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RADIATION DRIVEN WINDS OF HOT LUMINOUS STARS

IX. Constraints on the the wind temperature of O-stars

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ABSTRACT In this paper we present the basic framework of our treatment of theoretical models of radiatively driven winds. After a discussion of the critical assumptions, the present stage of our *wind models*, which recently have been extended to include *atmospheric models*, is described. Our calculations, which have been applied on two objects, the O4I(n)f-star ζ-Pup and the O9.5Ia-supergiant α-Cam, reveal that only the population of trace ions of low and extremely high stages are affected by the incompleteness of our models, while the basic ionisation structure and hence the wind-dynamics are correct. By means of our calculations it is also indicated that for the existence of "superionised" ions the Auger ionisation is possibly of secondary importance in the *accelerating part of the wind.* We conclude that a small amount of non-radiative heating is probably necessary to explain all of the observed O-star characteristics. Following this assumption consequently we used a slightly increasing cool wind temperature structure ($T_e \leq 1.2\ T_{eff}$ for ζ-Pup and $T_e \leq 1.5\ T_{eff}$ for α-Cam) and calculated additional models, which then reproduced the observed UV wind lines of super-ionised ions almost perfectly.

I. INTRODUCTION

Hot stars, including OB-stars, Luminous-Blue-Variables, Central Stars of Planetary Nebulae and Wolf-Rayet stars produce an intense radiation field. This radiation field is absorbed by thousands of UV metal lines leading to an outward acceleration much larger than gravity. Lucy and Solomon (1970) and Abbott (1979) were among the first to show that this radiative line force is sufficient to initialize and to maintain stellar winds.

The evolution of massive stars is strongly affected by the mass loss caused by stellar winds. Since the rates of mass loss are still considered as a free parameter in evolutionary calculations, the development of a quantitative theory for the winds of hot stars is of great astrophysical importance. Additionally, with such a theory we are also able to check the stellar evolutionary scenarios by independent, purely spectroscopic mass determinations. This is accomplished via a comparision between observed and predicted terminal velocities.

As the calculated v_{∞} is unique for a given set of stellar parameters, whereas T_{eff}, log g and abundances are provided by photospherical NLTE analyses , the stellar mass can be obtained directly from this comparison (see Kudritzki, these proceedings, Pauldrach et al., 1988, Pauldrach and Puls, 1989). The primary aim of this paper is to demonstrate that the theory, even if incomplete in its present stage, is already appropriate to reproduce the observed O-star features. This is shown in sect. IV by means of a detailed comparison with observations. Moreover, we will show in this section that the winds, although cool, are probably *not in radiative equilibrium.* For this purpose we will briefly summarize (sect. II) the concept of our computational method. In sect. III we will discuss the influence of the approximations applied to our models.

II. CONCEPT OF THE COMPUTATIONAL METHOD

The problem we have to tackle is the development of a self-consistent theory for homogeneous, stationary and spherically symmetric expanding atmospheres that describes correctly the time average mean of the most important spectral features . Using this theory we want to determine mass-loss rates and radii for hot stars by comparing observed and calculated UV line profiles, where the only input parameters required are T_{eff}, log g and abundances.

This objective requires the "time—independent" radiation-hydrodynamics, the NLTE rate equations of the most abundant elements, including line and continuum radiative transfer, and the energy balance to be solved simultaneously. Especially the calculation of the last item causes a sophisticated problem, since radiative equilibrium throughout the wind cannot be assumed a priori. It is obvious that in an expanding atmosphere energy is not only transported by radiation, but also by the accelerated material itself, which may destroy the radiative equilibrium. (Note that in hot stars only the metal ions with a number fraction of a few ‰ are accelerated and that the coupling to the bulk of the material via collisions may also heat up the gas). Other mechanisms of energy transfer like energy dissipation due to instabilities in the wind, inferred from observations (e. g. Henrichs, 1988) , have still to be investigated. These instabilities may speed up only partially to form the shocks, regarded as the origin of the observed X-rays (see Lucy, 1982, Owocki et al., 1989, Mac Farlane and Cassinelli, 1989), that appear to be present for all O-stars. The remaining part of these instabilities may dissipate and thus heat up the gas further.

In view of the complexity of the problem we are faced with, the theory is not yet in a final stage. However, several important steps to a fully self-consistent description have been taken already.

Castor, Abbott and Klein (1975) formulated the theory of radiation driven winds in a self-consistent way for the first time, but due to the many simplifications their approach was only qualitative which may leave the theory open to doubt.

Radiation driven wind theory has in recent years been drastically modified to reach a state which we would like to call "the first quantitative approach". Since our treatment of stellar wind models was recently described comprehensively (Pauldrach et al., 1989), we briefly repeat only the most important points of our procedure.

1. Detailed statistical equilibrium calculations are performed, (see Pauldrach, 1987) including:
   * 26 elements, 133 ionisation stages, 4000 levels, 10000 radiative bound-bound transitions and electron collisions
   * the *correct* continuum radiative transfer with respect to bound-free groundstate opacities, free-free opacities of H and He 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 the idea of D.Husfeld of an "accelerated lambda iteration" (Werner and Husfeld, 1985), modified and adapted to the case of O star winds (Pauldrach and Herrero, 1988).
   * dielectronic recombination and autoionisation for C III and N III, 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 to be considered, but also of the autoionisation process, which is non-negligible)
   * 100000 lines in NLTE for the line force

2. In cases where effects of multiple scattering turn out to be crucial, they are considered consistently for the most important 2000 or so lines (Puls, 1987).

3. The hydrodynamical structure is computed by means of the improved theory of radiation driven winds (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. Compared to our prior models this new method requires several modifications, which are reported here (for details see Berger and Pauldrach, 1990):

1. Up to 81 depth points and 600 frequency points have to be used.

2. A spherical grey temperature structure is applied to the photospherical region, whereas for the wind region the temperature is fixed at a certain level in the outer part (see Fig. 9).

3. Bound-free opacities of up to 100 excited levels and free-free opacities of all metals are taken into account additionally for the continuum radiative transfer.

4. Atomic data including photoionisation cross-sections, collisional cross-section and dielectronic recombination data sets (Butler, private communication) have been updated.

