1990RvMA....3..124P

Radiation Driven Winds of Hot Luminous Stars. Applications of Stationary Wind Models

A.W.A. Pauldrach and J. Puls

Institut für Astronomie und Astrophysik, Scheinerstr. 1,
D-8000 München 80, Fed.Rep.of Germany

ABSTRACT

In this paper we describe the status of a continuing effort to calculate NLTE models of rapidly expanding hot star atmospheres including the hydrodynamics selfconsistently. In order to test our theoretical concept, we calculated a wind model for the O4I(n)f star ζ-Pup. An additional test was performed by calculating stationary wind models along evolutionary tracks. The fact that such models satisfactorily reproduce the observed luminosity dependence of the Si IV resonance line indicates that the theory can soon be used for quantitative analysis of stellar wind lines. We show further that the calculated dynamical parameters can already be used for a direct spectroscopic determination of stellar masses and radii. This is done not only for massive stars in our galaxy, but also for an O-star in the SMC.

I. INTRODUCTION

Massive hot stars do not preserve their mass. As a consequence of their intense radiation field, which is scattered by thousands of UV metal lines, they loose a substantial fraction of their initial mass via rapidly expanding stellar winds. Lucy and Solomon (1970) were among the first to show that the radiative line force exerted by the metal lines is sufficient to initialize and to maintain stellar winds and Castor, Abbott and Klein (1975), Abbott (1979) and Abbott (1982) formulated the theory of radiation driven winds in a self-consistent manner for the first time. Due to many simplifications their approach was, however, only qualitative, so that severe discrepancies with the observations remained: for OB-stars the mass loss rates ($\dot{M}$) were systematically too large by a factor 2-3 (Abbott, 1982) and, far more significantly, the terminal velocity (v_∞), a quantity which is measurable quite easily, was predicted to be a factor 2-4 too small. Moreover, the observed ionization ratios were not matched by the calculations.

The latter discrepancies were especially pronounced for highly ionized species like N V and O VI (Pauldrach, 1987) pointing to the problem of "superionization" (Cassinelli and Olson, 1979).

Although the work of Castor, Abbott and Klein was ground-breaking, these results made clear that a quantitative description of the radiation driven wind theory requires a careful solution of the complete equations of radiative transfer and atomic statistics including hydrodynamics at least in a one-dimensional, steady state model. There are many reasons to want to tackle this problem, but perhaps the most important one regards the evolution of massive stars, which is strongly affected by the mass loss due to stellar winds. Note that the rates of mass loss are still considered as a free parameter in evolutionary calculations. Of similar importance is the need to determine accurate and complete sets of stellar parameters in order to determine the evolutionary status of the stars studied and to check stellar evolutionary scenarios. Such parameters include effective temperature, surface gravity and chemical composition, for the determination of which the methods of photospheric quantitative spectroscopy (Kudritzki, 1988) is an excellent tool, and the stellar luminosity and mass, which can be obtained from the analysis of stellar wind lines (Kudritzki, 1990; Pauldrach and Puls, 1990; Pauldrach et al., 1990). Since the radius follows directly from this parameter set, the stellar distance can in principle also be obtained purely spectroscopically, i.e. without the need for any other assumptions. Massive hot stars can thus be used as ideal distance indicators.

We describe our effort to achieve this result in sect. IV, and partly in sect. III, where it is also shown that our calculations reproduce the observed changes of the Si IV spectral morphology. For this purpose it seems to be convenient to summarise the concept and the status of our computational method, which is done in sect. II.

II. CONCEPT OF THE COMPUTATIONAL METHOD

As in the basic framework for computing line driven winds (Castor, Abbott and Klein, 1975) we assume a radially symmetric, stationary, one-component flow, which should be appropriate to describe the time average mean of all important spectral features correctly. The primary aim is to develop accurate simulations of the basic physics in order to determine mass-loss rates, masses and luminosities for hot stars by only comparing observed and calculated UV P-Cygni profiles. For these calculations the only input parameters required are the effective temperature, the chemical composition and a guess of the surface gravity. In order to extract the desired information from this very small set of parameters we just need a 'black box' which solves the

