DIFFUSION AND HE OVERABUNDANCES: HYDRODYNAMICAL IMPLICATIONS

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ABSTRACT. In the absence of mass loss, diffusion leads to *underabundances* of He in main sequence stars. Because of a very strong observational link with Ap and He weak stars, it has however been suggested that diffusion is the explanation for the He rich stars of the upper main sequence. This requires a mass loss rate of 10^{-12} $M_{\odot}$ yr^{-1} or slightly lower. The mass loss rate must decrease as T_{eff} increases. Magnetic fields must apparently be involved to *reduce* the mass loss rate. Since this model predicts that the CNO abundances should be normal in the cooler He rich stars, it leads to a clear observational test. Detailed calculations should be made to confirm the importance of this test. The effects of separation in the wind, the atmosphere and the envelope are discussed to conclude that separation in the atmosphere is likely to be most important. The importance of diffusion for He rich white dwarfs and horizontal branch stars are briefly discussed.

1. THE OBSERVATIONAL LINK

The difficulty to find a model based on nucleosynthesis to explain the abundance anomalies of the AmFm, HgMn and magnetic Ap stars has been a major factor in the acceptance of the model based on chemical separation for those objects. It is not easy to find a nuclear process that will build large overabundances of, say, Mn and Hg while not modifying Fe or O. However, most of the He rich stars are believed not to have large anomalies of other elements. Furthermore, it is well known that stellar evolution produces He. At first sight the He rich stars are *not* a likely product of diffusion.

In their original paper, however, Osmer and Peterson (1974) already suggested that diffusion was the likely process responsible for the He rich stars and this suggestion is now generally accepted even if it has been shown that diffusion, by itself, always leads to He underabundances. One of the main reasons invoked by Osmer and Peterson was the surface gravity of the He rich stars. It is the same as that of young main sequence stars of the same effective temperature suggesting that the anomalies are only superficial. Their argument was supported by the magnetic field

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measurements of Borra and Landstreet (1979). Their results suggested that more than 50% of the He rich stars (6 out of 9 observed) had measurable magnetic fields, linking them to the magnetic Ap stars where diffusion is believed to be responsible for the anomalies. Since they furthermore constitute a temperature sequence with the Ap and He weak stars (Osmer and Peterson 1974), the observational link now seems overwhelming.

After showing that the parameter free model always leads to He underabundances (§ 2), except perhaps for some white dwarfs (§ 3), we will study the effect that mass loss (§ 4) and magnetic fields (§ 5) may have on helium abundances and show that, through the interaction of hydrodynamical processes and diffusion (§ 6), abundances are powerful indicators of stellar hydrodynamics. Only through that interaction are overabundances of helium produced by chemical separation.

2. THE PARAMETER FREE MODEL

Diffusion is a basic physical process and plays a role everywhere a more efficient transport process does not wipe out its effects. If one assumes that a star arrives on the main sequence with the convection zones as given by standard evolutionary models and one allows the chemical separation to go on unimpeded, one obtains a parameter free model. It is a simply defined stellar model that, as we shall see, leads to underabundances of He but to large overabundances of many heavy elements. It is hardly in agreement with the observations of He rich stars! It contains the hydrodynamics that can currently be described without arbitrary parameters.

As the star arrives on the main sequence, diffusion starts occuring below the He II convection zone. The diffusion velocity gives the direction that migration takes:

$$v_D = -D_{12}\left\{\frac{\partial \ln c}{\partial r} + \left[g\left(A - \frac{Z}{2} - 1\right) - A\, g_R\right]\frac{m_p}{kT} - k_T\,\frac{\partial \ln T}{\partial r}\right\}. \quad (1)$$

Since the star is presumably formed homogeneous, the derivative of c (c = N(A)/[N(H) + N(A)]) is originally zero. The thermal diffusion term is never very large according to Michaud et al. (1979) and Paquette et al. (1985) have recently shown that the thermal diffusion coefficient is even smaller than that used by Michaud et al. (1979). It goes in the same direction as the gravitational settling term which is much larger. To stop gravitational settling, the radiative acceleration must then nearly equal gravity. Michaud et al. have however shown that it was never the case on the main sequence for normal helium abundances. The diffusion of helium then always starts downwards and its abundance decreases. Equation (1) assumes trace abundance of an element diffusing in H. This is not the case for He because of its relatively large abundance, but Montmerle and Michaud (1976) have shown that this did not change substantially the diffusion equation. I refer the reader to Pelletier et al. (1985) for a simple diffusion equation that is accurate even for elements that are

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not trace. It is shown there that the new diffusion coefficients of Paquette et al. (1985) increase the He abundance that can be supported by the radiative acceleration by a factor of about 3 compared to the results of Michaud et al. (1979) even though underabundances of He by a factor of 30 are still predicted.