III. PRESENT APPROXIMATIONS

Our first quantitative approach to the theory of radiation driven winds is in principle self-consistent. However, our present treatment is still somewhat imperfect so that further assumptions have to be applied:

i) With respect to our wind models, emergent fluxes of photospheric plane-parallel models including LTE line blocking are used at the inner radiative boundary for the NLTE calculations in the *optically thin* part of the wind. This approximation is of course not necessary for our atmospheric models, but the important shortcoming of these models is that line opacities, which reduce the emergent fluxes considerably, are neglected in the continuum radiative transfer. The correct description of NLTE line blocking and blanketing would also require a NLTE temperature structure to be constructed for the photosphere.

ii) As already outlined in the previous section, the solution of the energy balance in the wind poses a problem of great complexity. Hence, we have adopted the simplest case, and set $T_e = T_{eff}$ throughout the wind. Although this is quite a restrictive assumption, it is not unreasonable, as inferred from IR-observations (e.g. Lamers et al., 1984). Moreover, cool wind models with $T_e(r) \sim T_{eff}$ lead, at least roughly, to the observed ionic species in the wind, if correct NLTE calculations are performed (Pauldrach, 1987). Nevertheless, we must keep in mind that this approximation is only qualitatively correct.

iii) Our cool wind models neglect the presence of X-rays, which appear to be a common feature of O stars and are related to shocks caused by instabilities in the wind. These X-rays produce additional photoionisation by Auger processes, which seems to be necessary to explain the presense of superionised ions like OVI (Cassinelli and Olson, 1979), at least for stars later than O 7 (Pauldrach et al.,1989). However, the influence of Auger ionisation depends strongly on the assumptions concerning the origin of the observed X-rays. As we have up to now no detailed knowledge of the physical properties of the shocks as a function of distance from the stellar photosphere, it is difficult to include this process and to prove its significance in a *realistic way.*

The influence of the above approximations on our models is definitely not purely cosmetic. Hence, in the remaining part of this section we will examine in detail whether and how results for dynamics and ionisation predicted with our improved cool wind theory are affected by the approximations described above.

Consequences

First of all our approximations affect the ionisation conditions in the wind, because the rate equations depend strongly on the radiation field, which is influenced directly by our incomplete treatment. However, we know that it is primarily the continuum opacity which is related to the radiation field. Hence, the significance of line blocking and of the accurately determined wind temperature depends most strongly on the optical thickness of the continua in the wind.

This is because in cases where the continuum is optically thin the ionisation balance is mainly determined by the emergent flux formed in the photospherical region (henceforward expressed by radiation temperatures-T_ν^{rad}), whereas the dependence on the local electron temperature is only weak. Since the frequency dependent radiation temperatures depend on line blocking, ionisation stages situated in the optically thin part of the wind are only poorly described by our approximative treatment of this effect. On the other hand, in the optically thick part of the wind the radiation field and thus the ionisation balance depends strongly on the run of the electron temperature via the opacity.

From this discussion it is evident that we have to know the behaviour of the continuum in the wind before the influence of our approximations can be estimated. Fig.1 shows the radii and density at which the optical depth reaches unity as a function of frequency for a typical O-star (ζ-Pup, see Pauldrach, 1987). Both cases of extrema in the optical thickness exist. The continuum is optically thin up to the He II edge and optically thick beyond. As indicated in Fig.1, this means that trace ions of "low" ionisation stages like C III, N III, Si IV are affected by the approximative treatment of line blocking, so that they can be regarded to be correct within a factor only. A self consistent treatment of line-blocking and blanketing is required in order to reproduce these ions in detail (see also the contribution by J.Puls in these proceedings). Trace ions of the upper ionisation stages like O VI, S VI are affected in the optically thick part of the

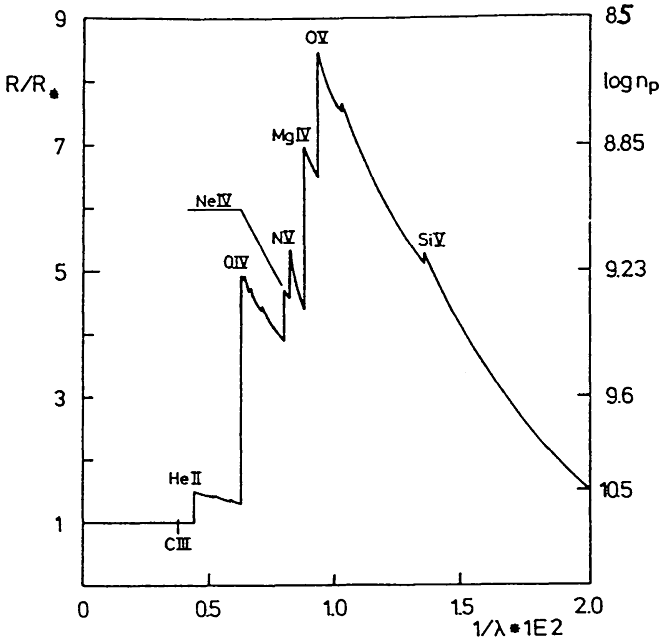


Fig.1 Radius of continuous optical depth equal unity – for a typical O star

wind via $T_e(r)$. Thus a more precise description, or at least constraints on the wind temperature are required for reproducing these superionised ions. Anyhow, we have to face the problem that *enhanced radiative ionisation caused by processes of non-radiative heating* (see sect. II) compete with Auger ionisation from X-rays neglected in our calculations. Moreover, it is also possible that superionised ions are entirely produced by Auger ionisation in which case we can no longer deduce constraints on the temperature from the presence of these ions. It is therefore important to estimate an upper limit of the influence of Auger ionisation . In this context several aspects have to be considered:
Recent calculations of shock-generated X-ray emission by Mac Farlane and Cassinelli (1989) strongly indicate that the X-ray source is located far out in the winds. This is also observationally supported by the absence of K-shell absorption (see Cassinelli and Swank, 1983), which requires the *observed X-rays* to be almost entirely produced in the outer part of the wind. (From the Auger cross section of oxygen (see Deltabuit and Cox, 1972) and our calculations for ζ-Pup we found an optical depth of 1 at the oxygen K-shell edge corresponding to a density of 10^{-15}g/cm^3 and a velocity of 0.9 v_∞). Nevertheless, one could argue that X-rays are produced uniformly in the wind and absorbed. However, this is not possible because O-star winds are *optical thin shortly above the oxygen K-shell edge* (~1.4 keV, see Cassinelli and Olson, 1979). Therefore, if a considerable amount of X-rays were produced in the wind, they would be superimposed on those produced in the outermost part, which is not observed (Cassinelli and Swank, 1983). As observations of O VI line profiles show that superionised ions are present in the whole wind region and not only in the outermost parts (Olson and Castor, 1981), we have to conclude that at least in the inner, accelerating part of the wind, superionised ions are produced simply by ordinary radiative ionisation. Moreover, a model where the X-rays are produced at the base of the wind - which is known to be wrong - (Cassinelli and Swank, 1983, Baade and Lucy, 1987) would present upper limits to the Auger rates from X-rays below 0.9 v_∞! Even in this case too much X-ray flux is found beyond 1.4 keV (Cassinelli and Swank, 1983). Hence, the ionisation fraction of O VI ($5 \cdot 10^{-4}$) deduced from this model by Cassinelli and Olson (1979) for ζ-Pup presents an *upper* limit to the influence of Auger ionisation. We will examine in the next section whether this is sufficient to reproduce the observed O VI profile and, if this were not the case , how much non-radiative heating is needed. Thereby, we hope to give constraints on the temperature structure of O-stars.

From the above discussion we can already conclude that the basic ionisation structure is hardly affected by our approximations (see also Pauldrach et al., 1989) and that, therefore, *the dynamics of the average flow is correctly treated*, whereas the approximations are decisive for trace ions.

