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Can classical model atmospheres be of any use for the study of hypergiants?

ABSTRACT

In illustrating the use of classical model atmospheres in studies of hypergiants, the limits of stability against radiation pressure and turbulent pressure gradients are discussed, as well as the significance of dust formation and molecular opacities for mass loss. The effects of using spherically symmetric models instead of plane-parallel ones when deriving fundamental stellar parameters is also reviewed.

1. INTRODUCTION

No doubt, classical model atmospheres in hydrostatic equilibrium have limited value when used to represent the atmospheres of hypergiants and other very luminous stars. However, the classical models belong to the rather few products of astrophysical theory that are reasonably self-consistent, detailed enough to motivate comparisons with accurate observations and still easy enough to calculate for making systematic differential work possible. Therefore, they are used and misused regularily, far outside any domain where they may be regarded as "safe", if such a domain exists at all. It is thus of some interest to ask: For what purposes in the study of the most luminous stars may classical models be used?

One traditional use of model atmospheres is the determination of fundamental parameters like effective temperature, surface acceleration of gravity and chemical composition. Another application deals with the study of physical processes in the atmospheres, where the model may be used as a scene where the phenomena are performed or simulated. A third application, related to the second, is the use of models as zero order representation in stability analyses. A fourth is the use of model atmospheres for proving the failure of these models themselves, or sooner the underlying basic assumptions, and to estimate the effects on observational analyses of these failures. Here, these various methods to exploit classical model atmospheres in the study of hypergiants will be illustrated. In the concluding section, the question whether classical models are useful at all in this study will be addressed again.

Attempts to discuss the properties of hypergiants using classical model atmospheres meet severe numerical problems which in turn reflect the inadequacy of the physical approximations behind the models. Thus the model atmosphere calculations often do not converge, even if algorithms are used that are normally very efficient. This is primarily due to the fact that the models are so close to the Eddington limit that hydrostatic equilibrium cannot be fulfilled in the final model or one of the preliminary ones on the way towards convergence. Therefore, many of the results that are given for stars of this type are in fact based on extrapolations from models with higher surface acceleration of gravity. This further limits the value of studies of this character.

As examples of the possible use of classical model atmospheres for hypergiants we shall discuss the following questions below:

(i) Where in the HR diagram is the upper limit for static atmospheres?

(ii) How does turbulent pressure affect this limit?

(iii)Are static photospheres of red giants cool enough for dust to form?

(iv) Could molecular lines play a role in driving mass loss?

(v) Are multiple solutions to the model-atmosphere problem significant?

(vi) Should classical models be used for spectral analysis?

It is clear from these questions that the main emphasis will here be on late-type stars which reflects our personal interests.

2. WHERE IS THE EDDINGTON LIMIT FOR LATE-TYPE STARS?

The luminosity of a star is above the Eddington limit when radiation alone is able to