The time scales for the appearance of underabundances are short, typically of the order of 10^5 years in main sequence stars of $T_{eff} = 20\ 000$ K (Martel 1979).

One may question one aspect of the calculations I just referred to. They were all made in the diffusion approximation for the radiative transfer. This is valid below the atmosphere but could it happen that in the atmosphere, where the radiative transfer is more complicated, the radiative accelerations be actually much larger? It seems highly unlikely that the increase could be large enough to explain the He rich stars since the radiative accelerations would need to be multiplied by a factor of ten to be able to support the observed He abundance. Still, it should, some day, be investigated.

As can be expected the degree of He underabundance that diffusion leads to depends on both T_{eff} and log g. The cooler the star, for a given gravity, the smaller the radiative flux and so the smaller the radiative acceleration. This can be seen by comparing Figures 2 and 3 of Michaud et al. (1979). At $T_{eff} = 10\ 000$ K the radiative acceleration can support some ten times less helium than at $T_{eff} = 20\ 000$ K. The difference is even more striking between main sequence stars, horizontal branch stars and white dwarfs. For the radiative acceleration to support the same He mass fraction as in a 20 000 K main sequence star, a subdwarf star must be 40 000 K while a white dwarf must be 90 000 K (Vennes 1985). In all cases only underabundances can be supported.

3. HYDROGEN BURNING IN WHITE DWARFS

The gravitational settling of He concentrates hydrogen in the superficial layers of white dwarfs, leading in particular to the H rich white dwarfs (Schatzman 1958). Diffusion does not however lead to a complete disappearance of H from the interior. At equilibrium, the hydrogen abundance decreases inwards exponentially as given by:

$$v_D = D_{12} \left(- \frac{\partial \ln c}{\partial r} - \frac{5}{4} \frac{\partial \ln p}{\partial r} \right) \qquad (2)$$

for $v_D = 0$. Equation (2) gives the diffusion velocity for trace hydrogen diffusing in helium. In words, diffusion leads to the hydrostatic equilibrium gradient for hydrogen, it stops once this is achieved and starts in the opposite direction if it is exceeded. In white dwarfs with regions warm enough for hydrogen to burn ($T > 10^7$ K), the nuclear reactions will drive down the hydrogen abundance where it can burn, the equilibrium gradient will be exceeded and diffusion will start transporting hydrogen downwards (Michaud, Fontaine and Charland 1984, Michaud and Fontaine 1984). The most important nuclear reaction for this process is with carbon since the pp chain shuts itself off at low hydrogen abundances. The carbon is being constantly replenished by diffusion from the interior since there is a carbon layer starting at less than 1% of the stellar mass. See Pelletier et al. (1985a) for a detailed discussion of the uppard diffusion of C from the interior and how it pollutes the surface.

How important the process is for white dwarfs of a given effective temperature depends sensitively on the internal temperature. A temperature change by a factor of 1.6, changes the nuclear burning timescale by 4 orders of magnitude, so making the process either very efficient or very inefficient (see Table 1 of Michaud, Fontaine and Charland 1984).

This process has potential effects for white dwarfs but not for main sequence stars. For it to be efficient, the distances that hydrogen has to travel to get to the burning region must be small, otherwise, the time scales become too long. It could play a role both in maintaining at a low level the surface abundance of hydrogen in DB white dwarfs and in reducing the depth of the hydrogen layer on DA white dwarfs, even conceivably transforming DA into DB white dwarfs.

Some white dwarfs are known to be extremely He rich and to have traces of metals (Liebert 1980). Because of the high efficiency of gravitational settling in white dwarfs, it appears that the metals can only come from recent accretion episodes. But then how could the star have accreted the metals efficiently while not accreting the hydrogen? Even a very small amount of hydrogen would show strong H lines once concentrated by diffusion to the surface. The process just described can reduce the hydrogen abundance below the observational upper limit of N(H) / N(He) = 10^{-4} so long as the accretion rate remains below 10^{-19} $M_\odot$ yr^{-1} (Michaud, Fontaine and Charland 1984).

In DA white dwarfs, the superficial hydrogen layer can also be reduced by hydrogen burning. Evolutionary models typically leave a surface layer of 10^{-4} $M_\odot$ of hydrogen. During the white dwarf cooling, Michaud and Fontaine (1984) obtained that the hydrogen layer could be reduced to 10^{-9} $M_\odot$. The exact factor by which the hydrogen abundance is reduced is however very sensitive on the detailed internal structure of white dwarfs and can only be determined by stellar evolution models. In their evolutionary models, Iben and MacDonald (1985) obtained that the process just described consumed a significant fraction of the hydrogen remaining at the end of the shell burning phase though it either left a mass fraction of hydrogen of order 10^{-4} $M_\odot$ or lead to an hydrogen flash as the star was approaching the white dwarf sequence. This depended mainly on the exact depth of the He layer buffer between the hydrogen surface and the carbon core. Furthermore given the great sensitivity of the burning rate on temperature, an increase of the internal temperature by a factor of 1.5 would considerably lengthen the time during which the process is effective and so increase the effect on the hydrogen layer. For the destruction of H to be as efficient as proposed by Michaud and Fontaine (1984), the internal temperature of white dwarfs would need to be about 50% larger than in the models of Iben and Macdonald (1985).