IV. RESULTS

In this section we will report the results of our calculations, which have been applied to two well observed standard stars, namely the O4f star ζ-Pup and the O9.5 Ia supergiant α-Cam. The position of these objects in the H-R diagram is shown in Fig. 2.

IV.1 A wind model for ζ-Pup

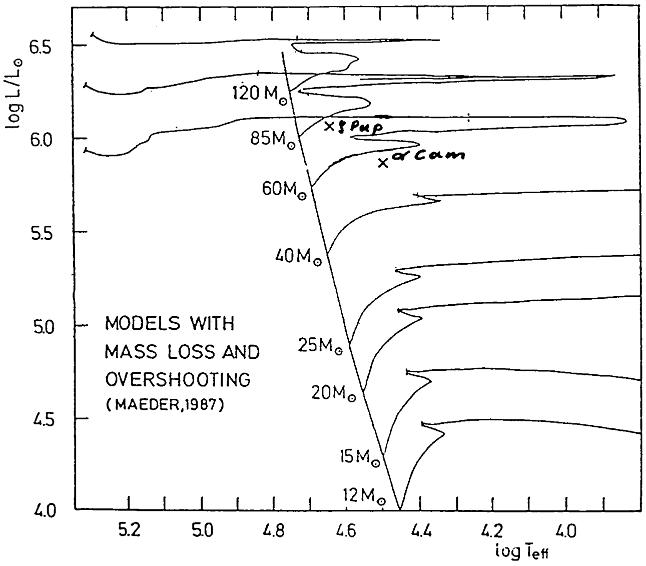


Fig. 2 Evolutionary tracks in the HR diagram with indications of the positions of ζ-Pup and α-Cam.

As we pointed out in previous papers (Pauldrach, Puls, Kudritzki, 1986 Pauldrach, 1987, Kudritzki, these proceedings), the appropriate choice of stellar parameters is of crucial importance for the solution of the wind dynamics. Although ζ-Pup was the subject of two detailed NLTE analyses (Kudritzki et al., 1983, Bohannan et al., 1985), which yielded the parameters T_{eff} = 42 kK, log g = 3.5, R = 19 $R_\odot$ (which will be used for model 1), the deduced values are still affected by systematical errors due to wind blanketing (Abbott and Hummer, 1985) and deviation from hydrostatic equilibrium (Gabler et al., 1989), so that values of T_{eff} = 45 kK, log g = 3.6 and R = 18 $R_\odot$ can be assumed as an upper limit (model 2).

From our self-consistent wind calculations, we obtained dynamical parameters of

$$\dot{M} = 3.6 \cdot 10^{-6} M_\odot/yr \qquad v_\infty = 2200 \text{ km/s} \qquad \text{(model 1)}$$

and

$$\dot{M} = 6.0 \cdot 10^{-6} M_\odot/yr \qquad v_\infty = 2200 \text{ km/s} \qquad \text{(model 2)}$$

For both models the calculated terminal velocity agrees quite well with the observed value. Furthermore, a comparison between observations and spherical comoving frame line formation calculations of HeII λ 4686 (for details see Gabler et al., 1989, A. Gabler these proceedings) shows that the shape of the theoretical line profile is a bit too small for model 1 and a bit too large for model 2 (see Fig.3). This indicates that model 1 and model 2, which are calculated on basis of stellar parameters at the lower and upper limits of the range of uncertainty, respectively, yield values that indicate the lower and the upper limit of the *mass loss rate*.

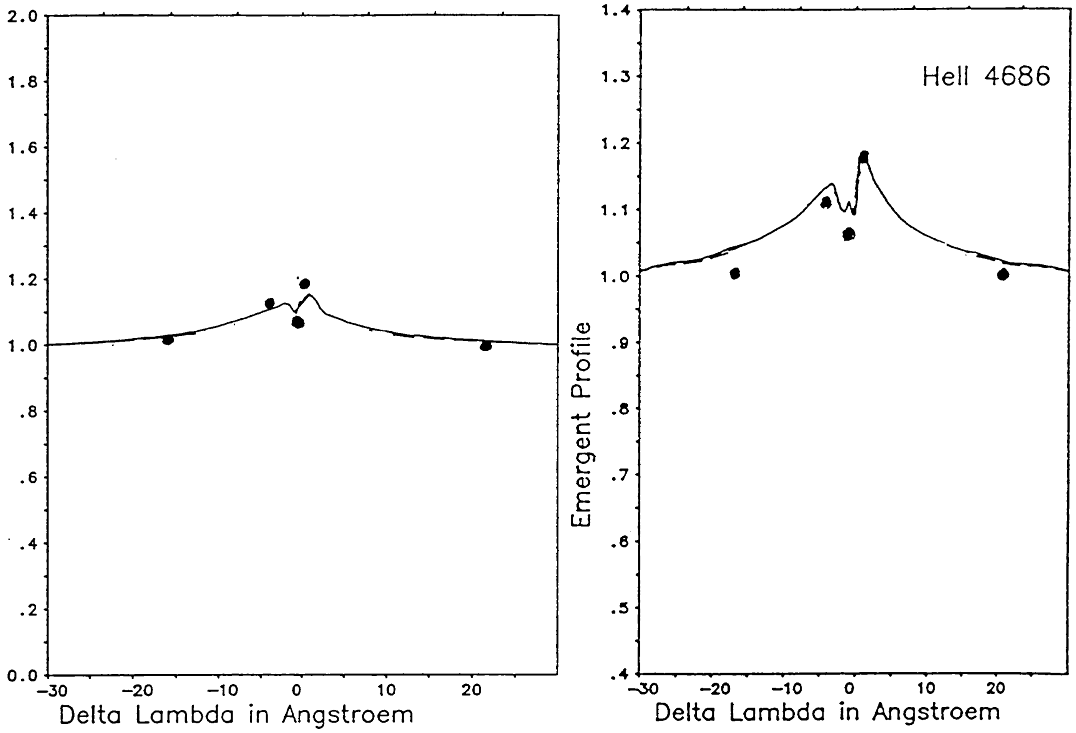


Fig. 3a

Fig. 3b

Fig.3 Profiles of He II 4686 from comoving frame calculations. a model 1; b model 2. The observed profile of ζ– Pup is indicated by dots (Voels, 1989, private communication).

Constraints on the wind temperature structure

In the above calculations the electron temperature was set equal to T_{eff} throughout the wind. In the following we want to investigate the influence of a slightly decreasing and increasing wind temperature.

