conclusions: Garmany and Conti (1985) and Garmany and Fitzpatrick (1988) used low resolution (!) IUE spectra to demonstrate that (statistically) the inequality

$$v_\infty^{SMC} \leq v_\infty^{LMC} \leq v_\infty^{GALAXY}$$

holds. The situation is not so clear with regard to mass-loss rates. Adopting *ad hoc* 1/10 solar nitrogen and carbon abundances for their SMC O-stars Garmany and Fitzpatrick deduced from the strengths of the N V and C IV wind lines that the mass-loss rates in SMC and Galaxy are comparable. However, as they point out, this might be a marginal conclusion because of the low-resolution quality of the data. On the other hand Leitherer (1988a,b) came to a similar conclusion using a completely different technique: the observed strengths of stellar H_α–lines. But again, his LMC/SMC H_α observations were only of intermediate resolution and S/N so that, in particular, the contamination with nebular H_α recombination (although accounted for in the reduction) might have affected the measurement of equivalent widths.

What is the prediction of the theory with regard to v_∞ and $\dot{M}$? We have used the improved wind theory as described in section 2 and calculated wind models along evolutionary tracks. For galactic metallicity we used the tracks by Maeder and Meynet (1987). For LMC (0.25 $Z_\odot$) and SMC (0.1 $Z_\odot$) metallicities we collaborated with M. El Eid and N. Langer (both Göttingen) to couple our wind code with their stellar evolution code (details of the collaboration will be published in *Astron. Astrophys.*) so that mass-loss rates and evolution are consistent. (These new calculations supersede the older ones by Kudritzki *et al.* 1987, see also Kudritzki *et al.* 1990). Fig. 1 shows v_∞ as calculated along the tracks and compared with the observations. The agreement between theory and observations is satisfactory. The lower v_∞ in the SMC are nicely reproduced. Fig. 2 shows $\dot{M}$ resulting from the computations revealing a metallicity dependence of roughly $M \sim (Z/Z_\odot)^{1/2}$, which contradicts the conclusions drawn so far from observations (see above).

There are two ways out of the $\dot{M}$-discrepancies. First, the winds of the LMC, SMC stars are mainly driven by iron lines. If the SMC iron abundances in massive young stars were 1/4 solar instead of 1/10 solar, then - as Fig. 2 indicates - the problem disappears. Second, as we shall show in the next section, the very few cases where we have better quality data indicate the existence of lower mass-loss rates. The lack of adequate observational data will be overcome very soon, when the HST provides us with high-quality UV spectra of LMC and SMC stars. This will allow us to determine precisely abundances, mass-loss rates and velocities for individual objects in all evolutionary stages and to compare with the predictions of the theory. We are confident that this will settle the question of winds and metallicity.

4. Detailed diagnostics: results from the pre-HST era

4.1 QUANTITATIVE SPECTROSCOPY OF PHOTOSPHERIC LINES

The deeper atmospheric layers ("photospheres") are unaffected by stellar winds. Analysis of their absorption-line spectra by means of hydrodynamic NLTE model atmospheres provides useful and precise information about stellar T_{eff} log g and abundances. The Munich group and their Boulder collaborators have applied this technique on optical spectra of O-stars and B-supergiants in the Clouds using the ESO 3.6m telescope (e.g. see Kudritzki *et al.* 1989a,b). In this way accurate stellar parameters ($L/L_{\odot}$, $R/R_{\odot}$, T_{eff}, N(He)/N(H), log g) for a large sample of objects were obtained. The next step is to determine abundances, which for hot stars needs the UV capacity of the HST. However, for B-supergiants, which have a richer metal line spectrum in the optical, a first estimate of abundances differential to corresponding galactic objects is already possible (Lennon *et al.* 1990) (see Table 1):

Table 1. Relative abundances (log $\varepsilon_{MC}/\varepsilon_{Gal}$)

Element	LMC		SMC
	Sk 41-68°	Sk 21-65°	Sk 159
C	+0.06	-1.12	≤ -1.09
N	+0.03	-0.45	-0.07
O	-0.42	-0.82	-1.59
Si	-0.14	-0.87	-0.75
Mg	-0.78	-0.62	≤ -1.0

4.2 MASS-LOSS RATES

In Section 3 we reported a discrepancy between observed and theoretical mass-loss rates. For three objects of our sample discussed in section 4.1 we have data available already which allow a more precise test of the theory. The O7 If-star Sk 80=AV232 in the SMC is bright enough to allow a line profile fit of its high resolution IUE-spectrum (see Kudritzki *et al.* 1990, Fig. 17). The resulting log $\dot{M}$=-5.7 agrees with the prediction of the theory for $Z=1/10\ Z_{\odot}$. The early main sequence objects AV242 and 388 were observed with the ESO 3.6m telescope (EFSOC) to obtain H_{α} line profiles. The observed H_{α} absorption equivalent widths of 3.2 and 3.1Å, respectively, lead to very small mass-loss rates of log $\dot{M}\leq$-6.6 and -6.4, respectively, again in agreement with the theory. During the reduction of the H_{α}–data, the crucial point concerning H_{α} turned out to be the adequate subtraction of the contribution of the nebular recombination lines.

4.3 DIRECT DETERMINATION OF STELLAR MASSES, RADII AND DISTANCES

The theory of radiation-driven winds predicts that v_{∞} and $\dot{M}$ will depend significantly on stellar mass, temperature and radius (Kudritzki *et al.* 1989). If, for instance, temperature and radius are known from photospheric analysis and distances, v_{∞} allows the determination of the mass M (Kudritzki 1990). Fig. 3 shows masses obtained in this way compared with masses derived from the gravity. The agreement for galactic objects is striking. Note that the uncertainty for the v_∞-mass is significantly smaller than for the log g-mass. We have already obtained masses for five objects in the Clouds in this way. The HST will provide further masses for a large sample.