It should be pointed out that any small turbulence would strongly enhance the efficiency of the process to the point that even such a small turbulence implied by $D_T = D_{12}$ nearly completely eliminates DA white dwarfs. The mere existence of DA white dwarfs then puts a strong upper limit on the amount of turbulence in white dwarf interiors (see Fig. 2 of Michaud and Fontaine 1984).

This process is however negligible for main sequence or horizontal branch stars because of the larger distances that have to be covered by the diffusing elements and so the much longer time scales involved. Then other hydrodynamical processes must be included in the model to explain helium overabundances.

4. MASS LOSS AND HELIUM OVERABUNDANCES

Vauclair (1975) has suggested that, if the mass loss rate is appropriate, it could lead to overabundances of helium in the atmospheres of the relatively hot stars observed to have such anomalies (Osmer and Peterson 1974). If the mass loss rate is appropriate, hydrogen will drag helium along and He will accumulate where the dragging is least effective that is where He is most in the form of neutral helium, since the diffusion coefficient is then some two orders of magnitude larger than when it is ionized. In the stars where it is observed to be overabundant, helium is least ionized in the atmosphere, so that is where it accumulates.

The simplest model based on mass loss assumes that the star is losing mass at a constant rate in a spherically symmetrical way. The chemical separation can be calculated using equation (1) along with the mass conservation equation of the dominant specie in the presence of mass loss:

$$\frac{dM}{dt} = -4\pi R^2 N_H \, m_p v_w \quad . \qquad (3)$$

In order to simplify the argumentation, we neglect, in this discussion, the fact that He is not really a test element. The diffusing element must also satisfy a conservation equation:

$$\nabla \, (c \; N_H (v_w + v_D)) = 0 \quad . \qquad (4)$$

To calculate the chemical separation, it is convenient to separate the star in three zones: the coronal-wind region, the photospheric region and the envelope region. The frontier of each of these zones is somewhat arbitrary. For the corona, it can be fixed where the hydrostatic solution stops to be accurate; for this reason I also call it the wind region even though the outward movement caused by the wind pervades the whole photosphere and envelope but with negligible dynamic effects. This definition applies even to stars that would have a cool wind and so no proper corona. For the envelope we choose the bottom of the He II convection zone for a normal He abundance as a convenient boundary (see Figure 1).

4.1 The Wind

To what extent does the wind cause the abundance anomalies in the atmosphere? Does the wind leave with the abundances of the top of the atmos-

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T_{eff} = 25 000 K

HYDRODYNAMIC REGION (WIND)

__________________________ $\tau = 10^{-4}$

PHOTOSPHERE (OVERSHOOTING?)

__________________________ $\tau = 3$

HELIUM II CZ

__________________________ $\tau = 30$

ENVELOPE

Figure 1. Outer structure of a 25000 K main sequence star. The chemical separation could take place in three regions, the envelope, the atmosphere and the dynamical or wind region. Two of them are separated by a convection zone.

phere or does additional separation occur in it? This depends to some extent on the unknown hydrodynamic structure of the wind but we investigate these questions under the assumption of the simplest wind structure: that of a corona with a constant temperature. We investigate the uncertainty of such a model by considering the effect of varying Z, the degree of ionization, on the separation.

The equations governing the element separation in the wind region are actually a little different from those given above because of the importance of the dynamical terms. Details of the calculations will be given elsewhere (Michaud et al. in preparation). It turns out that the solution is dominated by a comparison of the gravitational settling and wind velocities. Depending on which is largest, a term changes sign in the differential equation and the nature of the solution changes completely from one where element A is completely dragged to one where it is essentially left behind (Fakir 1985). Using equations (1) and (3) and equating the wind velocity to the gravitational settling velocity, one obtains:

$$v_W = \frac{-dM/dt}{4\pi R^2 N_H m_p} = D_{12} \frac{Ag\, m_p}{kT} , \tag{5}$$

where it has been assumed that only gravitational settling is important in the diffusion equation. After replacing the physical constants, one obtains:

$$\frac{dM}{dt} = \frac{2.4\ 10^{-15} M\ A\ T_5^{1.5}}{Z^2} \tag{6}$$

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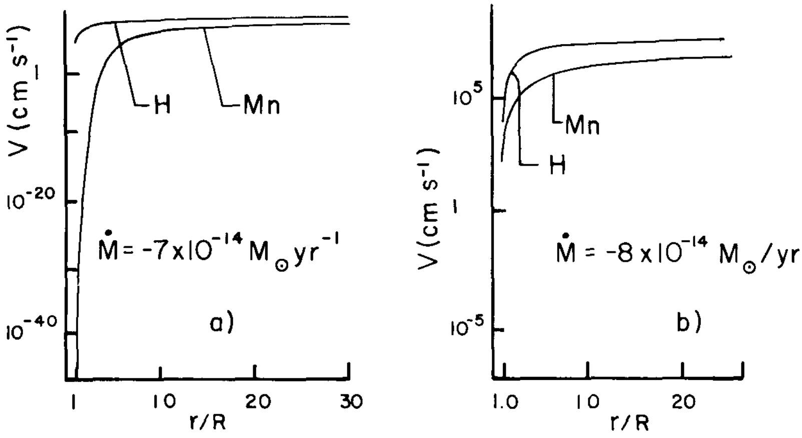

Figure 2. Transport velocity in the wind as a function of the distance to the star center in units of the stellar radius. Hydrogen is assumed to be the dominant specie. Because of chemical separation the velocity of Mn is smaller than that of hydrogen. For a mass loss rate of 10^{-12} $M_\odot$ yr^{-1} the curve for Mn cannot be distinguished from that for H. Note the difference in scale for parts *a* and *b*.

where the logarithmic Coulomb term has been replaced by an average value. This causes the mass loss rate to be overestimated by a factor of 1.5 in the wind but underestimated by a factor of up to 3 in deep stellar interiors. The quantity T_5 is the temperature in units of 10^5 Kelvin. Detailed solutions of the chemical separation in presence of a wind are currently being calculated and I will use equation (6) to discuss the main results.

In Figure 2 is shown the particle transport velocity of Mn as a function of the radius in constant temperature coronas for a 3 $M_\odot$ star. The flux is conserved and is proportional to the velocity, so that if the velocity of Mn at the bottom of the corona is smaller than that of H by 47 orders of magnitude, so is the flux of Mn and no Mn then leaves the star. First, notice the high sensitivity on the exact value of the mass loss rate. A few percent change in the mass loss rate changes completely the solution if one is close to the limiting value given by equation (6). The limiting mass loss rate is close to 10^{-13} $M_\odot$ yr^{-1} in this case. Below that value no Mn is dragged by the wind while above that value Mn leaves with the abundance at the top of the atmosphere. There is a transition region but as can be seen from the figure it is approximately a factor of three in mass loss rate.

Since the important parameter is the expression appearing in equation (6), changing the atomic mass has an equivalent effect to changing the mass loss rate. A lighter element such as He would be dragged for a wind smaller by a factor of 14, *if* it were not for the fact that He is less ionized than Mn. Since He is 4.5 times less ionized than Mn, the critical wind is actually 1.5 times as large for He as it is for Mn. Note that the figure does not correspond to exactly the mass loss rate of equation (6) because of the approximations made in deriving equation (6).

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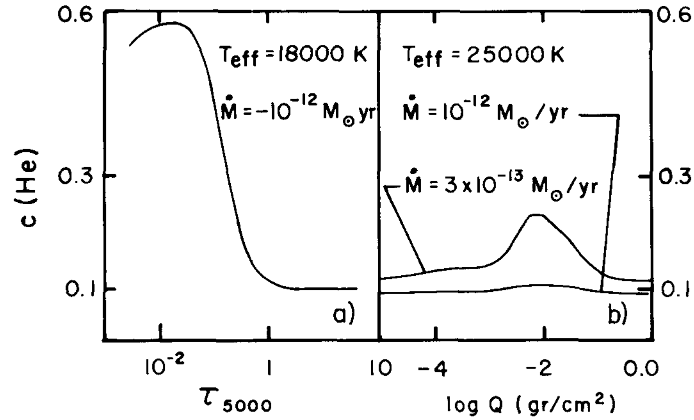

Figure 3. Abundance of He in the atmospheres of an 18000 K and of a 25000 K star. Because of higher ionization, the mass loss must be smaller in the hotter star for overabundances to materialize.

The critical mass loss rate for helium is then about 1.5 10^{-13} $M_\odot$ yr^{-1} in 3 $M_\odot$ stars while it is about 3 10^{-13} $M_\odot$ yr^{-1} in 6 $M_\odot$ stars, as is more appropriate for He rich stars.