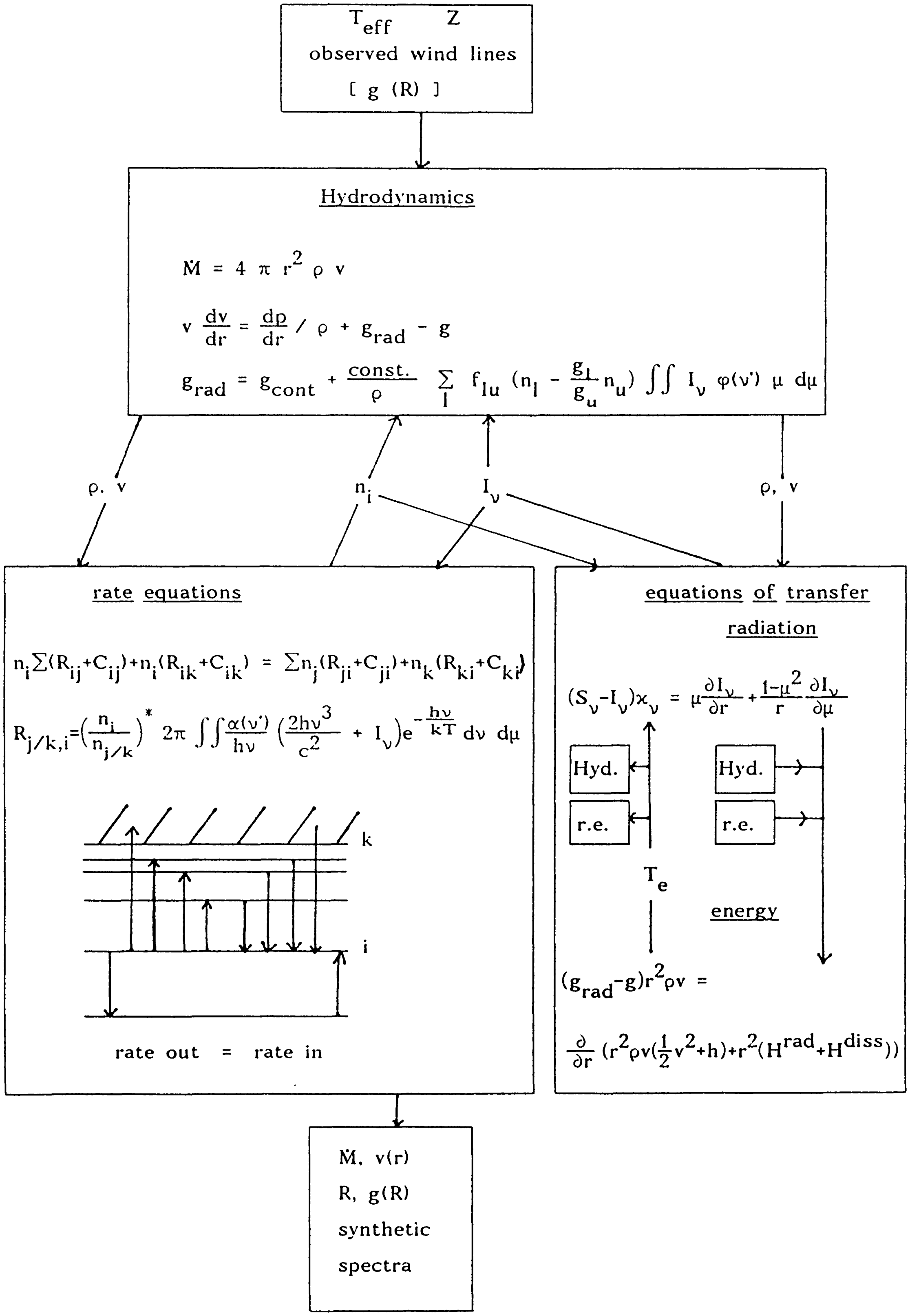


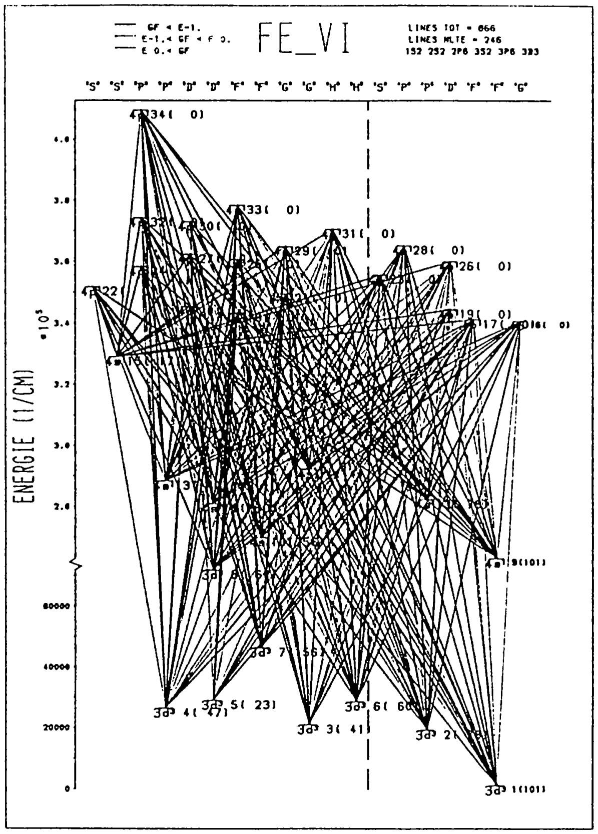
Fig. 1:
Schematic sketch of the extrem non-linear system of integro-differential equations which form the basis of radiation driven wind theory (symbols as usual – see e.g. Mihalas, 1978).

problem of time-independent radiation-hydrodynamics. As sketched in Fig. 1, this requires the simultaneous solution of several thousands of NLTE rate equations for the most abundant elements, of the line and continuum radiative transfer, the energy balance and the hydrodynamics. Since this is not an easy task, but a process requiring continuing effort, a final description is not yet available. However, as the theory has been drastically improved over the last years, the state of the art has reached a level which could be called "the first quantitative approach".

It is appropriate to summarise the present situation which led to this approach:

1. Detailed statistical equilibrium calculations are performed, (see Pauldrach, 1987) including:

   * 26 elements, 133 ionisation stages, 4000 levels, 10 000 radiative bound-bound transitions and electron collisions (Fig. 2a gives an



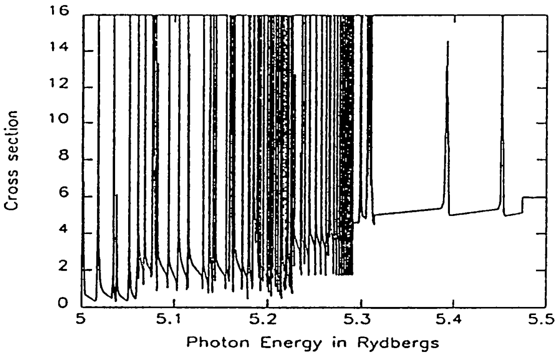


Fig. 2b: Photoionisation cross section of first ^3D state of Fe V (from Butler, 1990).

Fig. 2a: Grotian diagram of the used atomic model of Fe VI. On the right hand side of each level indicated: the excitation number and (in brackets) the number of lines for which only lower levels are considered, since the upper level lies above $5 \cdot 10^5$ cm^{-1} (data from K. Butler, private communication).

example of the atomic models used in our calculations. It should be noted that we have also begun to incorporate very detailed photoionisation cross sections (see Butler, 1990, and references therein) with all their resonances for all levels of the ions (see Fig. 2b)).

