OBSERVATIONS BEARING ON CONVECTION

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SUMMARY

1. Solar observations contain a considerable amount of information on the hydrodynamics of stellar convection. We emphasize and discuss especially

(a) the existence of two very different cell sizes,
(b) the unexpectedly high cross-correlation between vertical velocities and temperature fluctuations in the granulation,
(c) the fast "downdrafts" in intergranular regions,
(d) the existence of cells much larger than the scale height,
(e) the strange behavior of the temperature fluctuations in the supergranulation, and
(f) the importance of convective overshoot.

2. The Li-Be problem and its possible relevance as an indicator of convective overshoot is briefly summarized.

3. Convection may have a stronger influence on the observable properties of He-rich ("non-DA") white dwarfs than of most other stars. We discuss especially

(a) the persistence of outer convection zones through a very wide range of effective temperatures,
(b) the occurence of convection in high layers of the atmosphere,
(c) the relatively high efficiency of convection in white dwarf atmospheres, and
(d) the relevance of convection to the cooling problem.

1. INTRODUCTION

The main difficulty of the present topic is due to the fact that almost all spectroscopic and color observations of cooler stars are somewhat related to the convection problem but that there are so few observations which seem to be really crucial in this context. Almost all of the really decisive observations seem to refer to the sun. Though in the stellar case the conclusions concerning convection can be extremely interesting, the way to reach them is often indirect and some doubt is usually possible.

Consequently we feel that the topics of our discussion are quite obvious as long as we look at evidence from the sun, but that our selection of topics in the stellar cases will probably be somewhat subjective.

I shall first report on the solar evidence. After that I shall go on to discuss some observational evidence for convective mixing processes in stars.
Finally we shall consider a class of stellar atmospheres whose average temperature structure is strongly changed by the presence of convection in rather high atmospheric layers.

II. OBSERVATIONS OF SOLAR CONVECTION

A. GENERAL REMARKS

As we all know there are at least two groups of phenomena which are thought to be direct indications of the presence of convective motion (including overshoot) namely granulation and supergranulation. In the case of granulation it is more or less generally accepted that we see the direct effects of convective motion, in the case of supergranulation some slight doubts may be possible. Nevertheless most astronomers believe that supergranulation is the manifestitation of the penetration of large cell convection.

In addition to these direct convective effects there are indirect effects which give us some information about the structure of the convection zone. There are firstly the observed eigenmodes of the so-called five-minute oscillation. I refer to the work of Ando and Osaki (1975), Deubner (1975), the review given last year by. J.P. Zahn as well as the very interesting comment by McIntyre (1975). Secondly, there are observed mixing effects in the sun which may or may not be due to convective mixing. I refer specifically to the very low abundance of Li^7 and the apparent absence of Li^6.

I shall first discuss the direct evidence for convection from the observations of granulations and supergranulation.

One of the most interesting observed features of solar convection is that there are two scales of motion present near the surface of the convection zone, namely the granular scale of about 2000 km (maximum of the Δ I power spectrum) and the supergranular scale of about 32000 km. Both numbers correspond only to the relatively flat peaks of broad power spectra. This statement is of course not new. However, it is surprising how few theoretical attempts to understand this fact have been made. However, there are some notable exceptions including especially the paper by Simon and Weiss (1968).

Let me now try to summarize briefly our knowledge of granulation and then of the supergranulation.

B. GRANULATION

How do we describe the observational information on granulation ? There are essentially two possibilities. Either we use a description based on the autocorrelation function and power spectrum or we look at single granules and, maybe, derive from them the properties of an average (or typical) granule.

For some time it seemed that a description using correlation functions and power spectra would be the only useful method. However, more recently studies of properties of individual granules have found great interest. The reason for this is of course that a description is needed which permits a separate study of the granules on the one hand side and the intergranular lanes on the other side.

In studying granulation we should like (ideally) to obtain a three-dimensional picture of the velocity and the temperature fluctuations. This requires observations of very high spatial resolution, observations in a number of different lines (which are formed at different depths) and center-to-limb observations. One of the fundamental difficulties is, as we all know, the separation of the granular and the oscillatory velocity fields.