The model used here assumes a hot wind with a corona. Even if we have not calculated such models in detail, it is possible (using equation 6) to evaluate the effect of reducing the temperature of the wind on the critical parameter. If the charge remained the same, the critical wind would be 192 times smaller if the temperature were 30000 instead of 10^6 K. However the ionization of Mn is then reduced from Z = 9 to Z= 2 and that of He from 2 to 1. The diffusion coefficient of once ionized He is 4 times that of twice ionized helium. The critical mass loss rate is then, for helium, at 30000 K decreased by a factor of 50. It is equal to about 10^{-14} $M_\odot$ yr^{-1}.

Only in stars with T_{eff} < 20000 K does He become mainly neutral in the wind so that the separation can increase (to about 10^{-12} $M_\odot$ yr^{-1}) because of the much larger diffusion coefficient of neutral helium (Michaud et al. 1978). From equation (6) the same separation would be expected in a cool wind as in the atmosphere, since the temperature is about the same, however for helium in stars of T_{eff} = 20000 K, the ionization is larger in the wind. The separation should then be larger in the atmosphere than in a cool wind of a given star.

4.2 The Atmosphere

The separation in the atmosphere was first studied by Vauclair (1975). She considered the time dependant solution of the He abundance in the presence of a wind. She showed, for a mass loss rate of 10^{-12} $M_\odot$ yr^{-1} in a star with T_{eff} = 20000 K, that He would accumulate in the photosphere. Her result still stands.

I will discuss this model in a little more detail. The whole process is due to He being hardly ionized in the atmosphere at 20000 K and so

T_{eff}	N(He I)/N(He)
17 500	1.0
20 000	0.8
22 500	0.4
25 000	0.1
27 500	0.014
30 000	0.0013

Table 1. Maximum of N(He I)/N(He) from Mihalas (1972).

having a much larger diffusion flux than in the envelope, where it is ionized. Generally an element is least ionized in the atmosphere because of the smaller temperature there.

Since her paper appeared, new evaluations of the neutral helium diffusion coefficient have become available (Michaud et al. 1978). They are more accurate than her hard sphere approximation. They use a more realistic polarization potential to represent the interaction. They lead to diffusion coefficients that are some 4 to 6 times smaller than the hard sphere approximation. It reduces the critical flux by a factor of 4 to 6.

To understand in a little more detail the physics of the outgoing wind, it is interesting to consider an equilibrium solution in the atmosphere with as much He leaving the atmosphere as entering from the bottom. The time evolution of the flux arriving from the envelope is taken into account. The flux conservation (equation [4]) implies that, where the wind and diffusion velocities nearly cancel each other, the He abundance must increase so that the flux remains constant. When this happens in the atmosphere, the He abundance increases in the atmosphere. This occurs for wind velocities just slightly larger than the critical value given by equation (6). Such a solution is shown in Figure 3. This He distribution occurs for about a mass loss rate of 10^{-12} $M_\odot$ yr^{-1} at T_{eff} = 18000 K. At T_{eff} = 25000 K, there is hardly any separation for this mass loss rate. The critical mass loss rate decreases as the effective temperature increases. This can easily be understood from Table 1 where is shown the maximum fraction of unionized He in the atmosphere (from Mihalas 1972). As the temperature increases, the ionization increases and the large diffusion coefficient of neutral helium plays a smaller and smaller role. The maximum overabundance that can be supported by this process also decreases as T_{eff} is increased.

Larger mass loss rates lead to smaller overabundances. Smaller mass loss rates lead to a discontinuity when the wind and diffusion velocities are equal. Some of our hypotheses have broken down: it is not possible to assume flux conservation any more. Below that critical value of the flux, He accumulates in the atmosphere and, for yet smaller mass loss rates, settles gravitationnally.

4.3 The Envelope

In the absence of mass loss, gravitational settling through the bottom

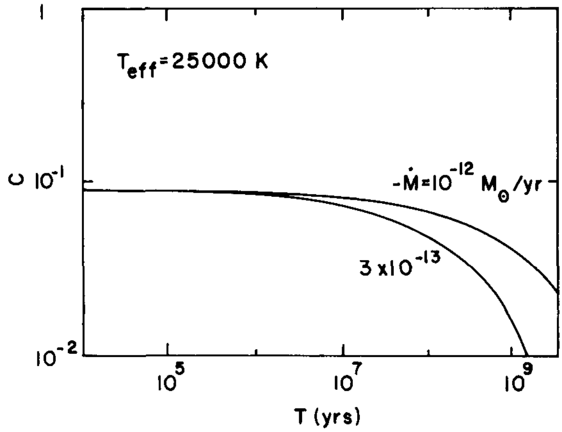

Figure 4. Time dependance of the He abundance in the convection zone of a 25000 K star. If the mass loss rate is 3 10^{-13} $M_⊙$ yr^{-1}, the gravitational settling does not have time to materialize in the life time of the star and overabundances can materialize in the atmosphere.