* the *correct* continuum radiative transfer with respect to bound-free opacities (up to 100 levels), free-free opacities of H, He and all metals and Thomson scattering. Since the NLTE-occupation numbers are a complicated function of the radiation field, an iteration cycle is required. For this iteration we used a modified form of the "accelerated lambda iteration" method, adapted to the case of O star winds (Pauldrach and Herrero, 1988).
* dielectronic recombination and autoionisation for C III and N III (data for other ions are on their way), using the method described by Mihalas and Hummer (1973). (Note that the wind conditions of O stars, which are not comparable to those of Planetary Nebulae, require the inclusion not only of the individual transition probabilities of each stabilizing downward transition considered, but also of the autoionisation process, which is not negligible)
* 100 000 lines in NLTE for the line force

2. In cases where the effect of multiple scattering turn out to be crucial, this is considered consistently for the most important 2000 or so lines (Puls, 1987; Puls and Pauldrach, these proceedings).
3. The hydrodynamical structure is computed by means of the improved theory of radiation driven winds which considers also stellar rotation in a simplified way (see Pauldrach, Puls and Kudritzki, 1986) and the whole procedure (1. to 3.) is iterated until convergence.

Very recently we took another step forward by extending our numerical concept of *wind* models to *atmospheric* models, which means that the wind is treated now together with the underlying photosphere (for details see Berger and Pauldrach, 1990; a short description is also given by Pauldrach et al., 1990b).

This approach to the theory of radiation driven winds is already self-consistent. However, one point should be borne in mind: our present treatment is still somewhat imperfect, because the energy equation is not solved consistently in the wind part, since in the winds of O-stars radiative equilibrium does not seem to be the proper assumption to make for the solution of the energy balance equations (Pauldrach et al., 1990b). The results of Pauldrach et al. indicate that energy is not only transported by radiation, but also by other dissipative mechanisms (H^{diss} in Fig. 1), which might be connected to instabilities in the wind (Owocki et al., 1989; Owocki, these proceedings), inferred from observations (e.g. Henrichs, 1988). Hence, up to now our procedure has been to choose a temperature structure based on empirical results (see Pauldrach et al., 1990, 1990b). The neglection of the presence of X-rays (see Cassinelli and Olson, 1979) and of NLTE line blocking and blanketing (the inclusion of these processes would require a NLTE temperature structure to be constructed also for the photospherical region) are additional shortcomings (see Pauldrach, 1990b).

Nevertheless, detailed comparisons with observations show that the basic ionization structure is not severely affected by these approximations and that, therefore, the dynamics of the average flow is treated correctly (see Pauldrach, 1987; Pauldrach et al., 1990a, 1990b). To demonstrate this, we report some results of our calculations for the O4f star ζ-Pup. For these calculations we adopted as input the parameters $T_{eff} = 42 \pm 2$ kK, log g = 3.5 ± 0.15, $R = 19 \pm 8\ R_{\odot}$, determined by Kudritzki et al. (1983) and Bohannan et al. (1985) via detailed photospheric NLTE analyses. From our self-consistent wind calculations we obtained dynamical parameters (v_{∞} = 2200 km/s, $\dot{M}$ = 3.8 · 10 $M_{\odot}$/yr) that agree quite well with the observed ones (v_{∞} = 2200 ± 60 km/s, Groenewegen et al. (1989), $\dot{M}$ = 4.5 · 10^{-6} $M_{\odot}$/yr, Bieging et al. (1989)). The same agreement was found for our calculated wind profiles, which are a by-product of our self-consistent treatment, when compared to the observed ones (see Fig. 3). This example demonstrates clearly that the various improvements in calculating hot star winds led to models which are also useful in a quantitative sense.

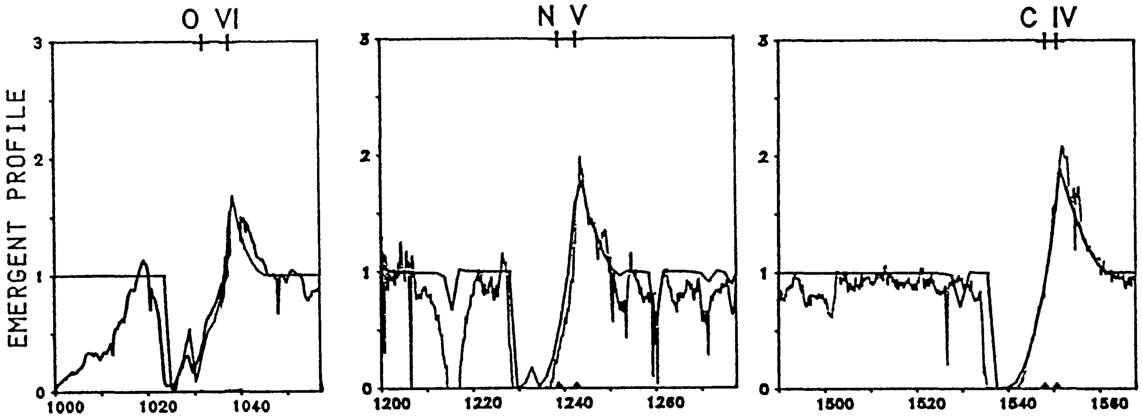
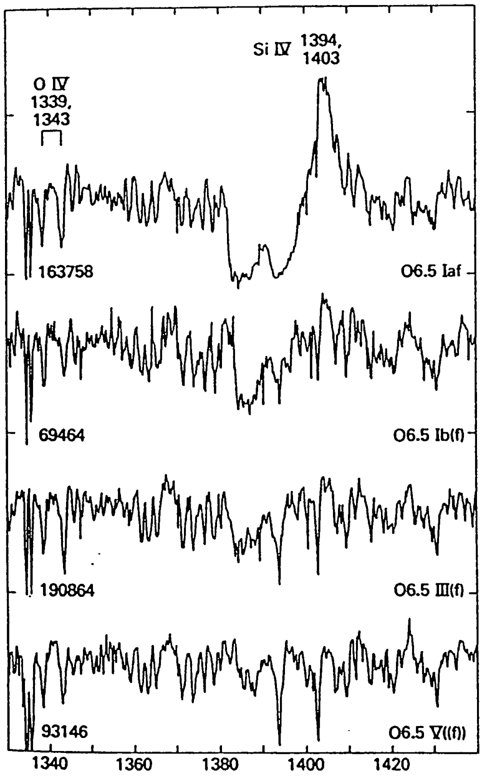


Fig. 3: Observed and calculated UV line profiles of O VI (λλ 1032, 1038), N V (λλ 1239, 1243) and C IV (λλ 1548, 1551) for ζ-Pup.