A lower limit for T_e

Let us firstly examine how our models react to a decreasing temperature stratification. The assumption of such a stratification corresponds to the optimistic case that energy is transported exclusively by radiation, which means that the temperature can be deduced from radiative equilibrium. In this case, our calculations show that the He II continuum (λ 228 Å) becomes suddenly extremely optically thick - and therefore dominates in the outer part of the wind - if T_e is decreased below 0.8 T_{eff}, thereby blocking the ionising radiation field via the increased opacity shortward of the He II edge. Consequently, a shift to lower ionisation stages of the metals occures in the acceleration part of the wind. Since the lower ionisation stages have more lines in the range of the flux maximum, the line force increases drastically, mainly due to Fe V. As this happens in the outer acceleration part, the mass loss rate is not affected. However, the terminal velocity increases significantly (v_∞= 3050 km/s), yealding a value of v_∞/v_{esc}= 5.25, which is much too large when compared to observations (v_∞/v_{esc}= 3.85). As the observed value was perfectly matched by the results of our standard model (T_e=T_{eff}), we conclude that *the wind temperature of ζ-Pup cannot fall below 0.8* T_{eff} and that *we encounter an extremely unstable situation if* T_e *is close to this value.*

A comparison with preliminary radiative equilibrium calculations by Gabler et al. (1989) and Drew (1989) reveals that Gabler's present results are very close to the limit we found, whereas Drew's results are considerably below the limit.

Thus, at least with respect to Gabler's results, we cannot exclude the possibility of radiative equilibrium for O star winds a priori. Therefore we ran a third model on basis of Gabler's temperature structure and found the calculated dynamical parameters to be nearly the same as those of model 1. Due to the superionisation effect, we obtained even for this model an O VI line profile (see Fig.4a), but with an absorption part, which is restricted to the lower part part of the wind, since only in this part photoionisation from the ground state is supported by photoionisation from excited levels (see Pauldrach, 1987 Fig.6a). Since a considerable amount of

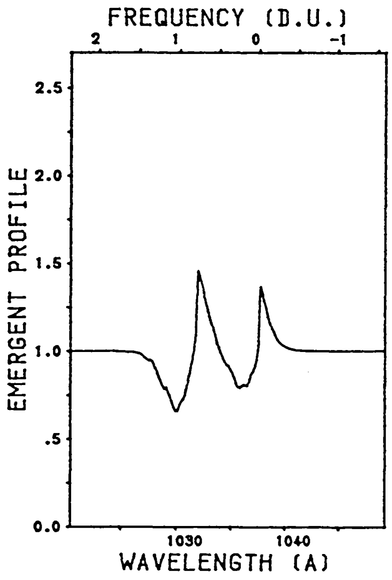


Fig.4a Profile of the O VI resonace line computed for model 3 of ζ-Pup.

Fig.4b Radius of continuous optical depth equal unity for model3 of ζ-Pup. At the edges the calculated T_{rad} are also given.

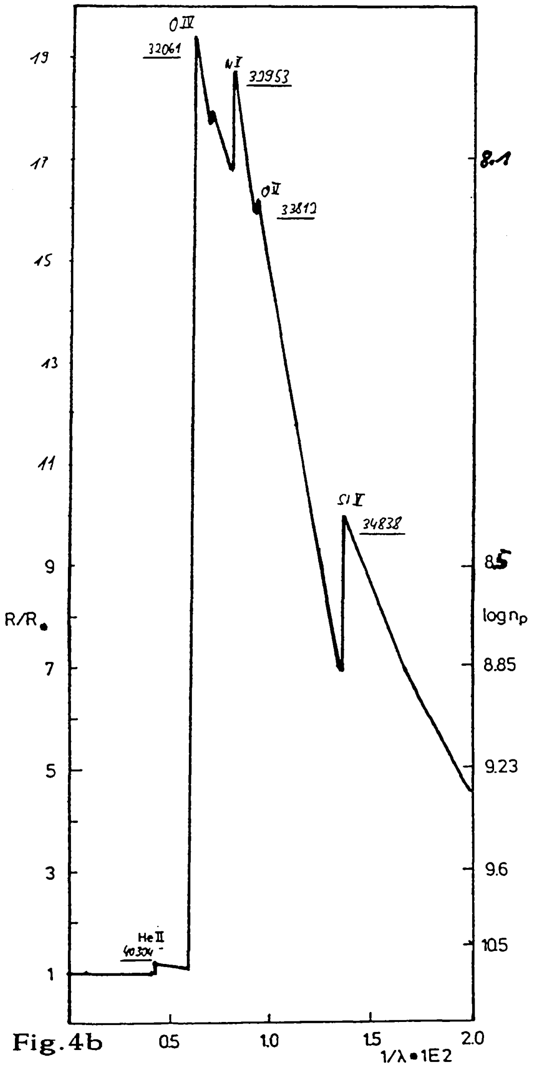


Fig.4b

the ionising radiation is blocked by metal opacities (see Fig.4b) and the radiation field cannot be amplified, because the electron temperature is not high enough, O VI is diminished then in the most parts of the wind.

A premature but possibile conclusion from this result is that for the wind of ζ-Pup radiative equilibrium holds and that O VI is produced by Auger-ionisation in the remaining part of the wind. Until further calculations, where the Auger-ionisation is included in a realistic way in our models, this possibility can neither be verified nor excluded. However, apart from the fact that it is rather unlikely that two different mechanisms (ordinary ionisation in the lower part and Auger ionisation in the upper part) are responsible for the presence of superionised ions there is a strong argument against this picture. This argument concerns the estimated upper limit of the ionisation fraction of O VI ($5 \cdot 10^{-4}$) deduced from Auger ionisation below $0.9 v_\infty$ (see sect. III).

According to our calculations (see below) this fraction is nearly one dex to small ($n_{\mathrm{O\,VI}}/n_{\mathrm{O}} \sim 3 \cdot 10^{-3}$ is required) to produce the observed O VI resonance line profile. Hence, one might conclude that the superionisation may be produced entirely by ordinary radiative photoionisation. This would, however, require a slightly increasing temperature stratification.

An upper limit for T_e

In order to investigate the influence of an increasing T_e in detail we applied our calculations to a fourth model where T_e was enhanced up to 1.2 T_{eff} (see Fig.7). Since the emergent flux in the IR depends strongly on density and also on temperature, we firstly checked whether the results of our model are in agreement with IR-obser-