of the He II convection zone reduces the helium abundance in the atmosphere by a factor of 3 in about 10^5 years (Martel 1979). For overabundances to be produced, the wind velocity (equation [3]) below the He II convection zone must be large enough to make gravitational settling inefficient. It must then be significantly larger than the diffusion velocity. Indeed the wind model is possible for He rich stars because, when He is neutral in the atmosphere, its diffusion velocity is substantially larger there than below the convection zone, where it is necessarily twice ionized. There comes however a point in the envelope where the two velocities are equal since, as the temperature increases, the ratio of the wind velocity to the diffusion velocity decreases as $T^{1.5}$, due to the $T^{2.5}$ dependence of the diffusion coefficient. As time proceeds and mass loss goes on, the matter that was originally where the combined diffusion and mass loss velocity was downwards finally arrives in the atmosphere, and the He abundance starts decreasing in the atmosphere. To evaluate how long this takes as a function of the mass loss rate, one must calculate the time evolution of the He abundance in the convection zone of a main sequence star with T_{eff} = 25 000 K. To separate the effects of the separation in the wind region and in the envelope, it is assumed that no separation occurs in the wind. The time evolution is shown in Figure 4 for two values of the mass loss rate. Since the stars of interest have main sequence life times of only a few times 10^7 yr (Iben 1966), it is clear from the figure that the envelope always supplies the convection zone with a normal abundance of He. The He abundance starts to decrease in the atmosphere only after the main sequence life is over. In Table 2 is shown the time it takes for the He abundance to be reduced by a factor of 3 in the convection zones as a function of the mass loss rate. Since this result is not very dependent on the mass of the star, and since mass loss rates of 10^{-13} to 10^{-12} $M_⊙$ yr^{-1} always lead to some He overabundances, one can say that the He overabundances are maintained for most of the main sequence life time only for stars that have lifetimes shorter than 10^8 yr.

dM/dt ($M_\odot$ yr^{-1})	τ (yr)
10^{-14}	2.0 10^{6}
3 10^{-14}	10^{7}
3 10^{-13}	3.0 10^{8}
10^{-12}	1.5 10^{9}

Table 2. Timescale for the helium abundance to decrease by a factor of 3 in the convection zone (T_{eff} = 18 000 K).

5. MAGNETIC FIELDS, MASS LOSS AND CHEMICAL SEPARATION

Many of the He rich stars have been observed to be magnetic (Borra and Landstreet 1979) so that it is generally believed that the magnetic field plays an important rôle in the appearance of the He rich phenomenon in at last some of the stars. Just as for the Ap stars, the magnetic field is probably essential in stabilizing the atmosphere and so to allow the separation to go on. However here we will only discuss its effect on the chemical separation and the mass loss rate. Both of these imply diffusion through the magnetic field lines when they are horizontal.

5.1 Diffusion Across Magnetic Field Lines

Magnetic fields affect diffusion across magnetic field lines according to the classical formulas that can be found for instance in Chapman and Cowling (1970). The diffusion velocity across magnetic field lines is multiplied by a factor:

$$\frac{1}{1 + \omega_i^2 \tau_c^2}$$

where:

$$\omega_i \tau_c = 1.7\ 10^4 H\ T^{1.5}/(N_p Z)\ .$$

All quantities are in the CGS electromagnetic system. For magnetic fields typical of those observed on Ap or He rich stars, diffusion is affected by the magnetic field only outside of the photosphere. Michaud et al. (1981) have shown that it started guiding elements only for τ_{5000} smaller than 10^{-2}. At that depth, the diffusion velocity perpendicular to the magnetic field is reduced by a factor of 2. It is only at an optical depth 10 times smaller that the diffusion velocity is reduced by a factor of 100. Deeper than this in the star, the proton density is too large and the diffusion velocity is hardly affected by the magnetic field. Note however that the diffusion flux is very rapidly reduced as one goes further outside the star since the reduction factor goes as the square of the proton density. Where the magnetic field lines are horizontal this leads to a nearly complete illimination of the wind if the density structure is not modified by the combined presence of the wind and the magnetic field.

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This correction factor has however been found not to be an accurate description of the flux diffusing across magnetic field lines in fusion devices. The flux has been observed to be much larger than predicted. It has lead to the development of the Bohm formula which is discussed for instance by Laing (1981). It is an empirical formula which does explain the measured flux in a number of fusion devices but not in all. In some cases the classical formula appears closer to reality, in particular in the thetatron where the gas is confined to a straight line. Laing suggests that the Bohm formula can be understood from the classical formula if proper account is taken of the detailed geometry of the field lines and of the instabilities that can develop in the magnetic field.