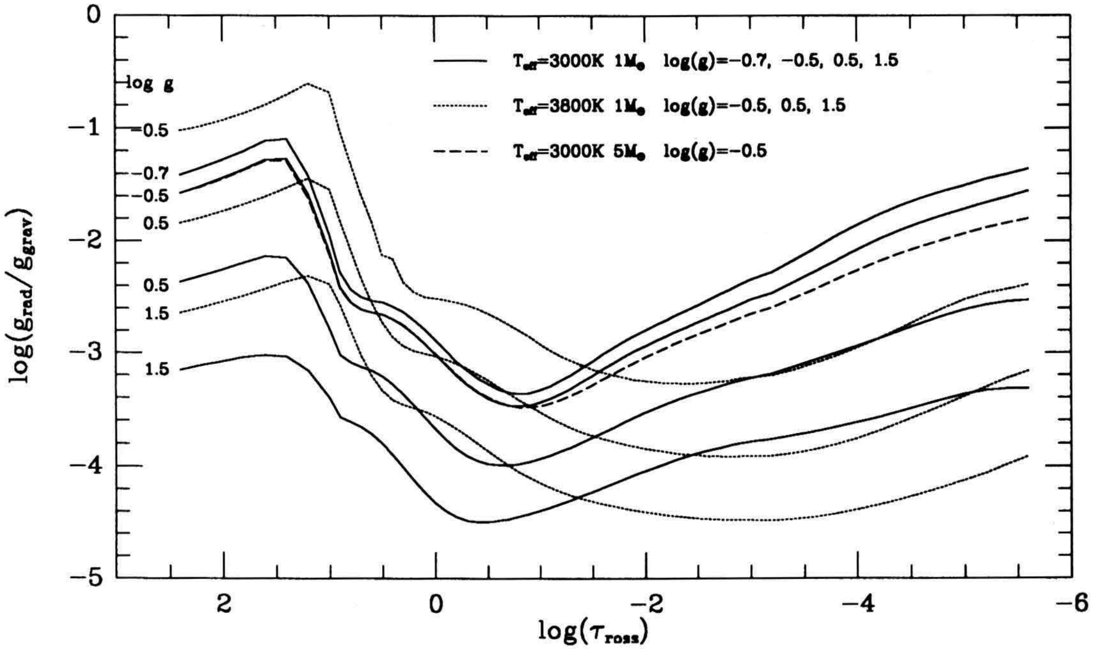

Figure 1: *Ratio of the radiative acceleration to the acceleration of gravity as a function of the Rosseland mean optical depth in various models from the grid of Plez et* al. *(1991). Note that the ratio has its maximum in the deep layers of the photospheres. Note also the effect of atmospheric extension in the* $T_{\rm eff} = 3000$K, *log g* $= -0.5$, $M = 1M_\odot$ *model compared to the corresponding* $5M_\odot$ *model.*

push matter out from the star or more precisely

$$g_{\rm rad} > g_{\rm grav}, \qquad (1)$$

with

$$g_{\rm rad} = \frac{4\pi}{c}\int_0^{+\infty} \chi_\nu H_\nu d\nu \qquad (2)$$

where χ_ν is the mass-absorption coefficient, H_ν the Eddington flux and

$$g_{\rm grav} = \frac{GM}{R^2}, \qquad (3)$$

M and R being stellar mass and radius, respectively. In deriving (1) we have neglected turbulent pressure, which may destabilise the atmosphere (see Sec.3 below). We have also assumed the gas-pressure gradient $\frac{dP_g}{dr}$ to be negative. This is often taken for granted - however, as will be seen below, rather different limiting gravities may be obtained if pressure inversions are accepted. In this case, $+\frac{dP_g}{dr}$ must be added to the RHS of (1).

In the diffusion approximation one may show that

$$L_{\rm Edd} = \frac{4\pi cGM}{\kappa_{\rm Ross}} \qquad (4)$$

where $\kappa_{\rm Ross}$ is the Rosseland mean opacity. Assuming that the gas is hot enough for Thomson scattering to dominate ($T_{\rm eff} \geq 50,000K$) one finds $\kappa_{\rm Ross}$ to be a constant. However, for later–type stars this is not realistic, and one then has to specify at which depth the strongly depth-varying $\kappa_{\rm Ross}$ is to be calculated. A more ambitious approach is to use model atmospheres to calculate the radiative acceleration according to Eq. (2) and study at which depth the ratio $\Re = g_{\rm rad}/g_{\rm grav}$ has its maximum. For a given effective temperature one may then extrapolate a sequence of models with different $g_{\rm grav}$ in the *log*($\Re$) – *log*($g_{\rm grav}$) diagram and read off the $g_{\rm grav}$ value at *log*($\Re$) = 0.0. This method was used by Lamers and Fitzpatrick (1988) for plane–parallel models of the Kurucz grid (1979), supplemented with consistent additional low-gravity models. These authors found Eddington luminosities about one order of magnitude below the classical (Thomson scattering) limit, which seems to be due to the metal line absorption in the Balmer continuum.

We have performed similar calculations for cool spherically symmetric giant models with $3000K \leq T_{eff} \leq 4000K$, as well as for plane-parallel models with $4000K \leq T_{eff} \leq 10000K$. The metal-line opacities were based on a new very much extended line list from R. Kurucz (1989) and in addition relevant molecular opacities were treated in full line-by-line calculation. The models were self-consistent, i.e. the radiation pressure gradient was used in the calculation of the hydrostatic equilibrium. The resulting maximal values of $\Re$ occur at optical depths between $\tau_{Ross} = 2$ (hottest stars) and 30 (coolest stars). For the cool stars it is noteworthy that the radiation pressure gradient may reach a pronounced maximum in the surface layers, where H_2O contributes considerably, in addition to the maximum in the deeper layers where the Balmer absorption gets important (cf. Fig.1 and Sec.4). The convection zone starts closely below the radiation pressure gradient maximum; this decreases the radiative flux and thus leads to the rapid drop in the radiation pressure gradient at greater depths. In this way convection acts stabilising. We have found consistent results from the grid of Kurucz (1979), which are also plotted in Fig.2a. An interesting result from our calculations, illustrated in Fig.2, is that the limiting gravity in the temperature interval $5000K - 10000K$ has a peaked maximum. This effect was qualitatively discussed by Lamers and Fitzpatrick (1988) and by Appenzeller (1989), but the limiting gravity seems higher than appreciated before.

