SESSION 3.

LUMINOUS BLUE VARIABLES.

Chairman : R. Sreenivasan.

1. I.APPENZELLER: Instability in Massive Stars: An Overview.

2. B.WOLF: S Doradus Type ; Hubble-Sandage Variables.

3. H.LAMERS: P Cygni Type Stars: Evolution and Physical Properties.

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INSTABILITY IN MASSIVE STARS: AN OVERVIEW

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ABSTRACT: Dynamical, vibrational, and thermal instabilities of massive blue stars are discussed as possible mechanisms for the observed brightness variations of such objects. Relaxation oscillations (on local thermal time scales) due to dynamical instabilities of the stellar wind flows appear to be the most likely mechanism, at least for the S Dor variables. Very massive main-sequence stars with $M > 10^3$ $M_\odot$ should be violently vibrationally unstable and therefore should differ significantly from stable main-sequence stars of lower mass.

1. INTRODUCTION

Except for main-sequence O stars all very bright blue stars are variable (cf. e. g. Maeder 1980). The amplitudes of the visual brightness fluctuations vary between a few hundreths of a magnitude in the less luminous stars and several magnitudes in some of the "Hubble-Sandage" or "S Doradus" variables (cf. B. Wolf's contribution to this volume). So far there exists no consistent and established theory of these light variations. But it is usually assumed that the variations are caused by some type of stellar instability (see e. g. Stothers and Chin, 1983). Therefore, in the following the known types of instabilities which may play a role in massive blue stars are reviewed and discussed.

In the astrophysical literature (as in daily life) the term "instability" is used with different meanings. In order to avoid misunderstandings I would like to emphasize that throughout this paper "instability" will be used in the conventional physical sense to describe <u>equilibrium configuration</u> only. An equilibrium state will be called "stable" if an (infitesimally) small perturbation does not result in a significant deviation from the unperturbed state. It will be called "unstable" if a small perturbation

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can lead to a substantial deviation (from the initial state) which is growing with time. Such an instability may lead to a disasterous runaway (as in the case of the dynamical instability which causes the supernova events at the end of a massive star's evolution), or the effects of an instability may be limited by non-linear effects (as in the case of the vibrational instability of the δ Cep stars). In the latter case the instability may cause no more than a minor modification of the equilibrium configuration. The above definition of "instability" does not cover non-equilibrium states. Hence, theories, which for massive stars (or their outer layers) assume the permanent absence of an equilibrium will not be discussed here.

2. HYDROSTATIC AND DYNAMIC EQUILIBRIUM

In the textbooks of stellar structure stars are defined as gaseous spheres in hydrostatic equilibrium. Hence, in order to study stellar stability we have to analyze the behaviour of the stellar hydrostatic equilibrium in the presence of various types of perturbations. Mathematically the stellar hydrostatic equilibrium is expressed by the hydrostatic equation

$$\frac{1}{\varrho}\frac{dP}{dr} = -\frac{G\,M_r}{r^2} \qquad (1)$$

where P is the total pressure, M_r the mass inside a sphere of radius r around the star's center, G the gravitational constant, and ϱ the gas density. P may contain several different significant contributions, e. g.

$$P = P_G + P_R + P_T + P_M \qquad (2)$$

where P_G is the gas pressure, P_R the radiation pressure, P_T the turbulent pressure, and P_M the magnetic pressure. Although magnetic fields may play an important role in the outer layers of luminous blue stars (cf. e. g. Friend and Mac Gregor 1984), too little is known about the strength and geometry of such fields to allow a meaningful discussion. Therefore, in the following the last term in Equ. (2) will always be neglected. P_T is negligible in the deep interior of all stars (cf. e. g. Cox and Giuli 1968). However, P_T may become significant in the outermost layers of stars with outer convection zones. P_R contributes significantly to the total pressure in all layers of massive stars. For $M \gtrsim 130\ M_\odot$ main-sequence stars P_R usually is the dominating term in Equ. (2). In the outermost layers of massive stars P_R may be more important than P_G even at lower mass values.

For the atmospheric layers (which form the outer boundary of a star) Equ. (1) is often rewritten into the form

$$\frac{1}{\varrho}\frac{dP_G}{dr} = -g_{eff} = -(g-g_R-g_T- \ldots) \qquad (3)$$

where

$$g_R = -\frac{1}{\varrho}\frac{dP_R}{dr} = \frac{4\pi}{c}\int \varkappa_\nu \pi F_\nu d\nu \qquad (4)$$

and

$$g_T = -\frac{1}{\varrho}\frac{dP_T}{dr} = -\frac{\alpha}{\varrho}\frac{d}{dr}(\varrho \overline{v^2_T}) \qquad (5)$$

and where the various symbols have the following meaning: $g = GM/r^2$ = gravitational acceleration, c = velocity of light, $\varkappa_\nu$ = monochromatic mass absorption coefficient, F_ν = monotonic flux of frequency ν, α = numerical factor, and v_T = velocity of turbulence elements.