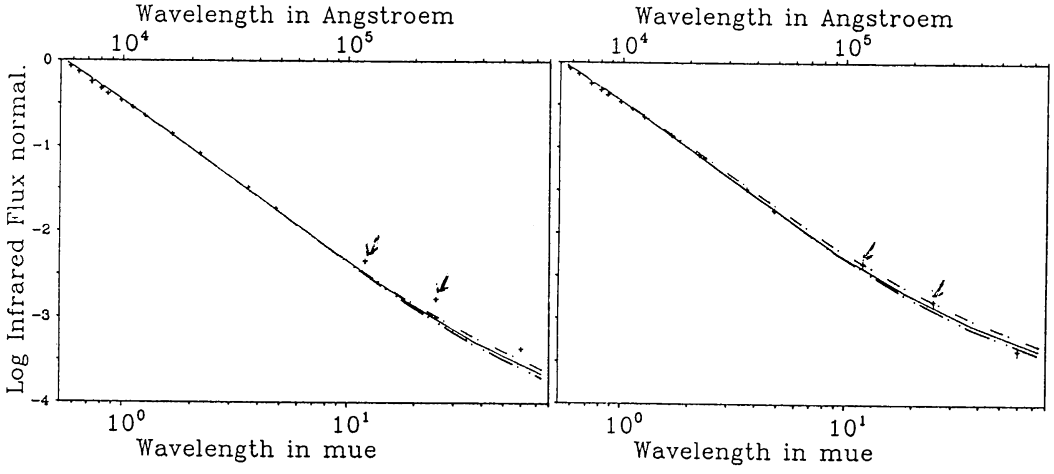
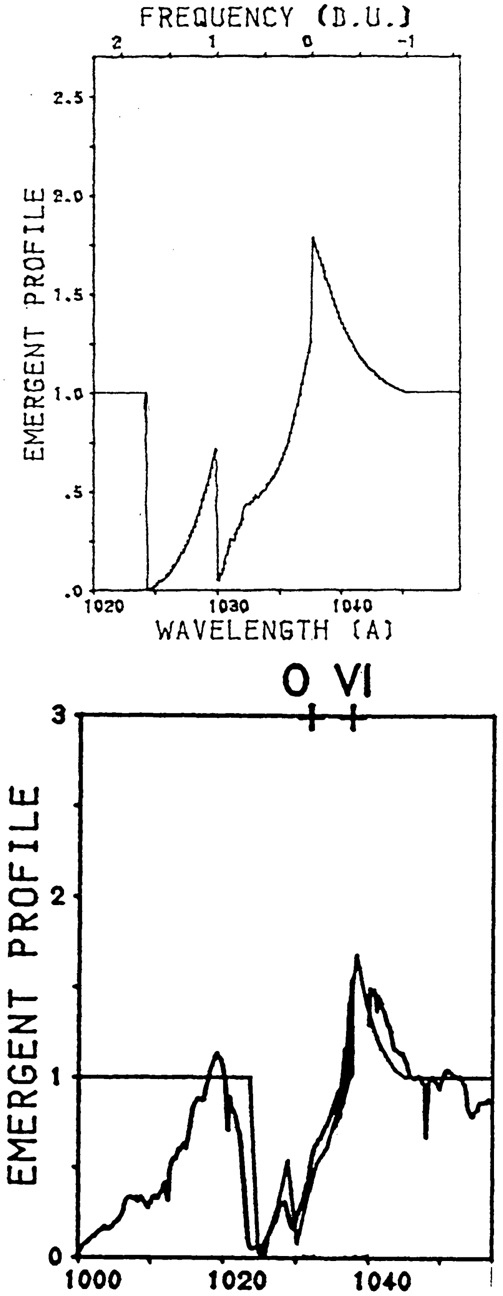


Fig.5a Fig.5b

Fig.5 IR energy distribution for ζ-Pup (a model 1; b model 2) of the unified models. Fully drawn T_e stratification from Gabler et al. ; long dash-dotted T_e from Drew ; short dash-dotted deduced T_e (see text). The crosses represent the observations.



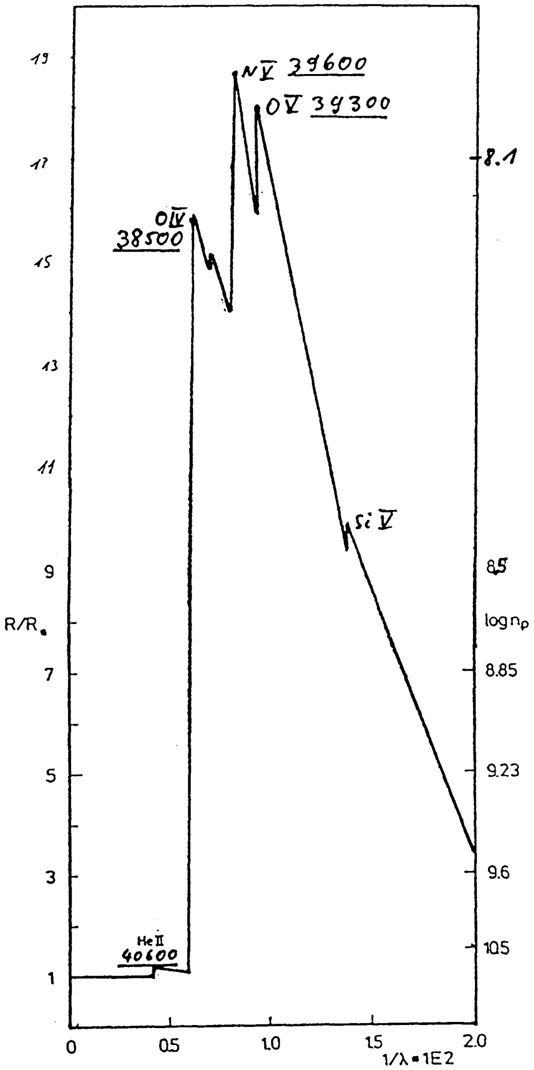


Fig.6b same as Fig.4b, but for model 4.

Fig.6a Profile of the O VI resonance line computed for model 4 of ζ-Pup. Below, the calculated profile is compared with observations.

Fig.7 Temperature versus density, the dashed curve represents our atmospheric model. The dash-dotted curve corresponds to our deduced stratification, while the fully drawn curve shows the result from Gabler et al. (1989).

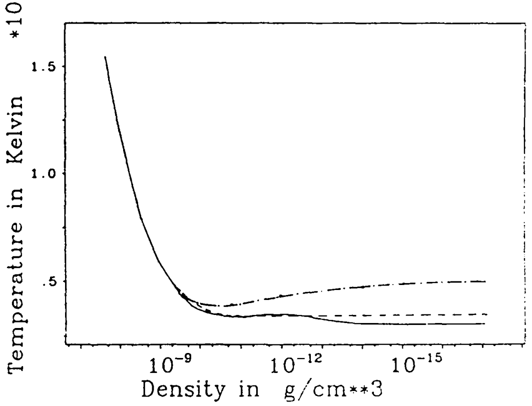


Fig.7

vations. In Fig. 5 it is shown that even for the stellar parameter set that gave an upper limit for the mass loss rate no contradiction with observations is found. This comparison then shows only that our adopted temperature structure is reasonable. That this structure is actually an upper limit can be concluded from Fig.6, where it is shown that *the observed line profile of O VI (λλ 1032, 1038 Å) is well reproduced by our model calculation.* It is also interesting to note that a radiation temperature of the emergent flux for the O V ground state edge of 39 kK (5.5 kK more than for model 3 - see Fig.4b) is enough to reproduce the O VI profile.