One way to do this is to identify the region in the k- Ω plane which corresponds to granular motion. A simpler method is to assume that all horizontal scales smaller than $\sim$ 4000 km correspond to granulation whereas all motions with a larger horizontal scale are due to oscillations (cf. Mattig, Mehltretter and Nesis 1969, Beckers and Canfield 1976).

In addition, one finds that the observed velocities first decrease with increasing height and then increase again (cf. Canfield and Mehltretter 1973, Mattig and Nesis 1974). This fact can also be used for a separation of the two velocity fields.

The component which decreases outward is usually identified with convection and convective overshoot whereas the increasing (or constant) component corresponds to the oscillations.

Even today the problem of correcting the observations for the effects of the contrast transmission function of the telescope and of the atmospheric seeing seems to be a very difficult one. This is true for the determination of the intensity and the corresponding temperature fluctuations but even more so for the velocity determination. Consequently we find a rather large scatter of the observational results which is certainly to a considerable part due to seeing differences. Another difficulty is due to the fact that different authors use different spatial domains and use lines which are formed at different depths in the atmosphere. Consequently it does not make much sense to take averages of measurement by different authors. Rather, we shall take the detailed high resolution observations by Canfield and Mehltretter (1973) as a typical example of modern results. These authors find a definite decrease of the r.m.s. velocity outward before it starts to rise again. (This result has been confirmed by Mattig and Nesis 1974, Mattig and Schlebbe 1974, Musman 1974, and others).

The largest r.m.s. velocity is found for the line formed at the relatively largest depth. The relatively faint FeI line 5178 shows a formation depth of about 40 km above the zero level of HSRA. Canfield and Mehltretter find a r.m.s. velocity of .54 km/s for this line if corrected only for instrumental effects and of .73 km/s if a reasonable correction for seeing effects is applied. By extrapolation the authors find a r.m.s. velocity of .8km/s at the height of continuum formation.

It seems that these velocities are very roughly compatible with predictions of the simple mixing length theory.However, this type of theory (without convective overshoot) predicts a much steeper variation of the r.m.s. velocity than is observed.(See Fig.1.) Any theory which includes overshooting (even linear mode calculations, cf. Böhm 1963 a) can reproduce the observational results in a qualitative way.

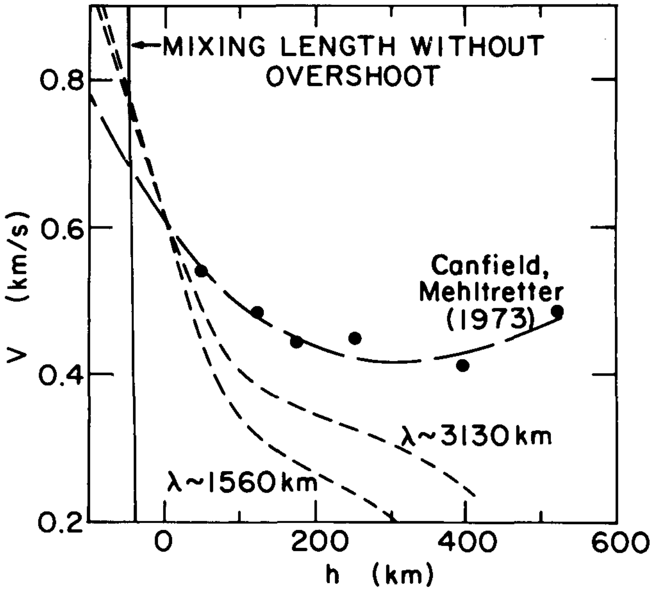

FIGURE 1

Comparison of the observed (vertical) velocity stratification (corrected for finite telescope aperture and for finite slit width but not for atmospheric seeing, Canfield and Mehltretter 1973) with some simple theoretical results.
The filled circles represent the observations by Canfield and Mehltretter (1973), the (long) broken line is the corresponding interpolation curve. The solid line shows the results for the standard (local) mixing length theory with l = H. The vertical velocity distribution for two linear modes with horizontal wavelength λ calculated for a detailed model of the solar convection zone (Böhm 1963) is given by the (short) broken curves. Note that the linear modes contain an arbitrary amplitude factor.