For all realistic stellar models we have $dP_G/dr < 0$. Hence from Equ. (3) follows for fully hydrostatic atmospheres $g_{eff} > 0$. However, as pointed out first by Parker (1958), instead of Equ. (3) stars may also have non-static boundary conditions, which in the strictly stationary case can be written

$$v\frac{dv}{dr} + \frac{1}{\varrho}\frac{dP_G}{dr} = -g_{eff} = -(g-g_R-g_T- \ldots) \qquad (6)$$

where $v = dr/dt$. (Equ. (6) can be extended to the more general non-stationary case by adding on the lefthand side the expression dv/dt). Physically Equ. (6) means that stationary equilibrium solutions with stellar winds, mass loss, or mass accretion are possible. At least the great majority of all stars show winds and some stars are known to show mass accretion. Hence Equ. (6) (and not Equ. (3)) should be considered the normal boundary condition of stars. In contrast to Equ. (3) Equ. (6) allows solutions with $g_{eff} < 0$, provided $dv/dr > 0$. Hence, contrary to claims in some textbooks, stationary stars can exist even for $g_R > g$, although for $g_R \gg g$ the mass loss $\dot{M}$ tends to become excessive.

3. RELATIVISTIC DYNAMICAL INSTABILITY

As noted above, with increasing mass P_R becomes the dominant pressure term in main-sequence stars. If $P = P_R$ the righthand and lefthand sides of Equ. (1) show exactly the same relative variation for adiabatic radius changes. Hence, we have <u>indifferent</u> hydrostatic equilibrium, independent of the radius, and a small velocity perturbation will result in a displacement growing linearly with time.

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Of course, in realistic stars the gas pressure contribution never vanishes completely. But for very high mass values P_R/P comes so close to unity that the indifferent equilibrium structure is approached very closely. Therefore, the stability behaviour is determined by the (normally utterly negligible) general relativistic deviations from the Newtonian hydrostatic equation (1). In general relativity the gravitational acceleration grows more rapidly with decreasing radius than in Newtonian physics. Hence sufficiently massive stars do not become dynamically indifferent but dynamically unstable. This instability is sometimes mentioned in the context of massive stars. However, model computations have shown that even under extreme assumptions this relativistic instability can only occur for $M > 4\ 10^5\ M_\odot$ (see e. g. Appenzeller and Fricke 1971, Appenzeller and Tscharnuter 1973, Fricke 1973). Thus, this instability is definitively not responsible for the variability of the massive and very massive stars discussed at this meeting.

4. VIBRATIONAL INSTABILITY

Because of the temperature dependence of the nuclear reaction rates mechanical energy is generated in the cores of pulsating main-sequence stars. In most main-sequence stars this gain of mechanical energy is compensated by a much stronger loss of mechanical energy (or heat generation) in the outer stellar layers. Only in very massive stars, with their very large energy output and a relatively slow decrease of the pulsation amplitude (of the fundamental radial mode) towards the core, is more mechanical energy generated than lost (Ledoux 1941, Schwarzschild and Härm 1959). Hence, sufficiently massive main-sequence stars are vibrationally unstable. For non-rotating Population I stars on the zero-age main sequence the maximum mass for vibrational stability seems to be about 90 $M_\odot$ (Stothers and Simon 1970, Ziebarth 1970). In more massive stars small random motions will result in finite amplitude radial pulsations. However, like in the more familiar case of the δ Cep variables the pulsation amplitude of very massive main-sequence stars is limited by nonlinear effects (cf. Appenzeller 1970a, b; Ziebarth 1970, Talbot 1971, Papaloizou 1973). Hence for $M < 200\ M_\odot$ the pulsating stars will not deviate substantially from the equilibrium models and the main effect of the pulsations will be an increased mass loss.