III. THE SPECTRAL MORPHOLOGY OF THE SI IV LINE - A MEANS FOR DIRECTLY DETERMINING THE LUMINOSITY

An important test of the reliability of the improved theory is to investigate whether it can properly describe the observed systematic changes of the spectral morphology as a function of stellar parameters (this work was recently fully presented by Pauldrach et al., 1990; a preliminary version was also given by Kudritzki, Pauldrach, Puls, 1987). One such systematic change of O star wind lines is implied by the observed *correlation* between *strength* of the Si IV (λλ 1394, 1403) *wind profile* and *luminosity class* (Walborn and Panek, 1984a,b, 1985; Walborn and Nichols-Bohlin, 1987; Walborn et al., 1985). The observations indicate the complete *absence of stellar wind features in Si IV* on the *main sequence*, and their gradual development from the intermediate luminosity class III into *saturated wind profiles* for *supergiants* (see Fig. 4 - note that all the features shown in this figure belong to objects of same spectral type (i.e. O 6.5), which means that the effective temperature decreases only slightly from class V to class Ia (see Kudritzki et al., 1989). It is, of course, crucial for a quantitative stellar wind theory to reproduce this effect. In order to investigate the behaviour of synthetic spectra of the Si IV line we performed self-consistent calculations of wind models along the evolutionary tracks of Maeder and Meynet (1987). The stellar parameters of the selected models are shown in Fig. 5. Fig. 6 demonstrates that the strong dependence of the Si IV profile on luminosity class is in principle reproduced by the theory. For early O dwarfs only weak photosperic lines are produced in agreement with the observations, where it is not clear whether lines are interstellar or photospheric and whether additional blends contribute (Fig. 6a). For the supergiants typical P-Cygni structures are obtained that match the observations in surprising detail (Fig. 6b) - for details see Pauldrach et al. (1990).

This encouraging result poses now the question, whether it is possible to determine luminosities directly from a comparison between observed and synthetic spectra of the Si IV resonance doublet. The sequence of calculated lines for models of equal effective temperature (T_{eff} 35.5 kK) and slightly increasing luminosity shown in Fig. 7 (from bottom to top) indicates that after a phase of calibration by detailed quantitative spectral analysis of individual standard stars this is surely possible. Note that even objects where $\Delta \log L/L_{\odot}$ differs by only *0.05* can be distinguished clearly with this method (remember that the error of the luminosity of cluster members is at least $\Delta \log L/L_{\odot} = 0.24$).



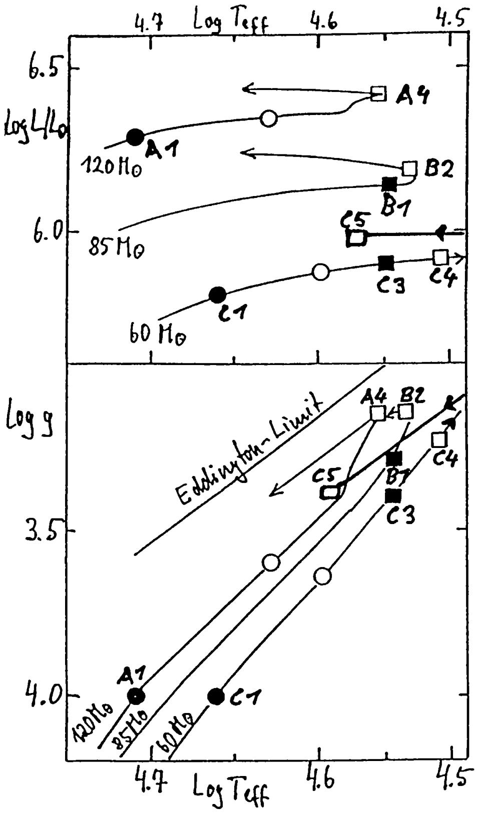


Fig. 4: Luminosity effect of Si IV (λλ 1397, 1403) at spectral type O 6.5 (from Conti, 1988).

Fig. 5: The HR-diagram and the (log g, log Teff) diagram for wind models along evolutionary tracks of initial masses 120 (A), 85 (B), 60 (C) and 40 $M_\odot$ (D). Filled circles correspond to early O dwarfs (V) and open squares to middle O supergiants (Ia/b).