This limit corresponds to the fulfilment of the inequality (1); we note, however, that Kurucz (1979) has given models with lower gravities which show greater radiation pressure gradients than accelerations of gravity but where this excess is compensated for by a gas pressure decreasing inwards. Thus, in the hydrostatic model grids there is a region in the $T_{eff} - \log g$ space where models with pressure inversion occur, limited towards low gravities by the condition that gas pressure and density should not become negative. We have attempted to derive this latter boarder line by integrating the hydrostatic equilibrium equation with different values of the gravity, however assuming a temperature-optical depth stratification adopted from the converged models with the lowest gravity at given T_{eff} in the Kurucz grid. The resulting limit is drawn in Fig.2. No doubt, this empirical method of establishing the low gravity limit is not rigid; on the other hand it seems probable that the true stability line occurs for higher gravities.

An important question is whether a configuration with positive gradients $\frac{dP_g}{dr}$ is stable at all, or, in the extreme case, whether a gas shell floating upon a layer essentially containing photons but little matter, could stay in equilibrium. This question is not settled, to our knowledge, c.f. Maeder (1989) and the subsequent discussion in the same volume, and Stothers and Chin (1983) for some early remarks on this problem. Maeder (1989) noted the presence of a density inversion in this region of the HR diagram and suggested this to be the reason for the mass loss.

An interesting aspect of this is the question whether a mass flow through the density inversion would further destabilise the atmosphere.

A preliminary perturbation study (Plez and Gustafsson, 1991) has shown that a flow indeed tends to destabilise the inversion zone, as long as the velocity gradient $\mid dv/dr \mid$ in its upper part is small enough. A steepening of this gradient will, however, occur and at the end damp the perturbation. Further more detailed hydrodynamic calculations are needed to study the problem further.

Anyhow, it seems probable that the possibilities for instabilities due to radiation pressure are significantly greater in the temperature range $6000K - 9000K$ at higher gravities than is often assumed.

The increase in the radiative acceleration around $T_{eff} = 10,000K$ was propsed by Appenzeller (1986) to cause dynamical instabilities in winds from massive stars as they evolve accross the HR diagram. Similarly, Lamers and Fitzpatrick (1988) argue that radiation pressure is the dominant mechanism determining the observed luminosity limit in the HR diagram, through the decrease of the effective gravity around $10,000K$. Our results (Fig. 2b) indicate that stars with masses as low as 10 $M_\odot$ may well experience instabilities due to radiation pressure as they pass this temperature interval. We note in pass-