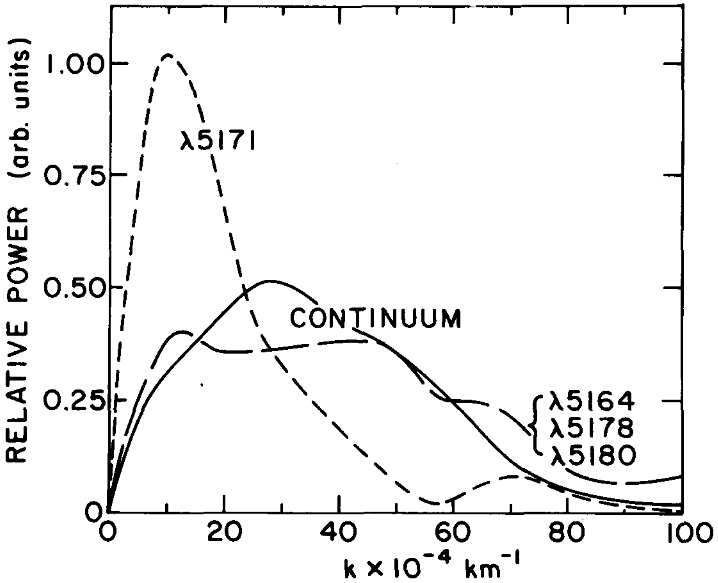

FIGURE 2

Comparison of the velocity power spectra for the lines FeI λ 5171 and FeI λ 5164, 5178, 5180 and the power spectrum of the intensity fluctuations in the continuum. The diagram is based on the data given by Canfield and Mehltretter (1973). The maxima of the contribution functions for the lines 5178, 5164 and 5180A occur at a height between - 20 km and+70 km in the Harward-Smithsonian Reference Atmosphere, the maximum for the line λ 5171 lies at h ≈ + 470 km in the HSRA. Note that the velocity power spectrum for the lines formed near the depth of formation of the continuum (λ 5178, λ 5164, λ 5180) looks very similar to the intensity fluctuation power spectrum for the continuum.

The continuum r.m.s. intensity fluctuations are $\sim$ 8.2% with a reasonable seeing correction (2% T-fluctuation) which (if naively interpreted) is lower than the mixing length predictions ($\sim$ 20%).

However, Canfield and Mehltretter believe that the higher value of $\Delta I \sim 12\%$ derived earlier by Mehltretter (1971) from his observations may also be correct.

The spatial power spectra of the intensity fluctuations show (after correction for seeing effects) a rather flat maximum at a horizontal wave number between 3 and $5 \times 10^{-3}\mathrm{km}^{-1}$ (λ between 2000 and 1250 km).

It should be noted that a number of investigators find the peak of the power spectrum at considerably longer wavelength (cf. Mattig and Nesis 1974). We assume that this is a consequence of seeing effects.

Power spectra of the velocity fluctuations for lines which are formed relatively deep in the photosphere seem to approach a power spectrum similar in shape to the Δ I power spectrum (Canfield and Mehltretter 1973) indicating that T-fluctuations and velocity field are really related below $\tau_{5000} \sim .4$.(Fig.2).

Earlier, Frazier (1968) had found a comparably high correlation between continuum intensity and the velocity in the SiII 6371 line which is formed very deep. (The peak of the contribution function is at $\tau \sim .65$.)

It is really astonishing how high the $v - \Delta I$ correlation is. One has to remember two things to appreciate this fact. Firstly, the velocity and the continuum intensity which are beeing cross-correlated do not refer to the same layers. Secondly, there is a possibility that for turbulent convection even at one given point the cross-correlation could be considerably lower than 1 (cf. Spiegel 1966 a).

It is also interesting to note that there seems to be roughly a 30 second phase lag in the sense that the maximum granular continuum follows the velocity (Frazier 1968, Edmonds and Webb 1972, Musman 1974, Beckers and Canfield 1976).

We shall now proceed to the description of individual granules which, as mentioned earlier, turns out to be useful and very interesting from a hydrodynamic point of view. A very fundamental study of this type has been carried out by Beckers and Morrison (1970). They observed a large number of granules at $\mu = .84, .70, .60$ and determined the velocity field of an average granule from these observations. By making use of the different positions on the solar disk (different μ) these authors derive the vertical as well as the horizontal velocity field for the average granulum. Since not all granula have the same size and shape we can not expect to get a really quantitative picture of the hydrodynamics of a granulum by this procedure. Since in the reduction process the granules are positioned such that their centers fall on the same point the upward velocities at the center of the granule are enhanced in the averaging process whereas horizontal and downward velocities (occuring in the outer parts of the granulum) are reduced. Nevertheless the "average" granulum shows very clearly the basic structure of the velocity field in a granulum. (Fig. 3).