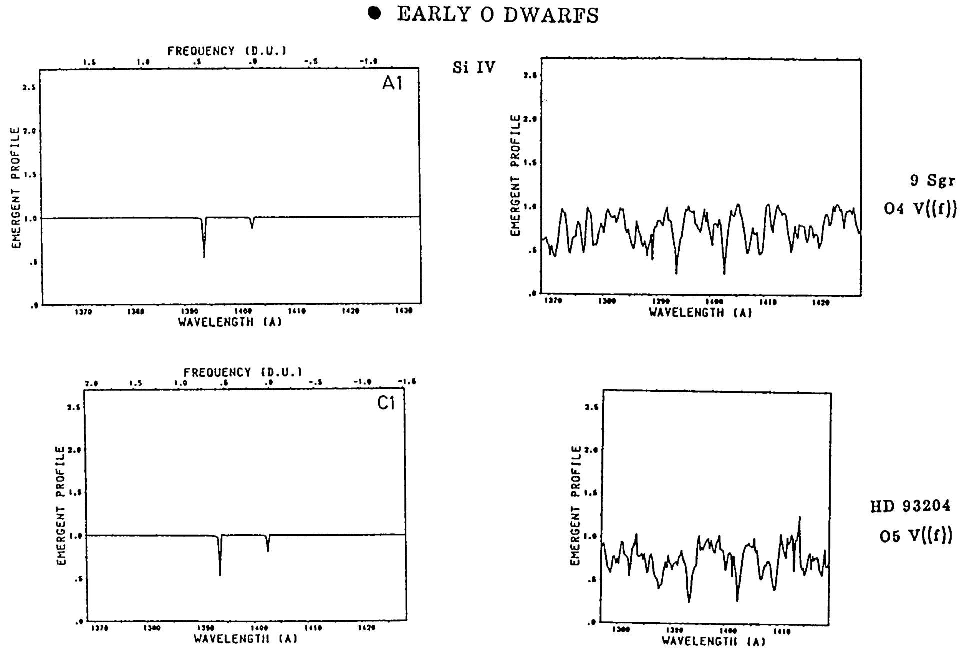


Fig. 6a

Fig. 6: Theoretical Si IV profiles versus observations displaying the strong observationally luminosity effect (Fig. 6a O dwarfs, Fig. 6b middle O supergiants).

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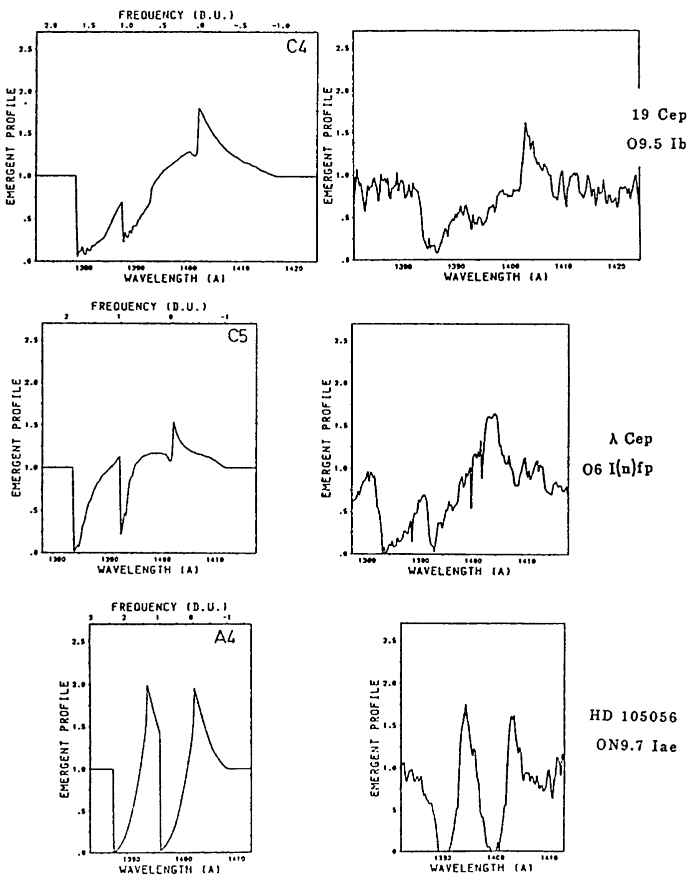
Fig. 6b

□ MIDDLE Of SUPERGIANTS

Si IV



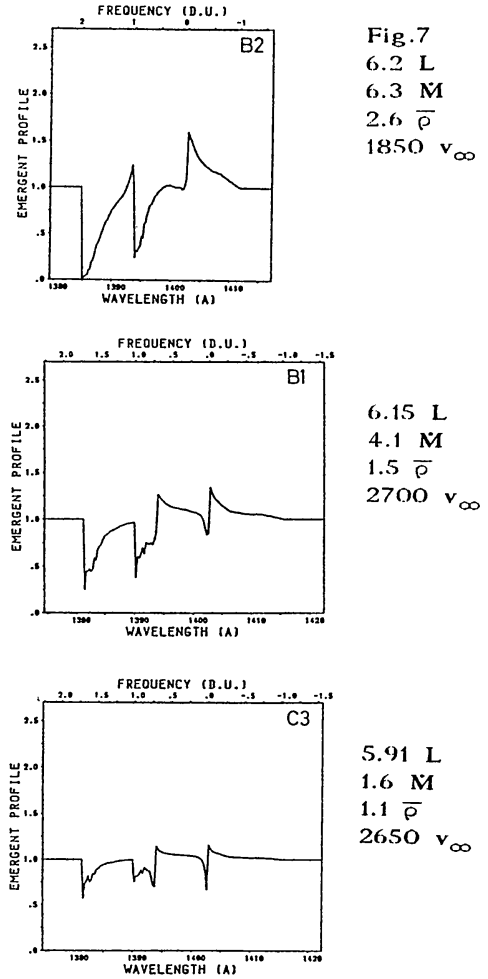


Fig. 7: Si IV profiles for a sequence of theoretical models at constant Teff (~35kK) and slightly increasing luminosity. The luminosity (log $L/L_\odot$), the mass loss rate (10^{-6} $M_\odot$/yr), the wind mean density (10^{-12} $(M_\odot/yr)/(R_\odot^2$ km/s)) and the terminal velocity (km/s) are indicated in sequential order.