Observationally we know a considerable number of stars which according to their L-T_{eff} values are expected to have mass values in the range 100 to 200 $M_\odot$, i. e. above the ZAMS minimum mass of vibrational instability. Examples are all O3 stars. But in spite of careful searches by many different authors no regular pulsations could be detected in

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any known O star. This has been explained by the assumption that all these stars have already evolved away from the ZAMS to stable post-ZAMS evolutionary stages. In fact, according to present theories of the formation of massive stars it would be quite unexpected to find $\approx 100\ M_\odot$ ZAMS stars, as in such massive stars core hydrogen burning starts already in the protostellar evolutionary phase when the future O star is still an IR object (see e. g. Appenzeller and Tscharnuter 1974).

As discussed in detail in other contributions to this volume, the object R136A in the LMC has been suggested to be (or to contain) a main-sequence star of $M > 10^3\ M_\odot$. At such high mass values the vibrational instability is expected to have more serious consequences: The nonlinear pulsation computations predict that such an object will loose most of its mass within a few per cent of its normal main-sequence lifetime (Appenzeller 1970b). Hence such objects should be very rare. Moreover, because of the high mass loss the wind from these objects is expected to become optically thick, forming a "false photosphere" of a relatively low effective temperature and high visual brightness. If one of the eight components of R136A (cf. Weigelt and Baier 1985) is indeed an $M > 10^3\ M_\odot$ main sequence star, the observations contradict the above predictions, as none of the components of R136A is visually excessively bright and since very high surface temperatures have been reported for the massive component of R136A.

Simon and Stothers (1970) pointed out that the expected high mass loss may prevent evolving very massive stars from becoming vibrationally stable again even after the end of core hydrogen burning. They suggested that the luminous WR stars could form this way. Unfortunately there is again no observational proof supporting this scenario.

Stothers (1976) also suggested a totally different vibrational instability of very massive stars based on the "κ-mechanism". This mechanism also could drive non-radial and higher harmonic pulsations. However, the opacity laws required for the onset of this instability in very massive stars appear not to be compatible with carefully determined L and T_{eff} values of the most massive stars. Hence the existence of κ-mechanism energized pulsations in massive stars can probably be ruled out.

5. THERMAL INSTABILITIES

Dynamically and vibrationally stable stars may be unstable against slow non-adiabatic thermal perturbations. Various authors suggested that such "thermal" or "secular" instabilities of the nuclear core and shell energy sources of massive stars may cause the observed brightness variations. Recently this proposal has been studied in detail by

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Stothers and Chin (1983), who found that under certain conditions in massive post-main-sequence stars unstable hydrogen-shell burning or core hydrogen flashes may occur. However, the computations of Stothers and Chin also showed that if these types of instabilities are present in massive stars, they are not expected to be observable, since they would cause only very small light variations (<0.05 mag) on very long time scales ($\gtrsim 10^3$ years). Therefore, according to our present knowledge thermal instabilities of the nuclear sources also can be excluded as the cause of the observed variability of massive luminous stars.

6. MASS LOSS INSTABILITIES

The wind flows from luminous blue stars are known to be unstable to Rayleigh-Taylor and related instabilities (see e.g. Nelson and Hearn 1978, Kahn 1981). These instabilities may be very important for heating the wind flows. But because of their small-scale nature they probably contribute little to the visual brightness variations.

Radiatively driven winds can also become dynamically unstable if a random increase of the wind results in an increase of the driving term g_R, which enters into Equ. (6). Any increase of g_R and the corresponding decrease of g_{eff} results in an expansion of the massive star's outflowing envelope and an increased optical depth of the flow. Hence the increase of the mass loss rate will be accompanied by a decrease of the effective temperature. For a constant luminosity $L = 4\pi\sigma R^2 T_{eff}^4$ the effective radius and the gravitational acceleration at a given optical depth are expected to vary approximately according to $g \sim R^{-2} \sim T_{eff}^4$. As the effective acceleration can be written as $g_{eff} = g - g_R - ... = g(1 - g_R/g - ...)$, the stability of the wind against $\dot{M}$ or T_{eff} fluctuations will depend on whether g_R varies (compared to g) more rapidly or less rapidly with T_{eff}. If g_R also decreases $\sim T_{eff}^4$ (or more rapidly), the wind is expected to be stable. If g_R decreases less rapidly, a temperature (or $\dot{M}$) fluctuation may lead to a slightly decreased T_{eff}, followed by an increased g_R/g, a consequently decreased g_{eff}, an increased $\dot{M}$ and consequently a rapidly growing further decrease of T_{eff}. Hence, for g_R decreasing less rapidly than $\sim T_{eff}^4$ radiatively driven winds are expected to be unstable.