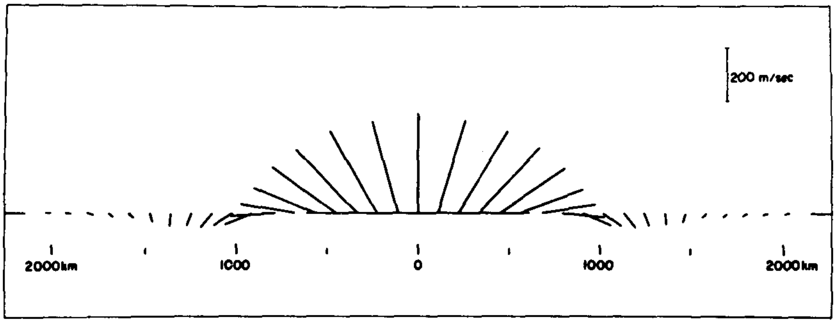

FIGURE 3

The vertical cross-section of the velocity field of an "average" granule.
(See text for a brief description of the averaging procedure).
From Beckers and Morrison (1970). By permission of Reidel Publi.Co., Dordrecht.

Of course, we have to keep in mind that all modes of smaller scale are smoothed out by atmospheric effects and by the averaging process.

The importance of such investigations lies in the detection of an ordered horizontal outflow from the granulum. This is, of course, not too surprising, but it is certainly an observational fact which is not emphasized in the mixing length theory.

The investigation of individual granules has lead to the discovery of another interesting phenomenon namely the "exploding granules". (Carlier, Chauveau, Gugan and Rösch 1968, Musman 1972, Beckers and Canfield 1975).

The phenomenon is shown (in a rather schematic way) in Fig. 4. Musman (1972) has interpreted this sequence of events as being due to the interaction of a thermal with the stable layers above the convection zone. He has carried out a laboratory experiment in order to confirm this point of view.

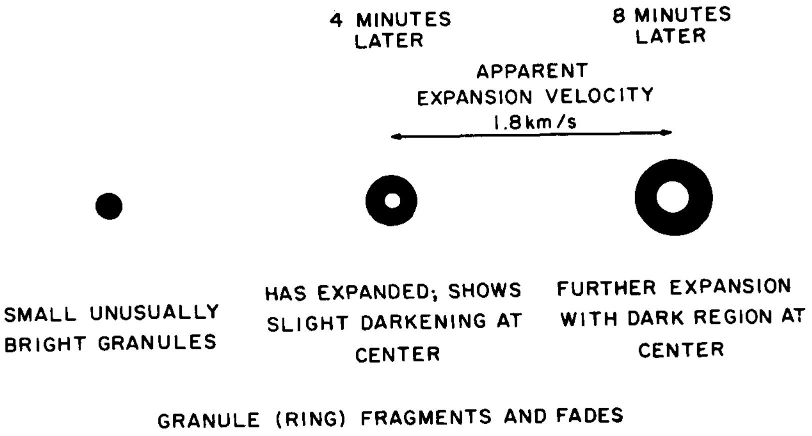

FIGURE 4

Schematic representation of the development of an "exploding" granule (after Musman 1972, see text). Note that the bright granular region is drawn dark here.

Another important group of investigation is concerned with phenomena occuring in the intergranular regions. It turns out that observers find a number of unexpected phenomena and that these observations change our idea about solar convection considerably. According to Deubner (1975) observations show that very large downward velocities can be observed fairly often in the dark intergranular lanes. He quotes that observations which have been made under excellent conditions show often downward velocities (uncorrected for seeing effects) of 2 km/s. He argues that these observations lead to corrected downward velocities of about 4 km/s or possibly to even somewhat higher values. These results indicate a very large asymmetry between upward and downward motion and should be of great relevance to an understanding of the hydrodynamics of solar convection. It is not surprising that this effect is not visible in the results of Beckers and Morrison who take average over many granules of different sizes.