IV. MASSIVE HOT STARS AS DISTANCE INDICATORS

Apart from the successes already described, the theory of radiation driven winds can also be applied to one of the most important goals of stellar spectroscopy, the direct determination of stellar masses and radii and, hence of distances. This possibility is offered by the strong dependence of the theoretical terminal velocity (v_∞), which is also a precisely measurable quantity, on the surface gravity and radius

$$v_\infty \propto (g \cdot R)^{1/2} \propto (M/R)^{1/2} \qquad (1)$$

To illustrate this behaviour, Fig. 8 shows this dependence for the case of ζ-Pup (see sect. II), within the error intervals of log g (± 0.15) and $R/R_\odot$ (± 8). The terminal velocity ranges from 290 km/s to 3070 km/s within the uncertainty of log g (where R was fixed at its mean value) and from 1140 km/s to 2243 km/s within the uncertainty of $R/R_\odot$ (here log g was fixed at its mean value). In principle this very large variation of v_∞ can be used to reduce the uncertainties on log g and $R/R_\odot$ and thus to determine stellar masses and radii by a comparison with the observed value (v_∞ = 2200 ± 60 km/s), however, we first have to show that this method yields reliable results. This test is possible for objects with known distance, because the mass can be determined directly by model calculations (see eq. (1)) which can then be compared to the mass obtained from log g, which is available from photospheric line analyses (see also Kudritzki, 1990). Fig. 9 gives an example for the first of these methods. For values of L comprised in the range of uncertainty of the luminosities, v_∞ is shown as a function of mass. A comparison with the observed terminal velocities yields directly the stellar mass and its uncertainty. Table I, which gives for a sample of O-stars a comparison of masses

TABLE I Stellar masses from v_∞ and log g for objects with known radii

star	log $M/M_\odot$ from v_∞	 from log g	source
HD 93129A	2.08 ± 0.10	2.07 ± 0.17	(1,3,4)
93250	2.01 ± 0.11	2.07 ± 0.18	(1,3,4)
303308	1.61 ± 012	1.75 ± 0.21	(1,3,4)
ζ Puppis	1.68 ± 0.10	1.62 ± 0.20	(1,3,4)
λ Cep	1.60 ± 0.09	1.54 ± 0.20	(3)
HD 15629	1.40 ± 0.16	1.36 ± 0.26	(2)
15558	1.70 ± 0.15	1.70 ± 0.26	(2)
34656	1.42 ± 0.28	1.42 ± 0.40	(2)
193514	1.46 ± 0.16	1.44 ± 0.26	(2)
192639	1.37 ± 0.15	1.26 ± 0.26	(2)
Sk 80 = AV232	1.54 ± 0.09	1.50 ± 0.20	(this work,3,4)

(1) Kudritzki (1990)
(2) Herrero, Vilchez, Kudritzki (1990)
(3) Kudritzki, Pauldrach, Puls, Hummer (1990)
(4) Pauldrach, Kudritzki, Puls (1990)

Fig. 8

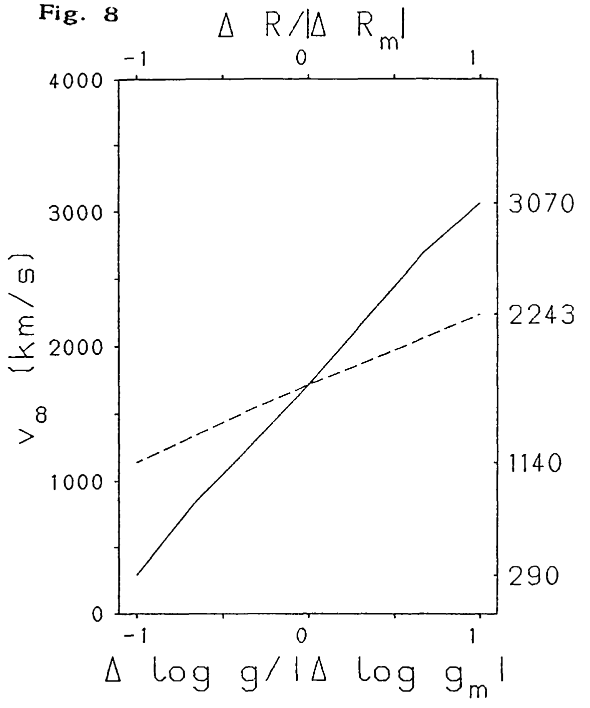
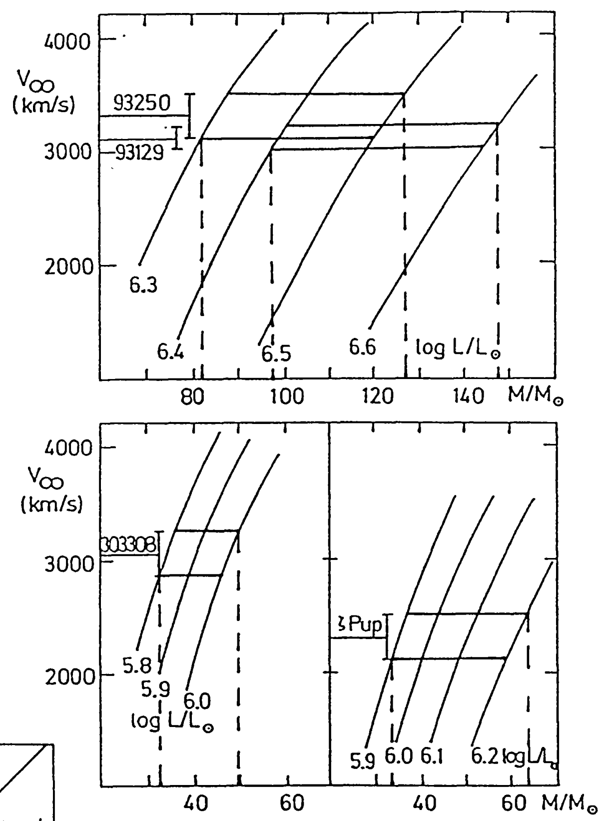