An accurate qualitative study of the functions $g_R(T_{eff})$ require a grid of detailed non-static atmospheric models of massive luminous stars. So far only very fragmentary data of this type exist. However, qualitatively some information on the behaviour of g_R as a function of T_{eff} can perhaps be obtained from the static (LTE) computations of Kurucz and Schild (1976) reproduced in Figure 1. (While LTE

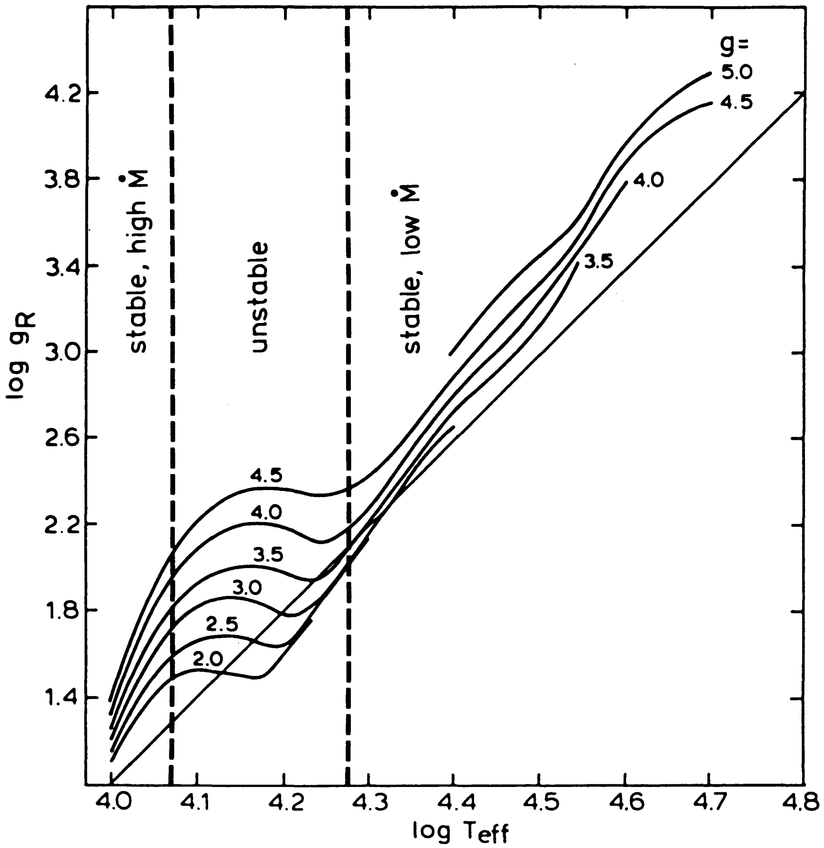

Figure 1. The radiative acceleration g_R (at a Rosseland optical depth of 10^{-4}) as a function of the effective temperature T_{eff} for different values of the gravitational acceleration g (Kurucz and Schild 1976). The solid straight line indicates the relation $g_R \sim T_{eff}^4$.

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is probably a poor approximation, the static approximation may be justified, as in the temperature range discussed below merging UV lines form a quasi-continuum.) According to Figure 1 for most values of T_{eff} g_R is expected to decrease (with decreasing T_{eff}) more rapidly than T^4_{eff}. However, for $10^4 \lesssim T_{eff} \lesssim 2\ 10^4$ g_R decreases less rapidly and for some values of T_{eff} we have even $dg_R/dT_{eff} < 0$. This "bumb" in the g_R-T_{eff} relations is caused by an increased κ due to the recombination of higher ions of the iron-group elements. In this range of effective temperatures the mass loss from sufficiently luminous stars (where g_R is important in Equ. (6)) should be unstable

The instability outlined above can possibly explain the observed variability of the S Dor variables. As described in detail in Dr. B. Wolf's contribution to this volume, S Dor variables are massive and luminous post-main-sequence stars. On their path in the HR diagram towards lower effective temperatures these objects are expected to encounter the upper T_{eff} limit of the "instability strip" of Figure 1. If the instability outlined above exists, at this effective temperature the mass loss rate will rapidly increase (on a dynamical time scale of the order of a few months), the effective radius will increase as well, and the effective temperature will decrease, until a new stable equilibrium is reached at the "red" boundary of the instability strip. However, this (now again dynamically stable) "maximum state" (characterized by high mass loss, low effective temperature, and - because of the lower bolometric correction - high visual brightness) very likely is not in thermal equilibrium: Strong blanketing by the now optically thick expanding envelope will result in a slow heating of the outermost stellar layers until (after a time interval determined by the thermal time scale of the stellar surface layers, which may be of the order of years or decades) g_R/g becomes too small to support the expanded envelope. The envelope will then collapse and after some oscillations settle back to the high temperature, low mass-loss equilibrium state. But, now the blanketing has disappeared. Hence, the photospheric and subphotospheric layers will start to cool again and a new cycle of the g_R-energized "relaxation oscillations" can begin.