IV.2. A wind model for α-Cam

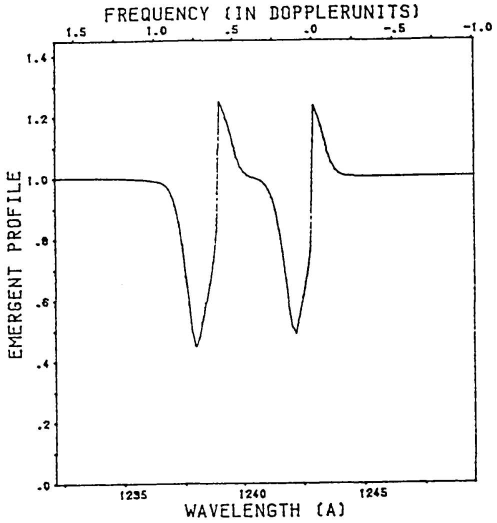
Since the presence of superionised ions is far more difficult to understand for late O-type supergiants, we applied our calculations also to the post-hydrogen core burning O9.5Ia object α-Cam (see Fig.2). As α-Cam was the subject of a recent NLTE study (Voels et al., 1989), its stellar parameters are accurately known: $T_{eff} = 30$kK, $\log g = 2.9$, $R = 29\,R_\odot$, $n_{He}/n_H = 0.2$, where the He-fraction indicates an increased nitrogen abundance and a decreased carbon abundance (compared to solar abundances ~factor 10 in both cases).

On the basis of these precise stellar parameters the observed terminal velocity ($v_\infty = 1850$ km/s, Snow and Morton, 1976) provides an interesting information, since it leads to an extremly large ratio of v_∞/v_{esc} (~ 5). Nevertheless, such large values of v_∞/v_{esc} are not unusual for O-supergiants and are induced by a line force arising primarily from lower ionisation stages, which occurs in cases where the continuum becomes optically thick in the wind at the He II ground state edge (see Pauldrach et al., 1989, or sect. IV.1). However, the shift to lower ionisation stages, which is caused by blocking of the ionising radiation due to the He II opacity, will diminish the presence of anomalously high stages of ionisation such as N V, which in α-Cam shows an almost saturated resonance line profile. Again, we could argue that N V is produced by Auger ionisation, but our self-consistent calculations show that an ionisation fraction of $\sim 10^{-2}$ is required to reproduce the observed N V profile, whereas from Auger-ionisation we expect only a fraction of $< 3 \cdot 10^{-4}$ (Cassinelli and Olson, 1979). Since this is nearly two dex too small, an increase of the wind temperature ($T_e > T_{eff}$) seems to be the only way out.

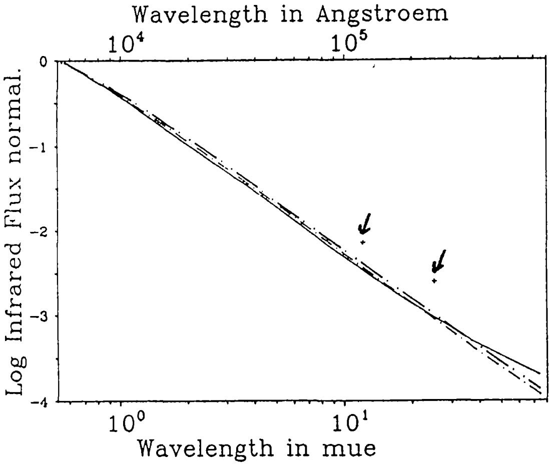
Before investigating this effect in detail, we have to check, whether the observed dynamical parameters can be reproduced by our model calculations. From our standard model ($T_e = T_{eff}$), we obtained

$$\dot{M} = 1.0 \cdot 10^{-6} M_\odot/\mathrm{yr} \qquad v_\infty = 1560\ \mathrm{km/s} \qquad v_\infty/v_{esc} = 4.3$$

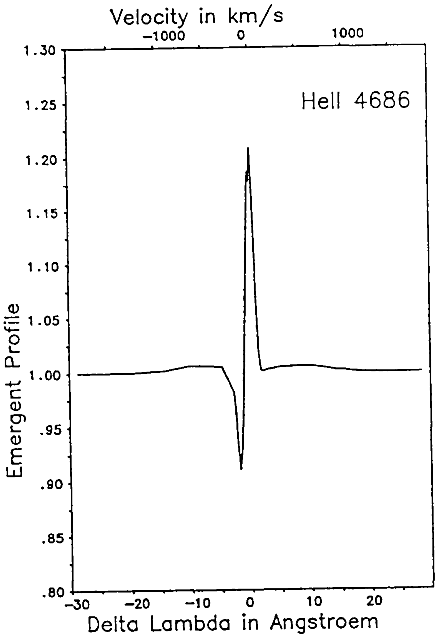
The fact that our value of v_∞/v_{esc} is a bit too small is not decisive, since it is of the correct order (the He II continuum is actually optically thick and N V is diminished in the outer part of the wind - see Fig.8). Much more alarming is the value found for the mass loss rate, since it is almost a factor of 4 smaller than the value deduced from the radio observations ($\dot{M} = (3.5 \pm 1) \cdot 10^{-6}\ M_\odot$/yr, Bieging et al., 1989).



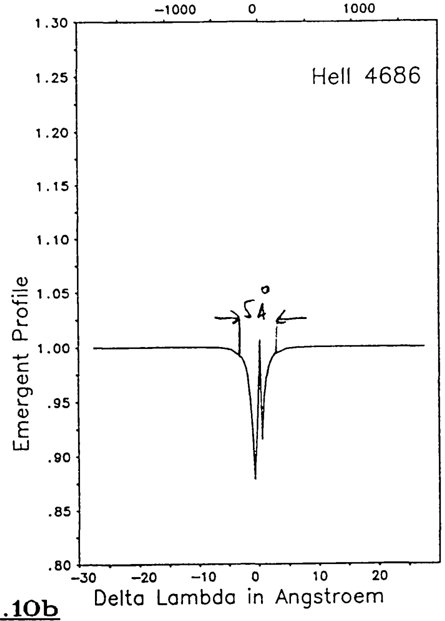
<u>Fig.8</u> Profile of the NV resonance line computed for the standard model of α-Cam.



<u>Fig.9</u> IR energy distribution for α-Cam (dash-dotted the standard model; fully drawn the model simulation - see text). The crosses represent the IRAS data.

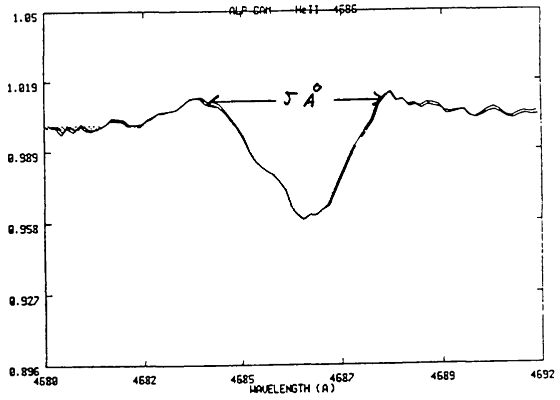


<u>Fig.10a</u>



<u>Fig.10b</u>

<u>Fig.10</u> Profiles of He II 4686 from comoving frame calculations. <u>a</u> model simulation; <u>b</u> standard model; <u>c</u> the observed profile of α-Cam (from Voels, 1989, private communication).