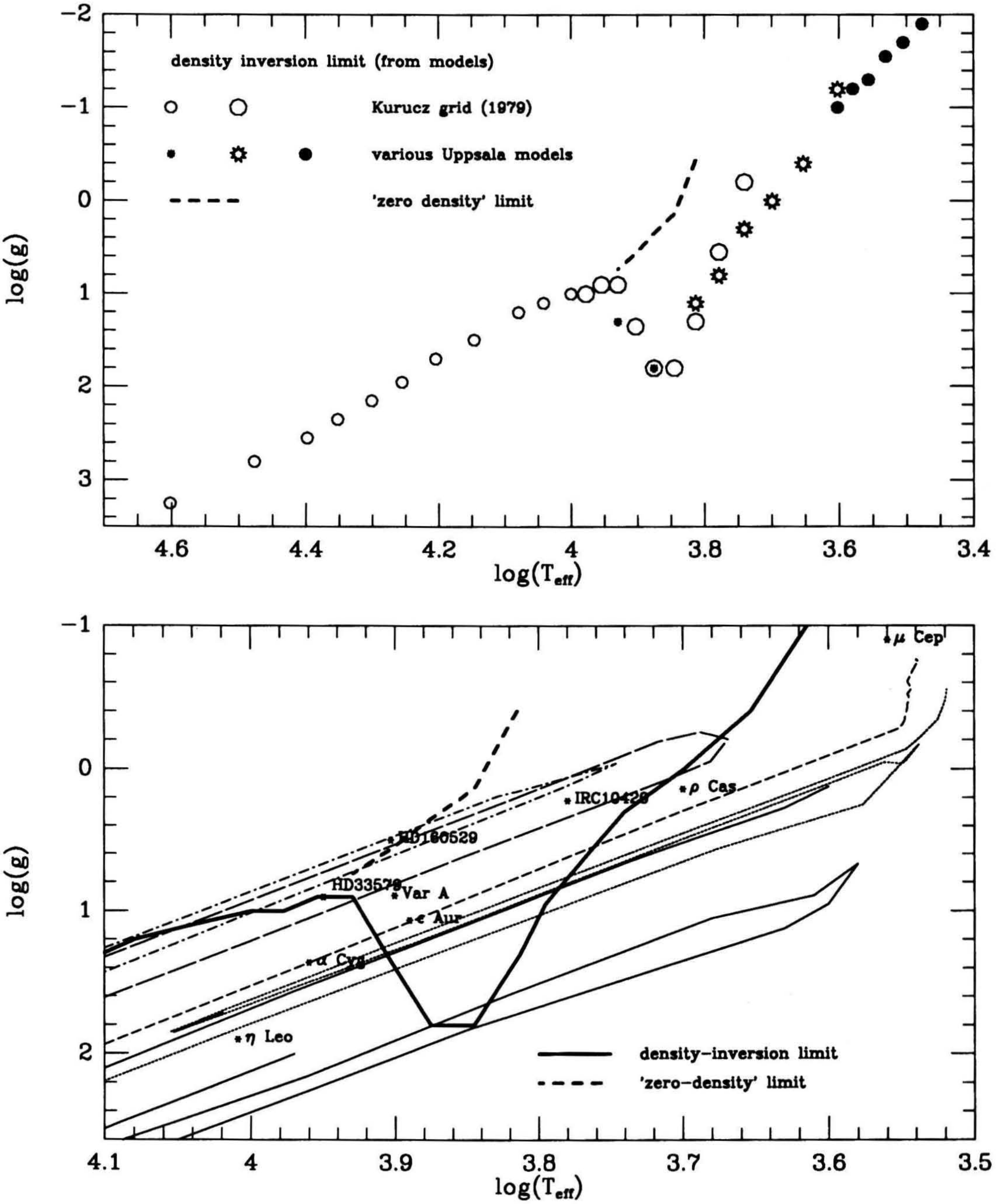

Figure 2: upper panel (a): *The limiting gravity where the radiative acceleration equals the acceleration of gravity, as derived from different series of models. This limit corresponds to the appearance of a density inversion in the models. The dashed line denotes the limit where negative densities appear (see text).*
Lower panel (b): *The limiting lines of Fig. 2a plotted together with evolutionary tracks from Maeder (1991): dashed-dotted:* $60M_\odot$*; long-dashed:* $40M_\odot$*; short-dashed:* $20M_\odot$*; dotted:* $15M_\odot$*. Full line:* $15M_\odot$ *and* $9M_\odot$ *from Iben (1967). A few stars, with parameters taken from de Jager (1985) and from Humphreys, 1990 (Var A), Stahl* et al. *(HD160529, this volume) and Lobel (ηLeo, this volume), are also plotted. For Var A and IRC10420, we have assumed* $M = 40M_\odot$.

ing that hypergiants in this temperature interval, such as IRC+10420, ρ Cas, HR 8752 and HR5171a, show indeed dramatic spectral variations with frequent shell ejections (Humphreys, 1990).

3. WHAT IS THE ROLE OF THE TURBULENT PRESSURE?

Turbulent motions with characteristic velocities $v_{\rm turb}$ produce pressures of order of magnitude $\rho v_{\rm turb}^2$ and thus an acceleration

$$g_{\rm turb} \approx \frac{1}{\rho}\frac{d(\rho v_{\rm turb}^2)}{dr} \tag{5}$$

which in principle should be added to the RHS of (1). A negative density gradient and the generally rather constant microturbulence velocity make this contribution negative. If $v_{\rm turb}$ were known, one might evaluate the effects on the stability condition.

De Jager (1984) and colleagues (Spaan et al. 1987, Boer et al. 1988, De Koter et al. 1988, Piters et al. 1988) have found that the microturbulence velocity is great enough in late-type hypergiants to decrease the effective gravity (i.e. to reduce the RHS of (1)) very significantly. De Jager (1984) suggested that this is the most important reason for the strong mass loss rate from late-type luminous supergiants as compared with hot stars with similar luminosities. This was also suggested to lead to the absence of cool hypergiants; i.e. the downward slope when proceeding to the right in the HR diagram of the upper border line of populated areas (Humphreys and Davidson, 1979).