Fig. 9



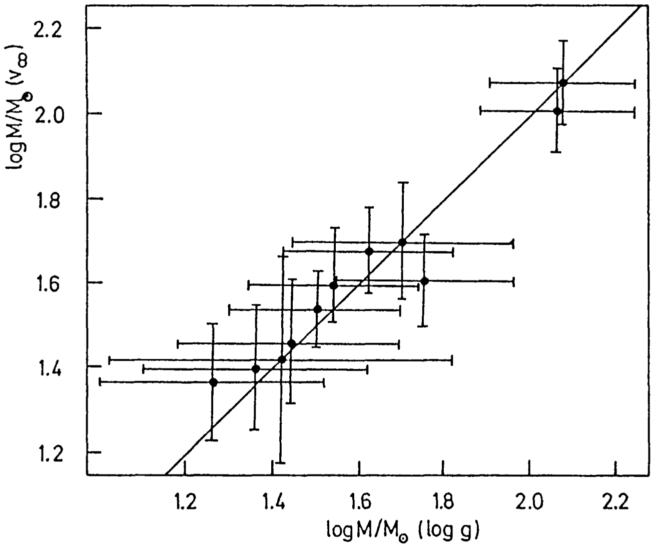


Fig. 10

Fig. 8: v_∞ vs. log g = 3.5 + Δlog g (fully drawn, Δ log g_m = ± 0.15) and R/R⊙ = 19 + ΔR (dashed, ΔR_m = ± 8 R⊙) for the case of ζ-Pup (from Pauldrach, 1985).

Fig. 9: Terminal velocity as function of stellar mass for four typical O-stars, where a comparison with the observed v_∞ yields the mass within the range of uncertainty of log L/L⊙ (from Kudritzki, 1990).

Fig. 10: Stellar masses from v_∞ versus stellar masses from log g for objects with known distances and radii.

obtained in this way and masses derived from log g, shows strikingly that *the two methods agree almost perfectly* (see also Fig. 10). However, there are two reasons why the v_∞-method should be preferred: first, the v_∞-masses have smaller uncertainties, a factor of two in logarithmic scale, secondly, log g cannot be determined with enough precision for objects close to the Eddington limit (e.g. P-Cygni). It should also be borne in mind that *the two methods* used are *completely independent* - one (the log g-mass) has its origin in the photosphere and the other (the v_∞-mass) in the wind. In view of the discrepancies between log g-masses and evolutionary masses found by Groenewegen et al. (1989), Herrero et al. (1990) and Blomme (1990) this indicates most probably that the *evolutionary tracks even for main-sequence stars are in error*. Nevertheless, it is also conceivable that the agreement found in Fig. 10 is just by chance.

After this convincing result we turn to the suggestion that luminous hot stars can be used as ideal distance indicators. This possibility rises from the fact that not only v_∞ but also the mass loss rate ($\dot{M}$) is a strong function of T_{eff}, log g and $R/R_\odot$. Hence, masses, luminosities, radii and distances can be determined using the theory of radiation driven winds, where only the knowledge of the effective temperature is required. This is of particular interest for objects close to the Eddington limit, since for these stars T_{eff} is indeed the only piece of information that can be obtained from the photospheric lines.

The method is very simple (Kudritzki, 1990): once T_{eff} has been derived from photospheric spectroscopy and v_∞ and $\dot{M}$ are determined from wind lines (the latter value can also be obtained from H_α, He II (λ 4686) - Leitherer (1988), Gabler et al. (1990) - or radio data - e.g. Bieging et al. (1989)) log g and $R/R_\odot$ can be directly determined from a comparison with calculated values of v_∞ and $\dot{M}$. Hence M, L and the distance are obtained (note that in cases where log g can also be determined from photospheric lines the method can again be checked). As an example, this method is applied in Fig. 11 to the O4(f) star ζ-Pup, the BIa^+ star P-Cygni and the SMC star Sk 80 (AV 232). ζ-Pup was chosen as a standard object, and P-Cygni due to its large absolute visual magnitude ($M_V = -8.5 \pm 0.6$, Lamers et al., 1983; see also Pauldrach and Puls, 1990) which makes it an object of special interest, because in the near future similar objects will be observable not only in the Local Group galaxies but also further beyond. (A comprehensive theoretical study of the expanding atmosphere of P-Cygni, which includes the determination of stellar parameters, was recently presented by Pauldrach and Puls, 1990). Such an extension of the method to other galaxies was performed with the study of Sk 80. For this object we adopted a composition of $Z = 0.1\ Z_\odot$ (Dufour, 1984). Table II shows the results obtained in the described way for all three objects.