We cannot be sure that similar effects are important in stars since the dimensions are so different. However it remains a possibility and while we feel that it is more appropriate to use the classical formula, it remains that it may overestimate the correction to the diffusion velocity. The effective reduction factor may possibly go as $1/H$ as Bohm suggests instead of as $1/H^2$ as the classical formula says.

This could be important when one considers the amplification of the effective radiative acceleration caused by horizontal magnetic fields as discussed by Alecian and Vauclair (1981), Mégessier (1984), Michaud, Mégessier and Charland (1981) and Vauclair, Hardorp and Peterson (1979). It is there argued that where the magnetic field lines are horizontal, the neutral state can diffuse accross the magnetic field lines but not the ionized states. If an element is efficiently pushed upwards by the radiative acceleration in the neutral state, but settles gravitationaly in the ionized state, the efficiency of the radiative acceleration is considerably increased. Even if, in non magnetic He rich stars, the radiative acceleration on He were to be smaller than gravity (Michaud et al. 1979), this effect may make it larger than gravity where the magnetic field lines are horizontal in magnetic stars. This however requires the magnetic field to be larger than is in practice observed (at least 10000 Gauss where the field lines are horizontal) and further requires it to be horizontal to a high accuracy (Michaud, Mégessier and Charland 1981).

5.2 Models of Magnetic He Rich Stars.

There are two papers where aspects of the interaction of magnetic fields with He overabundances are discussed in some detail.

Havnes and Goertz (1984) have studied the structure of magnetospheres of chemically peculiar stars. Their study applies in particular to He rich stars. They study what happens in the magnetosphere for a given mass loss. They do not assume the mass loss to be due to the radiation pressure (Abbott 1982) but rather look for the structure of the magnetosphere under the combined effects of gravity and rotation. This leads to an abundance gap close to the star that might not be there if the driving mechanism of the wind were included in the model. By comparing the particle energy density to the magnetic field energy density, they conclude that mass loss rates of the order of magnitude of those considered here lead to instabilities in the far magnetosphere. It does not appear possible, according to their result, for the wind to diffuse quietly across magnetic field lines. The various diffusion mechanisms they consider are not efficient enough. They conclude that the wind accumulates where the lines are horizontal until the magnetic field lines break. They do not study the problem of how the flux is reduced when the magnetic field is parallel to the surface in the photosphere.

This is however central to the separation process. According to the Shore and Bolton model as described by Bolton (1984) the mass loss is proportional to how horizontal the magnetic field lines are and so varies over the surface. Using the formula of Abbott (1982) for the mass loss rate, he argues it is essential that the mass loss rate be reduced for the separation to be effective. Without a magnetic field it would be too large. Where the magnetic field is horizontal, the mass loss is smallest. Various combinations of mass loss rates and magnetic geometries can then lead to a large variety in the distribution of anomalies over the surface. The basic idea of the importance of the magnetic fiel in reducing the mass loss rate and making the separation possible is probably right. Whether it occurs as they have calculated is impossible to tell since there are no details of the calculations in the account given by Bolton.

6. HYDRODYNAMICS AND ABUNDANCE ANOMALIES

Using the empirical formula of Abbott (1982), it is easy to calculate that the mass loss rate to be expected in main sequence stars with T_{eff} = 20000 K is about 6 10^{-11} $M_{\odot}$ yr^{-1}. It should increase as T^7_{eff} because of the dependence of Abbott's formula with temperature. This is more than an order of magnitude larger than the mass loss leading to He overabundances. There is no region in the star where He can separate if the mass loss rate is that large. For chemical separation to occur there must be a mechanism to reduce the mass loss rate as concluded by Bolton (1984). Since, as T_{eff} is increased, the mass loss rates leading to He overabundances go down (see §4.2), the mechanism must become more effective in reducing mass loss as the temperature is increased. Presumably that must be an horizontal magnetic field. If one accepts the empirical values of the mass loss as determined by Abbott (1982), there must be a magnetic field to reduce mass loss in all He rich stars. According to Abbott (1979), the mass loss formula should be reasonably accurate for the higher temperature He rich stars but may be an overestimate around T_{eff} = 20000 K.

In their outer regions, He rich stars have an He convection zone. It starts at an optical depth of 2 or 3 and ends at an optical depth of 30. It is due to He II ionization. It cannot disappear by He settling at its bottom because the mass loss rate is too large (see §4.3) to allow He settling. Some atmosphere models also have convection zones due to He I ionization at optical depths that are smaller than 1 (see e.g. Mihalas 1965). Given the high velocity of random motions in convection zones, they are nearly certainly homogeneous (Schatzman 1969). The separation cannot take place in convection zones. It is also believed that convection zones lead to some overshooting (Latour, Toomre and Zahn 1981). In the presence of such convection zones, can separation take place in the atmos-

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phere of He rich stars? The He separation can only start where overshooting is stabilized and the atmosphere is stable. Perhaps the magnetic field could eliminate the convection or at least the overshooting in parts of the surface. If, because of overshooting, the atmosphere were mixed, the separation could only take place in the wind. Whether the separation takes place in the wind or the atmosphere leads itself to an observational test.