Assuming microturbulence to actually reflect small scale motions in the atmospheres (c.f., however, Lamers and Fitzpatrick 1988 for some arguments against this), it is easy to derive a rough estimate of the effects of a turbulent pressure on the model structure as long as the microturbulent velocity is approximately constant with depth. Although the latter assumption seems to be reasonable for α Cygni (A2 Ia, Boer et al., 1988) and α Scorpii (M1.5 Iab, de Koter et al., 1988) and α Persei (F5 Ib, Spaan et al., 1987), it is probably not true for all stars (see, e.g., HR 8752, G0-5 Ia+, Piters et al. 1988). However, the contribution to the turbulent pressure gradient is dominated by the density gradient, and we may write

$$\frac{1}{\rho}\frac{dP_{\rm turb}}{dr} \approx \frac{v_{\rm turb}^2}{\rho}\frac{d\rho}{dr}. \tag{6}$$

The density gradient may be approximated, using the gas law and neglecting the temperature variation (approximating T by $T_{\rm eff}$), which leads to

$$\frac{1}{\rho}\frac{dP_{\rm g}}{dr} \approx -\frac{g(1-\frac{g_{\rm rad}}{g})}{1+\frac{120\mu v_{\rm turb}^2}{T_{\rm eff}}} \tag{7}$$

where $v_{\rm turb}$ is given in km/s and $T_{\rm eff}$ in K. μ is the mean molecular mass. We see that the effect of the turbulent pressure will be a lowering of the effective gravity by a factor $1/(1+120\mu v_{\rm turb}^2/T_{\rm eff})$ while, however, the gravity at which the density gradient changes sign is not affected. If this change of sign is taken as a criterion for mass loss we see that the gravity at which that occurs is not determined by the turbulent pressure, as long as there is no significant gradient in $v_{\rm turb}$. Basically, this reflects the fact that $P_{\rm turb}$ is proportional to the density and thus the turbulent pressure gradient gets less significant with decreasing density. On the other hand, if stars in the "dip region" above the density inversion limit in Fig. 2b are relatively stable in spite of the pressure inversion, there would also be a turbulent pressure gradient directed outwards in the inversion region, which would then help counteracting the radiation pressure gradient.

In conclusion we note that the turbulent pressure contributes to mass loss by lowering the effective gravity of the star, but it does not (in the hydrostatic model approximation) drive the mass loss; its effects decrease with decreasing density, and may be stabilizing in pressure inversion regions.

Other, more observational arguments against the turbulent pressure as a driving mechanism were discussed by Lamers and Fitzpatrick (1988). We also note that Blomme et al. (1991) have recently demonstrated that it is hardly responsible for the large mass loss rates found in the eruptive phases of the LPV:s.

4. WILL MOLECULES IN RED GIANT ATMOSPHERES CAUSE MASS LOSS?

If radiative pressure is driving mass loss from red giants - a possibility that is suggested by the final expansion velocities measured for the circumstellar envelopes (see, e.g. Holzer and MacGregor, 1985, for a review) molecules may play a significant and more or less direct role for this. The molecular opacities may cool the outer layers at high enough densities for dust or polyatomic species to form. These may then absorb enough of radiative momentum for dragging away gas from the star. An interesting question is whether molecular opacities alone may suffice for this, as was proposed by Maciel (1976, 1977) and Littleton (1981). A more recent study by Elitzur, Brown and Johnson (1989) based on plane-parallel model-atmosphere calculations with a rather detailed treatment of molecular opacities, in particular of H_20, suggests that for effective temperatures below $2500K$ and gravities below $0.01 \mathrm{cm/s^2}$, the radiation pressure on molecules should be enough to drive the mass loss. The limiting gravity is a very rapidly varying function of temperature; by $T_{\rm eff} = 2400K$ it seems to have increased to $0.1 \mathrm{cm/s^2}$. A somewhat increased effective temperature would probably decrease the limiting gravity to very low values. It should be noted that the effective temperature at which mass loss would occur due to the mechanism suggested by Elizur et al. is so low that all giants are unstable against pulsations, which may in themselves be of more fundamental significance in this respect.

We have studied this effect of H_20 and found it to, as expected, increase in significance for spherical models. However, we find that, due to saturation of the formation of H_2O and therefore a saturation in the number of H_2O molecules per gram of matter, the ratio $\Re = g_{\rm rad}/g_{\rm grav}$ is largest at $T_{\rm eff} \approx 3000$ to 3200K, at least for models with $\log g \gtrsim -0.5$. In our models with $T_{\rm eff} \lesssim 3000K$, $\Re$ reaches also a plateau value in the upper layers of the photosphere for this reason and as a result of line saturation. The limiting gravities at which $\Re$ tends to a value of 1 are rather low (of the order of -2.0 for models with $T_{\rm eff} \lesssim 3200K$), and moreover, the ratio $\Re$ deep in the atmosphere (cf. Sec.2) is then close to or larger than 1 in these low gravity atmospheres. It is thus highly questionable whether H_2O absorption will play any significant direct role in the onset of mass loss. Indirectly, it may still stimulate mass loss by affecting the atmospheric structure, thus promoting the formation of other species, e.g. dust, which will increase the radiation pressure effects.