It should be emphasized that it is not clear how large a fraction of the intergranular lanes really show these great downward velocities. Deubner discusses these problems in connection with the occurence of magnetic flux ropes in the photospheric network as observed by Stenflo (1973) but he definitely considers the possibility that the downward velocity is very high in all intergranular regions.

B. SUPERGRANULATION

We all know that the supergranular velocity field pattern is strongly correlated with the chromospheric network. The average diameter of supergranulation cells is about 32000 km. Cells with diameters in the whole range from about 10000 km to 60000 km are present. The typical horizontal (outflow) velocities are 0.3 - 0.4 km/s (Simon and Leighton 1964, Deubner 1971). Vertical downward motions specifically in the magnetic regions at the borders of the cell are in the range 0.1 - 0.2 km/s (cf. Simon and Leigthon 1964, Frazier 1970, Musman and Rust 1970, Musman 1971, Deubner 1971, Worden 1975). Supergranular motions have been detected also deep in the photosphere as indicated by Deubner's (1971) measurement of CI 5380 line ($\chi \sim 7.7$ eV).
It is generally agreed that the main downdrafts occur in the rather localized magnetic regions at the cell boundary.
Upward motions at the center of supergranulum of the order of 50 m/s may be present but have not yet been confirmed. (Worden and Simon 1976).
In order to judge whether supergranulation is really a convective motion a study of the corresponding temperature fluctuations is of great importance. The results of such studies are somewhat confusing though a clarification may now be in sight. Somewhat surprisingly one finds normally a slight temperature increase at the cell boundaries ($\sim$ 2.5°K) whereas according to the usual picture of a simple convective cell a temperature decrease would be expected (Beckers 1968, Frazier 1970). It is usually assumed that these very small temperature increases are due to the increase of the magnetic field and are not directly related to the convective flow (Liu 1974). One might hope to find the expected velocity – ΔT correlation more easily in deeper layers. Recently Worden (1975) has studied the supergranulation structure at 1.64 μ which represents the deepest observable layer in the solar photosphere. Using the HSRA (Gingerich et al. 1971) we find that at this wavelength we look down to about $\tau \sim 1.8$ where the temperature is $\sim$ 7000°K. Worden finds an 0.7% intensity increase near the cell boundaries. This has to be compared to an 0.4% intensity increase in the higher photospheric layers. These results can be translated into a temperature difference of about 50° in the deep photospheric layers. This rather small difference indicates that the supergranulation (if it is convection) contributes only very little to the total convective energy flux in the visible layers. Nevertheless, the fact that such large convection cells do exist is very important from a theoretical point of view.
I do not think that this conclusion is very much influenced if supergranulation is an overshoot phenomenon or if the supergranulation elements are counter cells (cf. Spiegel 1966 b).

Some of the immediate theoretical implications of the existence of convection cells of supergranular size have been discussed by Simon and Weiss(1968 a, 1968 b). They point out among other things that we should expect that the depth of cell is not very different from about one fourth of its diameter. This leads to a cell depth of about 10000km which is clearly much larger than a scale height. Simon and Weiss are to some extent guided by the results known for polytropic atmospheres in which the scale height is of the same order of magnitude as the distance to the surface of the convection zone. The possibility that cells of supergranular size will transport a large fraction of the convective energy flux in deep layers is of great importance. Simon and Weiss also predict giant cells which are comparable in size to the total thickness of the solar convection zone and which in the meantime have also been detected observationally.

We close this chapter by listing briefly some of the interesting and hydrodynamically relevant properties of solar convection in table I.

TABLE I

SOME INTERESTING PROPERTIES OF SOLAR CONVECTION

1. GENERAL

   A. Existence of two completely different cell sizes (2000 km and 32000 km)

2. GRANULATION

   A. Very high correlation between ν and Δ T (more than 80%)
   B. Flat maximum of ΔT power spectra between λ = 1200 and λ = 2000 km
   C. Very fast down-drafts ($\sim$ 4 km/s) in intergranular regions
   D. "Cell" structure
   E. Convective overshoot

3. SUPERGRANULATION

   A. Cell sizes much larger than scale height
   B. Concentration of magnetic fields at cell boundaries
   C. Positive Δ T in high layers, negative Δ T in deep photospheric layers of cell boundaries, Δ T unexpectedly small.