The strength of mass-loss rate $\dot{M}$ can be used to obtain additional information about the stellar radius (Kudritzki & Hummer 1990). Fig. 4 shows an example for Sk 80 in the SMC. It is obvious that this can become a powerful alternative technique to determine distances towards the Clouds. With the high S/N UV-spectra available soon with HST, we can apply this technique to a large sample of objects.

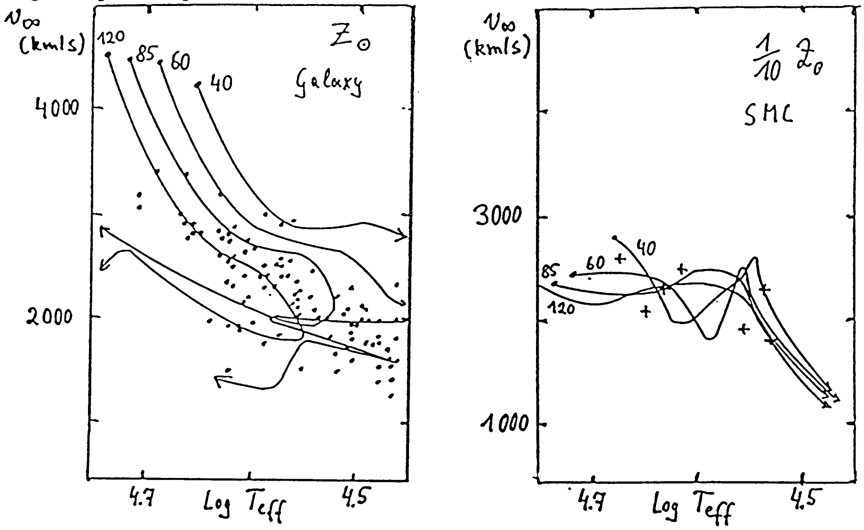

Figure 1. Terminal velocity v log T_{eff} along evolutionary tracks of different mass for solar metallicity (Galaxy) and 1/10 solar (SMC). The observations for the Galaxy (dots) and SMC (crosses) refer to O-stars with log $L/L_{\odot} \geq 5.4$ corresponding to track luminosity $M/M_{\odot} \geq 40$. The observed data are: Galaxy: Howarth & Prinja (1989); SMC: Garmany & Fitzpatrick (1988).

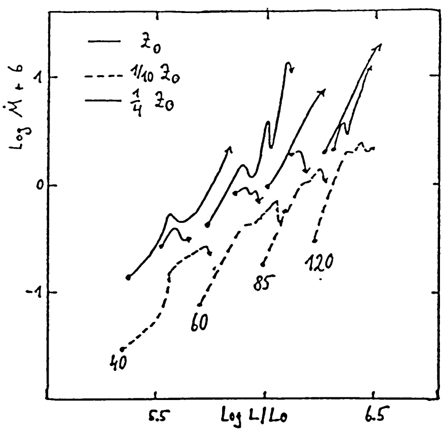

Figure 2. Logarithm of mass-loss rates as function of Z along evolutionary tracks.

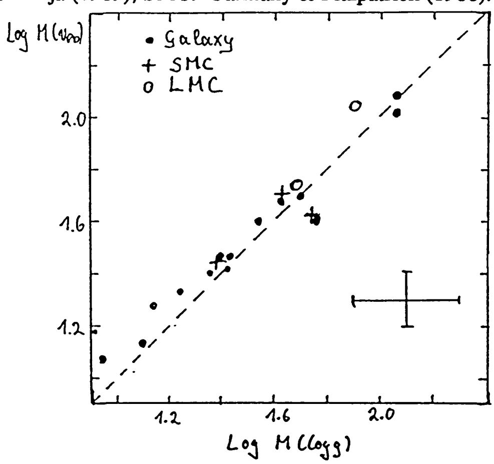

Figure 3. Log M derived from v_∞ v_s log M from gravity for objects in Galaxy, LMC and SMC.

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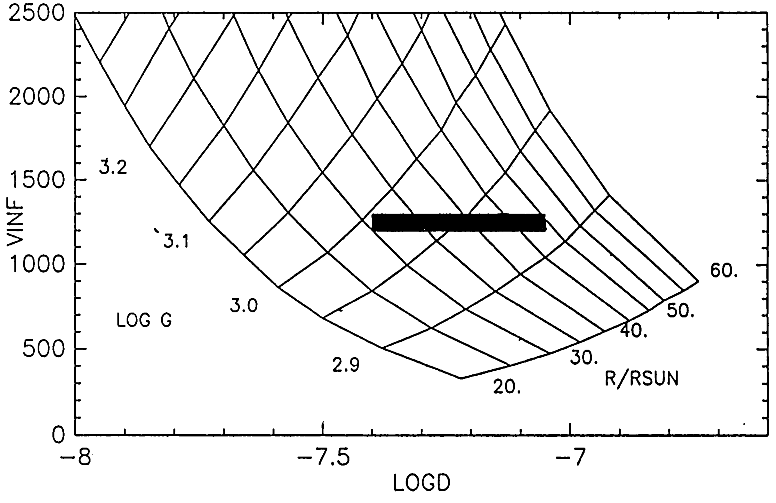

Figure 4. v_∞ and log D=log $\dot{M}$-log R/R$_\odot$ calculated for wind models for the SMC O7 If supergiant Sk 80=AV232. The solid box shows the observations within their uncertainties.

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