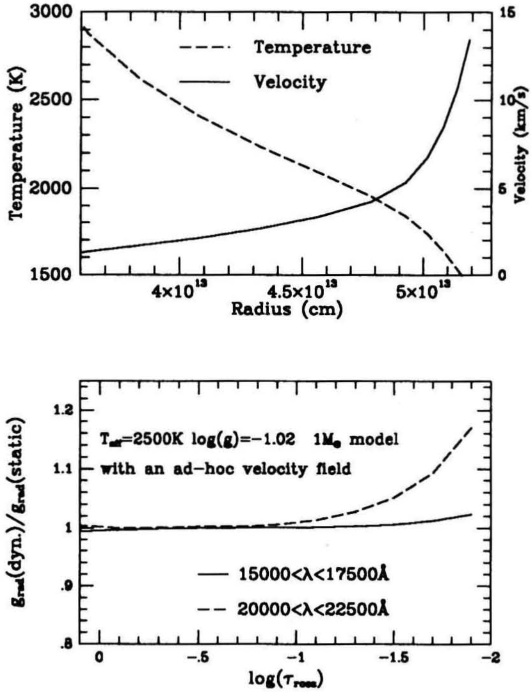

Figure 3: *Relative change of the radiative acceleration due to radiation pressure on water vapour lines, when an ad-hoc velocity field is added in a static model. The lower panel shows the ratio of the contribution to the radiative acceleration from a given spectral region in the 'dynamical' model to the same quantity in the static one.*

One should note that our conclusions concerning the role of H_2O are based on some extrapolation; we have not been able to construct cool models with so low gravities close to the instability border; since the structure of cool supergiant models varies in a complicated way with stellar fundamental parameters this is a serious limitation.

If a flow of gas would indeed be induced by the radiation pressure in molecular lines, the Doppler shifts, varying with depth, will increase the radiation pressure further. This positive feed back is illustrated in Fig. 3. We see that the radiative acceleration increases by 5-20% at the most in typical cases, thus this feed back is only of marginal importance except for when the star is close to the instability limit.

5. CAN DUST FORM IN THE OUTER PHOTOSPHERES OF COOL GIANTS AND SUPERGIANTS?

The formation of dust in stellar envelopes is a complex process where the dynamics of the dust-forming layers, and the feed-back of the dust on the thermal and dynamic structure of the envelope are of key importance. The knowledge about the physics and chemistry of dust formation is still not adequate for quantifying these effects. However, one may use grids of classical model atmospheres to investigate whether the outer layers of static models can ever be cool enough for dust to condensate in local thermal equilibrium. One may also, with assumptions concerning the size distribution and the composition of the grains estimate the dust opacity and take that into consideration in the calculation of static models. Using a grid of spherically symmetric models of M giants, Schmid-Burgk and Scholz (1981) demonstrated that the temperatures of the outer layers of models at $T_{\rm eff} = 3000K$ reached below the equilibrium condensation temperature of corundum (Al_2O_3) for high enough luminosities and small enough masses (for, e.g., $M = 1M_\odot, L > 10^4$). The authors found an interesting coupling between the temperature and pressure sensitive molecular absorption, the atmospheric extension and the temperature structure. However, their treatment of molecular absorption, which only included the water opacity, was schematic. We have calculated an extensive grid of spherical M-star models with a much more detailed consideration of molecular absorption than that of Schmid-Burgk and Scholz. These new calculations are discussed by Plez, Brett and Nordlund (1991). Results agree rather well with those obtained by Schmid-Burgk and Scholz. However, it does not seem probable that dust forms in equilibrium due to the very long time scales needed for e.g. Al_2O_3 to condensate. Therefore, the surface layers of the models are still too hot ($\gtrsim 1500K$), cf. Gail's discussion in the present proceedings.

For the carbon stars, the effects of extension were found to be less dramatic than for the M stars by Scholz and Tsuji (1984); this result has also been verified by us with more detailed opacity treatment. The condensation temperatures of amorphous carbon and silicon carbide at equilibrium are generally assumed to be just below or around $1500K$, although there are indications that dust could form at higher (cf. Tarafdar 1987) or lower (Rowan–Robinson and Harris, 1983) temperatures. Surface temperatures below 1500 K are only reached in our models for $T_{\rm eff} < 2500K$. There is, however, evidence from the ultraviolet and visual "normal" N star fluxes that significant amounts of dust may be present in, or around, the photospheres (Eriksson and Örndahl, 1991). Yet, it is very questionable whether this dust was formed already in the outer photospheres.

Finally, we note further observational arguments against radiation pressure on dust as a general mass-loss mechanism for red giants, as summarized by Judge and Stencel (1991), although it may work for dust-enshrouded carbon stars. Judge and Stencel (1991) propose instead long-period photospheric waves, often with small amplitudes, for driving the mass loss. The presence of sufficient low-amplitude pulsations in the atmosphere of Arcturus (K2 IIIp) supports this view.