III CONVECTIVE MIXING AND THE Li-Be PROBLEM

When we discuss convection in stars it is quite clear that the observational evidence concerning convection has to be rather indirect. Our conclusions are usually based on a mixture of observations and theoretical predictions (which often use a very crude form of theory). Sometimes we even forget that theoretical assumptions are used and claim that the result is purely observational though it is not.
Problems of convective mixing definitely belong to this category. In many cases we certainly see effects of mixing but we can not be absolutely certain that this mixing is really due to convection. Even if it is convective mixing it can have happened rather recently or during an earlier phase of evolution. Probably, the best known example of such situation is the lithium-beryllium problem. As is well known, the solar atmosphere contains no or almost no Li^6 and in contradistinction to other old material in the solar system (chondrites) very little Li^7. In order to explain this it is usually assumed that surface material has been mixed into layers of 2.5×10^6K where the lithium is destroyed by (p, α) reactions. A progressive decrease of the lithium content from G 2 V to K 0 V stars (Wallerstein, Herbig and Conti 1965, Zappala 1972) has been attributed to the effects of pre-main sequence convection. (Bodenheimer 1965, 1966). In addition a main sequence depletion time scale of about $1.5. \times 10^9$ years has been found (Herbig 1965, Zappala 1972). It is not yet completely clear whether very slow convective overshoot (cf. Böhm 1963, 1966, Weymann and Sears 1965, Spiegel 1968, Strauß, Blake and Schramm 1976) in combination with the relevant nuclear rates can produce this time scale. However, Strauss,Blake and Schramm (1976) argue very strongly that convective overshoot can explain the observed lithium abundances. They emplasize the fact that the energetically possible convective overshoot theoretically decreases with decreasing mass of the star and that this is just the feature which is required in order to explain the observations. If this result should be confirmed the investigations of the Li problem would give us an excellent opportunity to study convective overshoot below outer stellar convection zones. It seems that the lithium problem is more useful in the study of stellar convection than many other mixing problems since the time scale is known well and since it refers to main sequence stars which are better understood than the advanced phases of stellar evolution in which most other mixing processes seem to occur. The fact that it is probably related to convective overshoot makes it especially interesting.

IV INFLUENCE OF CONVECTION ON ATMOSPHERE STRUCTURE AND COOLING TIMES IN COOL WHITE DWARFS.

After these brief remarks about the Li problem I finally would like to talk about a group of convection problems which are also closely related to the above questions and in which I have been strongly interested in recent years. This is the field of convection in white dwarf stars. I personally feel that there may be more drastic effects of convection on observable properties in the case of white dwarfs than in most other stars for the following reasons (cf. Böhm 1968, 1970, Van Horn 1970, Wickramasinghe and Strittmatter 1970, Böhm and Cassinelli 1971, Wegner 1972, Grenfell 1974, Fontaine et al. 1974, Fontaine and Van Horn 1976, Muchmore and Böhm 1976).

1. Atmospheric convection persists over a wider effective temperature range in white dwarfs than in any other stars. This is especially true for the roughly 30 % of white dwarfs which are called non-DA's and which have very He-rich atmospheres. In these objects outer convection zones are present in the effective temperature range from about 25000°K down the lowest effective temperatures.

2. Convective instability sets in very high in cool white dwarf atmospheres. In a number of models this occurs at optical depths higher than 0.01. Consequently the atmospheric structure is strongly influenced by convection. This is especially true for white dwarfs with, say, $T_{eff} < 8000°$ in which the high atmospheric density leads to relatively high effectivity of convection and consequently to a temperature stratification which differs considerably from a radiative equilibrium stratification (cf. Wegner 1972, Grenfell 1972). In extreme cases (non-DAs with $3000°K \leqslant T_{eff} \leqslant 5000°K$) the convective flux reaches values of about 60 % of the total flux at $\tau \sim 1.0$ (Böhm, Carson, Fontaine and Van Hors 1976). So, we should be able to detect the presence of convection without difficulty by studying the line spectra of cool non-DA white dwarfs like Van Maanen 2 and Ross 640. (However, it should be emphasized convection in cool white dwarfs has to be studied through its influence on the mean stratification of the atmosphere. The velocities in these high density atmospheres are much too small to be detected directly.)