<u>Fig.10c</u>

In order to examine the reason for this discrepancy we compared the IR-flux with the fluxes resulting from our model and from a (simulated) model consistent with the upper limit of the observed "radio mass loss rate". Fig.9 shows a large discrepancy between IRAS data and *both of the models*, indicating strongly that *the observed IR-flux is not related to the wind.* As this is the case for the IR flux, it is most likely that this is also the case for the radio flux. However, this can not be checked directly, since radio data are available at only one frequency point for α-Cam. We may conclude that *the radio-$\dot{M}$ is highly uncertain,* but since the proof is not really convincing, we investigated additionally which value of $\dot{M}$ is favoured by the strongly density dependent He II λ 4686 line (for details see A.Gabler, these proceedings).

Fig.10 shows that both the observed profile and our theoretical model are absorption lines, whereas the He II line of our model simulation appears to be a typical P-Cygni line. It is evident now that the mass loss rate of α-Cam is actually very close to the low value we propose. An additional proof is given by the shape of the subordinate line N IV (λ 1718) (see Fig.11). As was shown by Pauldrach et al. (1989), the shape of this line profile reacts very sensitively to changes of the mass loss rate or the wind mean density ($\rho = \dot{M}/(v_\infty R_*^2)$) for O supergiants. By comparing the N IV lines from a sequence of model calculatons with those of 19 Cep (O9.5Ib) and λ Cep (O6I(n)fp), which have $\dot{M}$ of 0.4 (Leitherer, 1989) and 4.0 ($*10^{-6}$ $M_\odot$/yr) (Garmany et al., 1981), respectively, we see that the correlation between the shape of the profile and the mass loss rate is evident. Moreover, by including the observed N IV line profile of α-Cam in this scheme Fig. 11 immediately indicates $\dot{M} < 1 \cdot 10^{-6} M_\odot$/yr for α-Cam. Summarising, we conclude that our self-consistent model describes the dynamical properties of α-Cam correctly and that the radio mass loss rate is wrong by a factor 4.

The last point to show is that based on a slightly increasing wind temperature our modelling of α-Cam leads to an accurate description of the wind including the correct reproduction of N V.

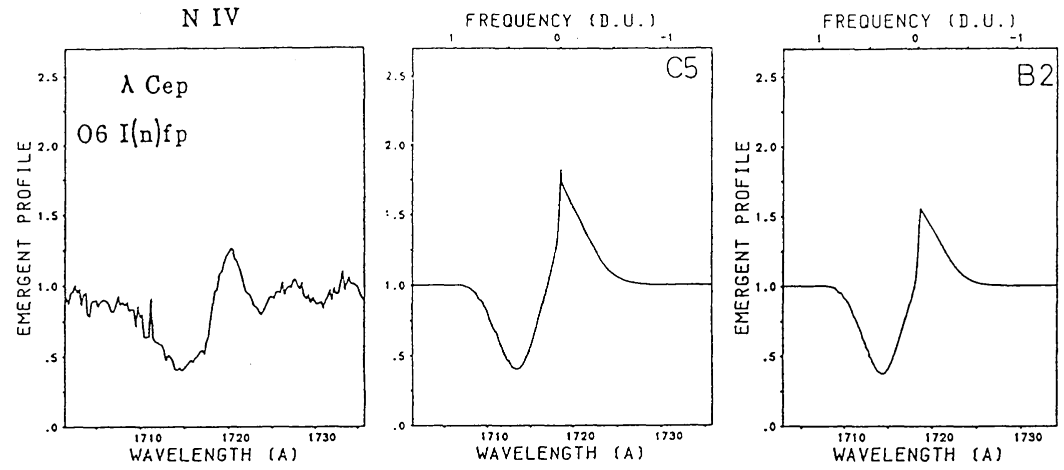
In the case of an optically thick He II continuum, only high stages of ionisation are affected by a small increase in T_e. Therefore the line acceleration remains almost unchanged, but a small number of very strong resonance lines (e.g. the N V resonance line itself) contribute also to the net radiative force. Hence we were able to fit the temperature structure to the terminal velocity of α-Cam and obtained

$$\dot{M} = 1.12 \cdot 10^{-6} M_\odot/\mathrm{yr} \qquad v_\infty = 1800\ \mathrm{km/s} \qquad v_\infty/v_{esc} = 4.9$$

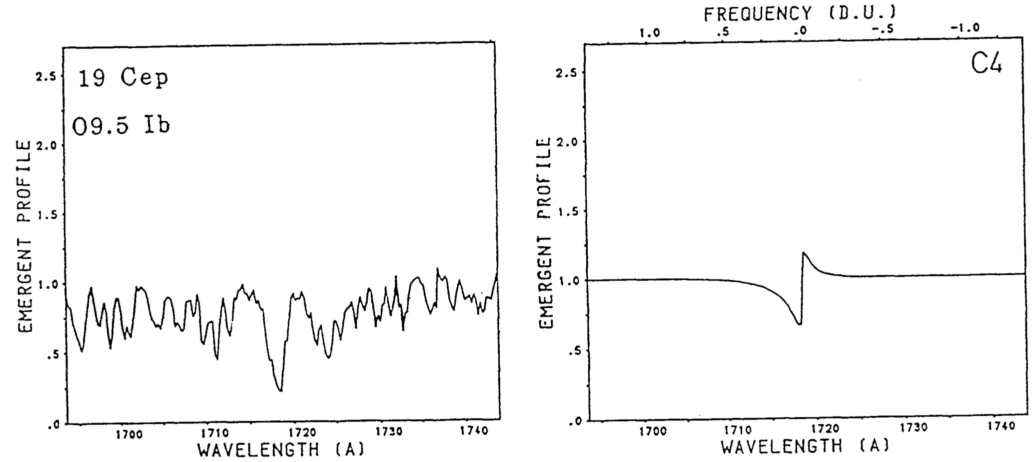
Fig.13 shows the adopted temperature structure, which was forced to increase mainly between 0.1 - 0.3 v_∞.

In this part of the wind, α-Cam is actually unstable. This is indicated by observations of H_α (Ebbets, 1982), showing the shape of the profile to be variable exactly in this region on a time scale of days (Fig.14). As a consequence of the enhanced electron temperature

MIDDLE Of SUPERGIANTS



37.2/ /4.0 38./3.8/4.2 3 4/2.6/6.3



30./ /0.4 32. / 0.4 / 1.0

T_{eff} / $\bar{\rho}$ / $\dot{M}$

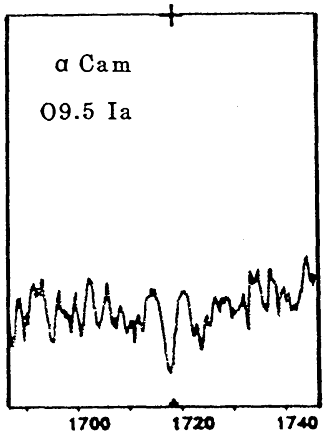


Fig.11 NIV (λ 1718) profile for O supergiants. On the right hand side this subordinate line is shown for a sequence of model calculations, where the effective temperature (in kK) the wind mean density (in units of $10^{-12}(M_{\odot}/yr)/(R_{\odot}^2\ km/s)$) and the mass loss rate (in units of $10^{-6}\ M_{\odot}/yr$) are indicated in sequential order. On the left hand side the observed profiles of (λ-Cep) 19 Cep and α-Cam are shown for comparison.