6. MOLECULAR CATASTROPHES - AS TRACED IN CLASSICAL MODEL ATMOSPHERES

The interesting fact that the photospheres of the Sun and Arcturus seem to show temperature inhomogeneities in the upper layers, as traced from the Ca II line profiles when compared with the CO line strengths by Ayres and collaborators (Ayres and Testerman 1981, Ayres 1986, Ayres et al. 1986; note also the recent demonstration of a similar two-component structure of the chromosphere of the carbon star TX Psc by Jørgensen and Johnson, 1991), led Kneer (1983) to suggest that the atmospheres of cool stars are affected by a radiative instability due to the high temperature sensitivity of the formation of CO and other cooling molecules. He also suggested that the instability would be reflected in double solutions to the classical model-atmosphere problem. Such double solutions were then actually obtained, for the Sun (Nordlund 1985), for M giants (Scholz 1985) and for carbon stars (Eriksson et al., unpublished). In the two latter cases the cooling of the cooler model was due to polyatomic molecules, while the alternative solution did not get cool enough for these molecules to form. Muchmore, Nuth and Stencel (1987) have also suggested that a similar instability might occur in red giants due to the formation of SiO. Muchmore (1986) discussed the CO bifurcation for the Sun using simplified models. Later, Cuntz and Muchmore (1989) published very interesting calculations for Arcturus where the propagation of acoustic waves in a spherically symmetric model of the atmosphere was investigated, with radiation damping by CO and SiO being allowed for. Depending on shock strength a chromospheric feature could occur, well separated in structure from the cooler molecular dominated regions.

One may wonder whether these kinds of instabilities might lead to even more drastic consequences for lower gravity giants. Muchmore et al. (1987) speculate that there may be a dynamic sequence of cooling molecules formed at gradually cooler temperatures in red giant atmospheres which could end by a massive formation of dust at rather high densities, triggering heavy mass loss through the radiation pressure.

A characteristic feature of the classical models that show double solutions is a fairly primitive treatment of the opacity and, in particular, the neglect of opacity sources of intermediate strength. E.g., for the carbon star models we only find double solutions when we neglect certain important polyatomic opacities. Similarly, the results by Nordlund (1985) for the Sun could only be obtained with assuming the ultraviolet metal-line opacity being formed in scattering processes, i.e. decoupling this absorption from the thermodynamic properties of the gas. In view of the fact that the calculations by Muchmore (1986) and Cuntz and Muchmore (1989) only include a very limited treatment of the radiation field with just few strong line opacities, one still should regard the results as tentative, learning from the, in this particular respect, more detailed classical models. However, as stressed by Muchmore (1990), departures from LTE (or even from statistical equilibrium) in the association equilibria as a result of the dynamics are probably at least as significant factors to consider for improvement in the modelling of these phenomena.

7. DETERMINATION OF FUNDAMENTAL PARAMETERS

The use of classical model atmospheres for determining effective temperature, surface gravity, microturbulence parameter, chemical abundances, etc from the spectra of hypergiants is obviously a dubious excercise. All possibilities to check the procedure must be taken into consideration. These possibilities include the use of a number of spectroscopic criteria for tracing internal inconsistencies, the use of other types of data for external consistency checks, and the relaxing of one or several of the basic assumptions behind the models in attempts to check the uncertainties introduced by these.

Here, we shall not try to review these different methods to check the derivation of parameters for very luminous stars - we refer the reader to the review by Kudritzski et al. (1989), and references cited therein for the hot stars, to Luck and Lambert (1985) for some discussion for intermediate spectral types and to Gustafsson (1989) for cool stars. Instead, we shall only give one example, the effects of departures from plane-parallel stratification for stars of late spectral types (some similar results for models with $T_{\rm eff} = 10,000K$ were presented by Fieldus et al., 1990). The non-trivial discussion of how fundamental parameters are defined for spherically symmetric model atmospheres was recently discussed by Baschek et al., 1991.

The importance of atmospheric extension in giants and supergiants was first stressed by Schmid-Burgk and Scholz (1975) and by Watanabe and Kodaira (1978, 1979). The effects of extension are amplified, especially for M-type stars, by the coupling between molecular opacities and atmospheric structure. Bessell et al. (1989) recently found large effects on the emergent spectra of spherical model atmospheres for M giants and supergiants; following Scholz and Wehrse (1982) these authors propose a 3-dimensional classification in $T_{\rm eff}$, $\log g$ and mass, using a combination of gravity and extension sensitive colours.