In the "stable" domain the g_R-T_{eff} relation seems to be relatively close to indifferent equilibrium. Therefore, if the $g_R(T_{eff})$ relation is not a smooth curve the above mechanism may possibly also cause smaller-amplitude variations as observed in the "normal" very luminous blue stars not belonging to the S Dor class. On the other hand, it must also be kept in mind that Figure 1 is based on static LTE computations which give only poor approximations for the conditions in the envelopes of luminous blue stars. Fully reliable computations are hardly possible at present. Hence, so far we cannot realy prove that the necessary conditions for the mechanism outlined above do actually exist. On the other hand, the dense forest of absorption lines observed in IUE spectra of S Dor variables during maximum state makes the existence of the wind instability very likely.

A related type of relaxation oscillation scenario for the variability of the S Dor stars was suggested by Maeder (1983), who pointed out that the turbulent contribution g_T to the effective acceleration may cause a recurring instability. Maeder's mechanism is based on de Jager's (1980, 1984) suggestion that the observed absence of very luminous cool stars (Humphreys and Davidson 1979) is due to turbulence-pressure induced mass loss, which increases with decreasing effective temperature. In fact, as shown by Maeder (1980), the extent of the outer convection zone of supergiant stars increases rapidly with decreasing effective temperature. If g_T is dynamically important it is expected to increase with decreasing T_{eff}, which obviously could lead to an instability. Unfortunately convection in stars and, in particular, in their outermost layers is a poorely understood topic and very little is known on convection in non--static atmospheres. (Practically all stellar evolution and interior structure computations are based on hydrostatic models.) Moreover, at present it is not clear, how a g_T-instability of the wind in massive stars would be limited. Nevertheless, g_T-driven relaxation oscillations also seem to be a viable possibility for explaining the variations of massive luminous stars.

7. CONCLUSIONS

Of the various instabilities discussed in the literature the conventional dynamical, thermal, and vibrational instabilities all seem to be inadequate to drive the observed light variations of luminous blue stars. On the other hand, mass loss instabilities may possibly explain the observations. In the case of the S Dor variables the observed amplitudes and time scales of the observations would be consistent with the existence of g_R-or g_T-relaxation oscillations of the mass loss rates. These oscillations would be caused by dynamical instabilities, but governed by thermal time scales. If main-sequence stars of $M > 10^3\ M_\odot$ exist, such objects are expected to be violently vibrationally unstable. They are expected to show surface properties which are quite different from the equilibrium main-sequence stars of lower mass.

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Discussion : APPENZELLER.

LAMERS :

I agree with the suggestion that radiation pressure due to FeII etc. might play a role in the instabilities of B and A hypergiants. In my paper I show that the acceleration of the wind of P Cygni is probably due to singly ionized metal lines.

STALIO :

The atmospheric structure of HS variables resulting from your presentation can be schematically seen as consisting of a star, a stellar wind and an expanding shell around. Do you have any estimate of the mass of the shell? What happens to the shell when an outburst occurs? Is it disrupted or does it act as a barrier for the newly ejected material?

KUDRITZKI :

1) Would it not be better to use Abbott's force multiplier for the calculation of g_{rad}, since it takes into account the velocity field?
2) What amplitudes and periods do you expect for the vibrational instability of O3-stars at the ZAMS?

APPENZELLER :

1) Abbott's results were obtained assuming relative high expansion velocities. For the low expansion velocity in SDor type stars the static computations of Kurucz and Schild may still be a better approximation.
2) For the most massive O-stars we would expect pulsation amplitudes (limited by nonlinear effects) of the order 0.1 mag. on timescales of hours.

DE JAGER :

My limit assumes that stellar photospheres become unstable and produce a large rate of mass loss because $g_{eff}<0$. Actually, g_{eff} consists of several terms: $g_{eff} = g_{grav} + g_{rad} + g_{turb} + g_{rot}$. In hot stars g_{rad} is important (the classical Eddington case) but in cooler stars dissipation of mechanical energy (most probably the energy of convective motions and non-radial pulsatation) may cause g_{turb} to become important. There is some recent evidence supporting this latter assumption. Nieuwenhuyzen and I (proceedings this symposium) found that, if other things remain the same, the rate of mass loss is positively correlated with the photospheric value of v_{turb}.

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