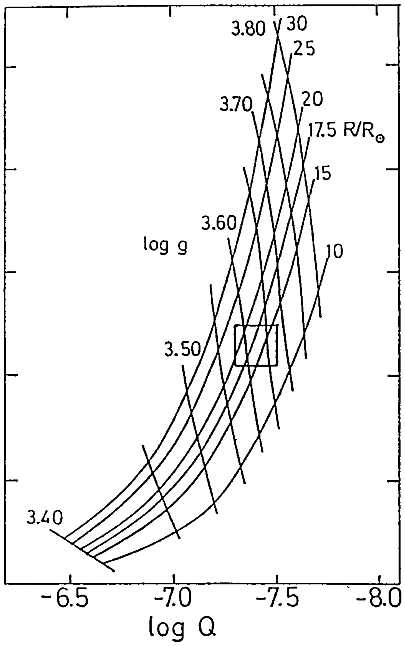


Fig. 11a

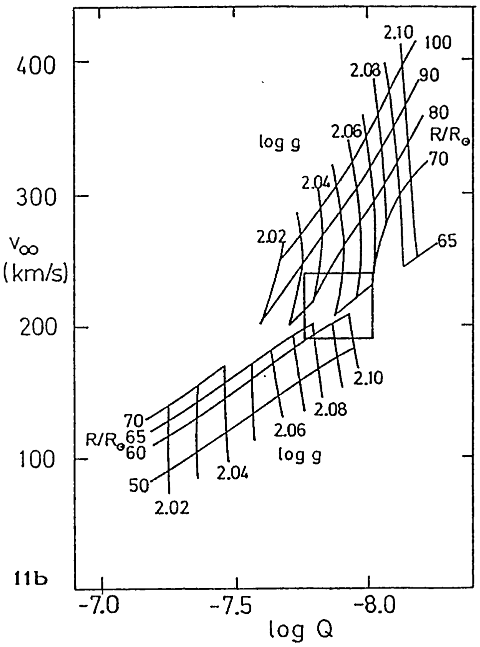


Fig. 11b

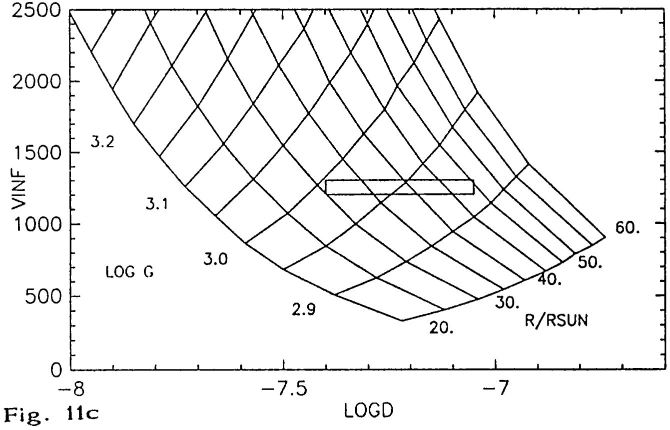


Fig. 11c

Fig. 11: v_∞ and $\dot{M}$ calculated for wind models with different log g and R/R$_\odot$; observed values are indicated by rectangular boxes (Fig. 11a: ζ-Pup; Fig. 11b: P-Cyg - log Q = log $\dot{M}$ (M$_\odot$/yr) - 3/2 log R/R$_\odot$ (from Kudritzki, 1990): Fig. 11c: the SMC-star Sk80 - log D = log $\dot{M}$ (M$_\odot$/yr) - log R/R$_\odot$).

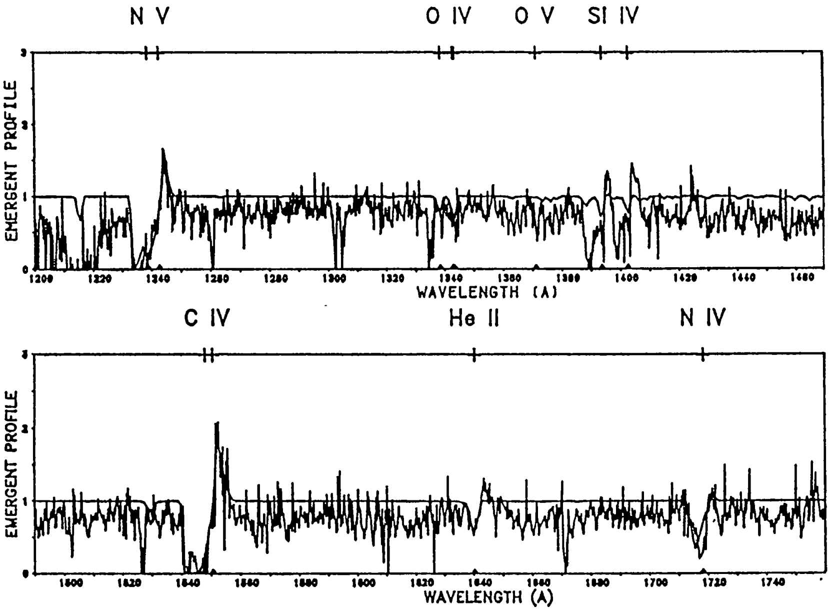


Fig. 12: Calculated and observed UV-spectrum for Sk80.

TABLE II: Log g, $R/R_\odot$ and error of distance modulus determined from v_∞ and $\dot{M}$. Log g from photospheric lines are also given.

star	log g	$R/R_\odot$	$\Delta(m_V - M_V)$	log g (phot.)
ζ-Pup	2.62 ± 0.05	17 ± 5	± 0.5	3.55 ± 0.1
P-Cyg	$2.05^{+0.05}_{-0.02}$	75^{+10}_{-15}	± 0.5	———
Sk 80	$2.95^{+0.05}_{-0.03}$	34^{+11}_{-9}	± 0.5	2.9 ± 0.1

Again, the agreement between photospheric-log g and wind-log g is striking, but the latter values have much smaller uncertainties. It is also encouraging that the error in the distance modulus, which is obtained directly from the error in radius, is not larger than ±0.5 mag, and thus comparable to values derived from other methods (e.g. δ-Cephei). This uncertainty in distance will possibly be further reduced if additional information obtained from a comparison of individual wind lines is considered. The UV-spectrum shown in Fig. 12 for the case of Sk 80 (for this model the input parameters T_{eff} = 34 kK, log g = 2.95, $R/R_\odot$ = 33, Z = 0.1 $Z_\odot$ yield $\dot{M} = 1.9 \cdot 10^{-6}\ M_\odot/yr$ and v_∞ = 1240 km/s) indicates that this will soon be possible.

V. CONCLUSIONS

Although our numerical concept of a quantitative description of stationary models of radiative driven winds is still in need of improvement, the results presented here have shown that the "evolutionary status" of this effort is already well advanced and ready for applications. These applications include the possibility *of using massive stars as distance indicators* by either comparing the observed and calculated Si IV resonance line, or comparing the observed and calculated dynamical parameters. As was shown by our encouraging first results, this method can be applied not only to galactic blue stars, but also to massive stars of large absolute visual magnitude in all Local Group Galaxies, and, with the telescopes of the near future - like HST and ESO-VLT - to stars in galaxies *"as far as the eye can reach"*.

Another important result of this paper concerns the discrepancy between spectroscopic and evolutionary masses. Since it was shown that two different and completely independent methods for determining spectroscopic masses yield values which agree nearly perfectly, it cannot be excluded that evolutionary tracks of massive stars are in error not only for evolved objects.

ACKNOWLEDGEMENTS: We wish to thank our "Tai-Pan" (Prof. Dr. R.-P. Kudritzki), who is not a coauthor of this paper only for reasons of modesty and possible misinterpretation. Special thanks go also to Dr. P. A. Mazzali for the careful reading of the manuscript. This work was supported by grants of the Deutsche Forschungsgemeinschaft (Ku 474/11-3).

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