Plez (1990) calculated a grid of model atmospheres for cool giants and supergiants with different masses and extension and investigated the effects on fluxes and spectral lines. Plez found that effective temperature determinations using the IR-flux method of Blackwell and Shallis (1977) are only little affected, as long as the IR "reference band" is chosen in a region comparatively free of molecular absorption. If IR colours are used for estimating T_{eff} the errors may amount to typically 100K (the T_{eff} estimated from the plane-parallel models being too low), and probably more for stars with $T_{eff} \lesssim 3000K$. An interesting sphericity effect was discussed by Plez (1990) for the CO V-R bands. The 1.6μm bands get stronger with decreasing gravity for the spherical models, just as for the plane-parallel ones. The fundamental bands, however, around 5μm get weaker, which is opposite to the behaviour for plane-parallel models. Some of this effect may also be seen in the 2.2μm bands. Thus, CO strength measurements could be used for estimating atmospheric extension effects; this could be a more reliable method than using TiO/H_2O ratios, proposed by Watanabe and Kodaira (1978), since these are also sensitive to abundance differences. However, the strengths of the fundamental lines are great enough to be sensitive to velocity fields in the outer atmosphere, which may cause problems when using the CO method.

The carbon abundances, as derived from CO lines in M giants using plane-parallel models, will tend to be too low. The effects may amount to typically 0.1 dex for stars with $T_{eff} = 3500K$ and $log\,g = 0.0$, and considerably less for hotter stars like Betelgeuse ($T_{eff} \approx 3900K$). For the nitrogen abundances, as derived from Red system CN lines, effects on the order of 0.1 dex or less are also expected in the temperature interval $3500K < T_{eff} < 4500K$, and $log\,g = 0.0$.

The sensitivity of the molecular bands to the structure of the atmosphere also leads to more indirect effects in the abundance determinations. E.g., the determination of Li abundances from Li I 6707Å and of O abundances from the forbidden 6300Å line is problematic for M stars due to the veiling by TiO lines (see, e.g., Luck and Lambert, 1982, Lambert et al., 1984). Now, the strength of this veil is depending on the pressure in the outer atmosphere, i.e. it is sensitive to the atmospheric extension and sphericity. The effects seem non-negligible and are worth further investigation.

For some time it has been known that there is a possible Na overabundance in F and K supergiants, and this result is also obtained in non-LTE analyses (Boyarchuk et al., 1988a, b). E.g., for ρ Cas these authors obtained [Na/H]=0.72. Denisenkov and Ivanov (1987) showed that this might be the result of processing of ^{22}Ne in the H-burning core on the main sequence, but some non-standard mixing process is needed to bring the results to the stellar surface. Plez (1990) has investigated what effects sphericity may have on this abundance result. For a standard spherical model he found stronger Na lines than for the corresponding plane-parallel one, leading to a reduction by 0.05 dex in the Na abundance when the spherical model was used. The effects on [Na/H] were thus found to be small, even for models considerably more extended than ρ Cas is supposed to be. Obviously, the reason for the high overabundance of Na is not spherical extension; however, other departures from the classical model atmosphere assumptions like inhomogeneities might be significant.

8. CONCLUSIONS

We have seen that classical model atmospheres may be of some use when discussing the physics of hypergiants:

The limits in the HR diagram where density inversions occur, and where hydrostatic equilibrium is impossible, may be delineated.

The role of the turbulent pressure for determining these border lines can be at least qualitatively discussed.

The role of molecules and dust for atmospheric structure and mass loss may be illustrated, although the basic physics of more or less regular pulsations is not included, which severely limits the value of the conclusions concerning mass loss (cf. also Bowen's paper in the present proceedings).

The idea about possible "molecular catastrophes" in cool atmospheres were inspired partly by multiple solutions of the (simplified) classical model atmosphere problem.

The fundamental parameters of the stars, needed for much further work, can be estimated using classical models, but it is not certain that the results obtained are free from severe systematic errors, and the magnitude of these errors is difficult to assess.

In this situation, and in view of the absense of strong gravitational fields, the presence of strong radiative pressure gradients and very significant velocity fields, it seems very questionable to base much science on the classical model concepts. As an alternative, one could think of constructing "toy models" of dynamic inhomogeneous atmospheres; in spite of the need then to introduce some ad-hoc assumptions and free parameters, such models might be useful as background for studying basic physical mechanisms and estimating systematic errors in standard work. Also, it does not seem totally unrealistic today, with contemporary progress in simulations of radiation hydrodynamics and radiative transfer, that detailed self-consistent models of hypergiant atmospheres will be constructed within the present decade. As a matter of fact, this task seems to be a challenging project for a young and brave theorist.

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