3. The existence of two different types of white dwarfs atmospheres, one consisting of almost pure helium (non-DA), the other one of almost pure hydrogen (DA) has lead to the suggestion that convective mixing processes in combination with gravitational separation and/or accretion may be important in determining the chemical composition of white dwarf atmospheres (cf. Strittmatter and Wickramasinghe 1971, Shipman 1972, Baglin and Vauclair 1973). However, the subject is controversial and simple convective

mixing is insufficient to explain the non-DAs (Koester 1976). Nevertheless, some interesting convective mixing effects are to be expected since it is clear that white dwarfs have a very thin envelope of hydrogen or helium surrounding the main body of the star which consists of C and O (cf. Weidemann 1975).

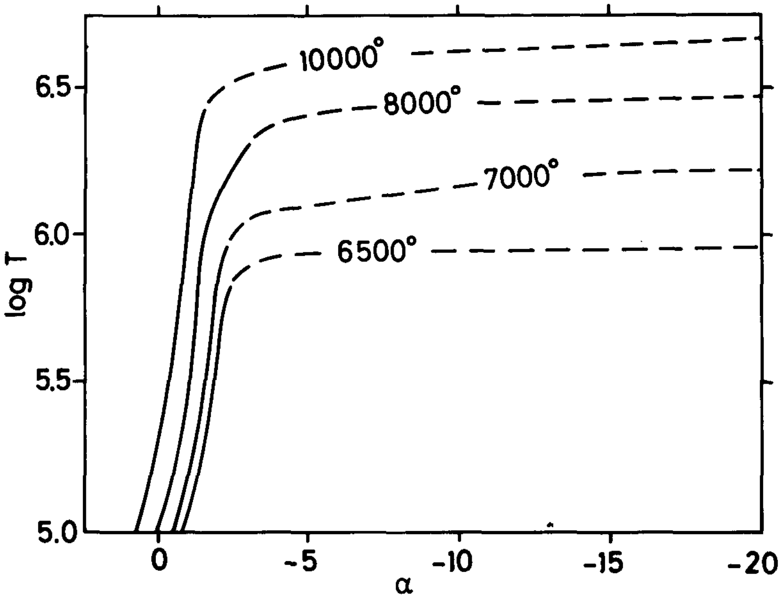

FIGURE 5

Temperature stratification in the outer layers of cool He-rich (non-DA) white dwarfs. The diagram is based on calculations by Muchmore and Böhm (1976). We have plotted the logarithm of the temperature as a function of the local degeneracy parameter $\alpha = -\mu/kT$ (with μ = chemical potential). T_{eff} is the parameter.
The solid parts of the curves correspond to convection zones, the broken lines to the radiative-conductive zones below. The diagram shows how the temperature in cool He white dwarfs approaches its asymptotic core value T_c and how large a fraction of the temperature rise towards T_c occurs in the (geometrically thin) convection zone. This gives some indication of the importance of convection for the determination of the T_c and T_{eff} relation (see text).

4. In the case of white dwarfs the evolutionary time scale is strongly influenced by the time it takes for energy flux to go through the outer non-degenerate and partially degenerate layers. When convection breaks through this "insulating" layer the cooling becomes considerably faster. Consequently, the cooling time and the luminosity function of white dwarfs is influenced by the presence of convection (cf. Böhm 1968, Ostriker 1971, Lamb and Van Horn 1975). Eventually we shall be able to derive information about convection from all these different effects. Some indication of the importance of convection for the determination of the relation between core temperature and T_{eff} is given in Fig. 5. Finally it should be emphasized that the comparison of theoretical predictions of white dwarf convection with observations involves one complication which is not present in most other stars. The calculation of the equation of state, the adiabatic gradient and the specific heat is made rather difficult by the presence of partial degeneracy, pressure ionization and electrostatic interactions between the particles. (In non-DAs of $T_{eff} < 3800°$ we face some fascinating problems because drastic complications of the equation of state, including partial degeneracy, occur already within the atmosphere, see Böhm, Carson, Fontaine and Van Horn 1976). However, we hope that the problems related to the equation of state will be overcome in the foreseeable future.

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