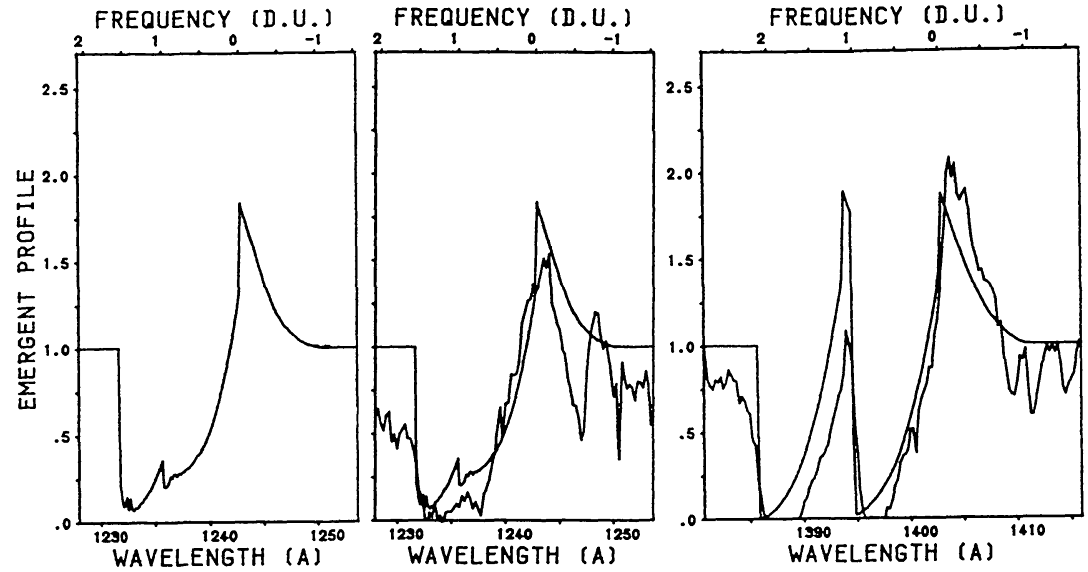


Fig.12 Profile of the NV resonance line for the model of α-Cam and a comparison with observation. On the right hand side the calculated Si IV (λλ 1393, 1402.7) profile is compared with observations.

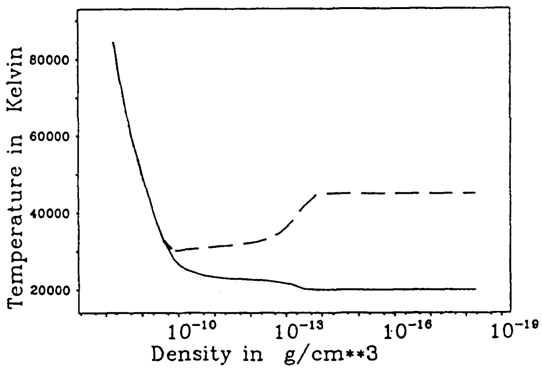


Fig.13 Temperature versus density for α-Cam. The dashed curve corresponds to our deduced T_e stratification, while the fully drawn curve follows from the unified model.

Fig.14 The H_α profile of α-Cam (from Ebbets, 1982). The shape of the profile is variable up to a velocity of 600 km/s.

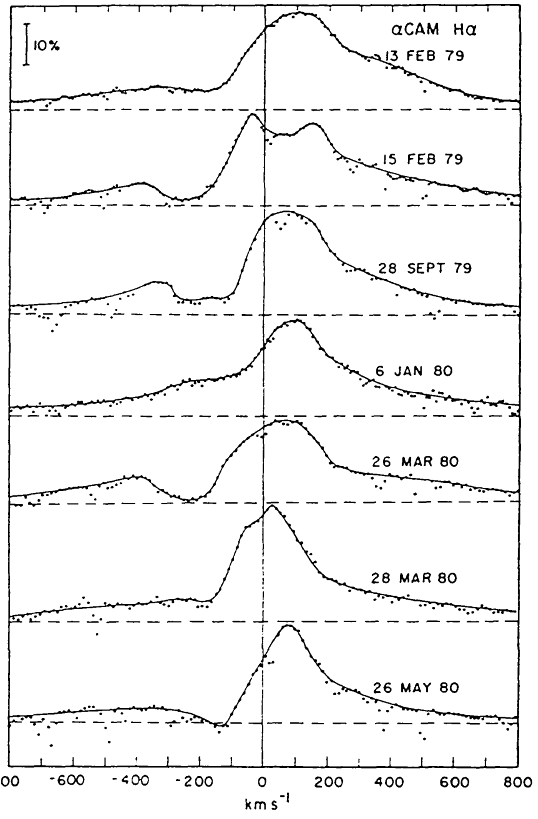


Fig.14

the radiation temperature of the emergent flux at the N IV ground state edge increases from 21 to 26 kK. The corresponding increase of ordinary photoionisation is sufficient to reproduce the observed N V resonance line (Fig.12). In this figure, the almost perfect reproduction of the Si IV resonance line also shows that the change in T_e does not affect the lower ionisation stages.

V. CONCLUSIONS

We analysed the "evolutionary status" of our numerical concept of radiative driven winds. We found that the averaged dynamical wind properties are satisfactory reproduced by our cool wind treatment, whereas the description of trace ions is still affected by the incompleteness of our models. One of the shortcomings is our approximative procedure of line blocking and blanketing, which influences the ionisation fractions of low stages like C III, N III, Si IV considerably. A self-consistent treatment of these effects is therefore required. A detailed study of the wind properties of ζ-Pup and α-Cam revealed that for an explanation of the "superionisation" the Auger effect seems to be of minor influence, whereas a small amount of non-radiative heating - which destroys the assumption of radiative equilibrium - can reproduce this O-star characteristic.
For a further improvement of the details of our radiation driven wind theory, a careful and comprehensive investigation of non-radiative heating mechanisms is therefore indespensable, where these mechanisms have to be connected either to the momentum transfer from accelerated ions to non-accelerated particles (H, He) or to the instabilities embedded in the wind.

Acknowledgements. We wish to thank our "Tai-Pan" and our colleagues Prof. Dr. D.G. Hummer, Dr. H. Henrichs and Dr. S.A. Voels for helpful discussions and informations and Dr. P.A. Mazzali for carefully reading the manuscript. It should be noted that this work was supported by the DFG under grant Ku 474/11-3.

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