The model that relies on the separation of neutral He in the atmosphere *requires* a relatively large mass loss rate of 10^{-12} $M_{\odot}$ yr^{-1}. From equation (6) this mass loss rate allows the separation of no other element. All other elements should be normal in He rich stars if this model is right. This applies to the CNO elements in particular. It does not appear possible to evade this consequence of the model though it should be checked by more detailed calculations. Furthermore I know of no other model to explain He overabundances that makes such a prediction. Surely, if He overabundances were to be explained by H burning in 5 $M_{\odot}$ stars, the relative abundances of the CNO isotopes would be modified.

Similarly, if the separation were to take place in the wind, other anomalies should be present. The mass loss rate is then smaller than that needed to cause overabundance from separation in the atmosphere and additional anomalies are expected from separation in the wind itself or the envelope. The search for other anomalies in He rich stars becomes a precise test of the models that have been proposed for these objects. It should be conducted in the cooler He rich stars since only there is the mass loss rate that allows He separation clearly larger than that allowing the separation of heavier elements.

The decrease in the fraction of neutral He as the T_{eff} increases puts the model based on the separation in the atmosphere in difficulty in the hotter He rich stars. According to Osmer and Peterson (1974) some of the He rich stars have T_{eff} = 29000 K. In such stars, the effect of neutral He is clearly negligible and an alternate model seems necessary. It could be that the separation actually occurs in the wind and not in the atmosphere in the hotter He rich stars. It is also possible that the effective temperature of some He rich stars has been overestimated by some 2000 K. It would be important to determine more precisely the effective temperature range of the phenomenom.

On the other hand the observation of abundance anomalies in various stars of the Herzprung Russel diagram allows the determination of constraints on the mass loss rates that are allowed. On the main sequence, the rates go from 10^{-12} to 10^{-15} $M_{\odot}$ yr^{-1} depending on the effective temperature. There are similarly constraining limits on the horizontal branch and its continuation. Heber (1985) has discussed constraints coming from the diffusion of He in the atmosphere. If one uses the upper limit determined by Michaud et al. (1985) to evaluate the amount of mass that can have been lost in the sdOB state one finds approximately:

$$\Delta = - \frac{dM}{dt} \tau = 10^{-14} \tau \quad M_{o} \; yr^{-1} \qquad (7)$$

where τ is the life time in the sdOB stage. Clearly, if the sdOB stage lasts only 10^{6} yr, only a very small mass (10^{-8} $M_{\odot}$) may have been lost

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and this has important consequences for the models that attempt to explain the He richness in the sdOs as a consequence of the loss of the H rich envelope during the sdOB stage. They would need to have become a sdOB with only 10^{-8} $M_\odot$ of hydrogen.

An alternative would try to explain the He richness of the sdOs as due to a wind in the sdO stage, just as is preferred for the main sequence. It must be noticed that similar constraints would apply. The implied mass loss rate would then be by 10^{-13} to 10^{-12} $M_\odot$ yr^{-1}. It is a very unlikely model since horizontal branch stars are known to be He rich objects in their interior.

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DISCUSSION

LYNAS-GRAY: The upper limits to mass-loss rates for helium depletion that you suggest are consistent with observation since no large mass-loss rates have been detected for such objects.

MICHAUD: I mainly wanted to insist on the strict constraint on mass loss rates that is implied by observations of He underabundances. There is no alternative to gravitational settling to explain the underabundance of He. The latter is possible only if the mass-loss rate is very small. This may have implications for some models of sdO's.

HEBER: What is the evolutionary time scale you adopted for the estimates of mass-loss rates for helium poor sdO stars.

MICHAUD: The most important time scale is probably for the disappearance of the He convection zone. For a mass loss rate of 10^{-14}, you have a factor of 3 underabundance of He after 2.10^{6} years. If you want to have a factor of 10 underabundance of He, then I think you run into problems with the sdO's. If you take 10^{-13}, then the time scale for diffusion would be about 10^{8} years, maybe a bit less.

HEBER: Since we believe that these stars are extended horizontal branch stars and, therefore, should have rather large evolutionary time scales, around 10^{8} years, the long time scale would pose no problems.

MICHAUD: Hence the mass-loss rate should be 10^{-13} solar masses per year, which is generally accepted.