METAL ABUNDANCES IN COOL WHITE DWARFS AND THE DIFFUSION THEORY

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In this theoretical review about cool white dwarfs, I will restrict myself to the problem of the metallic content in white dwarf outer layers. The first section will be a short review of what we know about the metal abundances. The hottest presently known white dwarf showing metal in its spectrum is the DB GD 40 (T_e = 15 000 K). This temperature will be considered here as the hot boundary of the "cool" white dwarfs. Many efforts have been recently devoted to the understanding of these metal abundances. Section 2 will be a summary of recent calculations of diffusion time scales in both hydrogen and helium white dwarfs. It will be seen that diffusion is so efficient in white dwarf conditions that the convection zone which develops in the envelope as the effective temperature decreases along the cooling sequence is never deep enough to bring back to the surface the metals which had previously diffused downwards. A discussion of the carbon white dwarfs, also called λ 4670 stars, will be presented in section 3. Recent calculations show that the convective mixing between a helium envelope and a carbon core would produce λ 4670 composition for only very special conditions and for this reason we believe that this is an improbable explanation for this type of white dwarfs. We clearly need another physical mechanism to compete with diffusion and to maintain an observable amount of metals in some cool white dwarf atmospheres. We discuss in section 4 the competition between diffusion and accretion. This seems a very promising mechanism in spite of the fact that considerable improvements are still needed in the theory of accretion. Substantial progress has to be made in this direction. A few problems related to this model are invoked in the conclusion.

I - Metals observed in cool white dwarfs.

Metallic lines have been detected only in white dwarfs cooler than ∿ 15 000 K. All the white dwarf atmospheres which show metallic lines have a helium dominated composition with an interesting exception at the very end of the cooling sequence : LP 701-29 at T_{eff} = 4200 K (Dahn et al, 1978 ; Cottrell, Bessell and Wickramasinghe, 1977).

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The number of known white dwarfs which exhibit metallic lines is still too small to draw any statistically significant conclusion and abundance analysis has not been performed for all of them. A number of observational biases may have led to difficulties in recognizing cool degenerate stars (Liebert 1978) and there is now observational evidence of a deficiency of very low luminosity degenerates (Liebert et al. 1979). In very cool high gravity atmosphere, line and molecular blanketing may become quite important as in LP 701-29 (Mould and Liebert 1978) making it impossible to recognize individual metallic line absorption. One thus must keep in mind that our knowledge about the metal abundance in cool white dwarfs is probably incomplete. At the time of writing there are 30 known white dwarfs which show metals in their spectrum. There is a dichotomy between those white dwarfs showing carbon features and nothing else and those ones showing other metals but no carbon.

The first group, the so-called C2 or λ 4670 stars, has been the object of many recent efforts and still escapes reasonable explanation. There are 22 such carbon white dwarfs if we include 6 stars classified "probable C2" by Sion et al. (1979). They are in the temperature range 10 000 K - 6000 K (Shipman, 1971 ; Grenfell, 1974). They all show the Swan band system of the C_2 molecule and the hottest one (G47-18) also shows some atomic C lines (Liebert, 1977a). While there is no doubt that these carbon white dwarfs have a helium atmosphere ($H/He < 10^{-4}$) with a normal (solar) or slightly deficient C/He abundance ratio : $10^{-3} < C/He < 10^{-2}$, according to Bues (1973), Grenfell (1974) and Liebert (1977), the C/O abundance ratio is still controversial. Considering the molecular dissociation equilibrium, Bues (1973) inferred that the C/O abundance ratio should be large enough ($C/O > 12$) in order not to tie too many carbon atoms into CO molecules which are more easily formed than C_2 molecules. However this argument does not consider the absorption of the C_2 bands. Using spectrum synthesis techniques Grenfell (1974) was able to reproduce the carbon bands in G47-18 and G99-37 with an almost normal C/O abundance ratio. The CO bands being in the near infrared, no direct detection has ever been attempted due to the faintness of these objects. No other metallic absorption feature has been discovered in the C2 white dwarfs than those due to carbon. The only other feature is the CH molecule in G99-37 (Greenstein, Gunn and Kristian, 1971) which anyway should be put apart from the group as the existence of a strong magnetic field in this white dwarf (Angel and Landstreet, 1971, 1974) may have perturbed the atmospheric structure.

The other group of metallic white dwarfs ranges in effective temperature between 15 000 K and 4000 K. Observations of eight metallic white dwarfs have been reported in the literature and some more recent discoveries will probably be reported during this colloquium. All of them show Ca, either alone or associated with some other metal(s): Mg, Fe. At the hot boundary GD40 (T_{eff} = 15 000 K) shows Ca II H and K lines (Wickramasinghe et al, 1975 ; Greenstein, 1976). Recent unpublished IUE observations by Greenstein revealed the existence of a strong Mg II resonance line in this star. Then, following the cooling sequence one finds G111-54 which shows Ca II, H and K lines. Its effective temperature is about 12 000 K (Greenstein, 1975). At Te = 8500K the white dwarf

Ross 640 shows a rich spectrum with Ca, Mg lines (Greenstein 1960 ; Eggen and Greenstein, 1965). Weak Balmer lines have been discovered in this helium white dwarf (Liebert, 1977b) and IUE observations by Greenstein (unpublished) revealed the presence of Fe II and Mg II lines. LP 745-46A at Te = 7800 K shows only Ca II H and K lines (Wegner, 1972). In the same range of temperature (Te = 7000 K according to Greenstein, 1976) G165-7 shows the richest metallic spectrum seen in a white dwarf with Ca, Fe, Mg, CH and possibly Mn (Hintzen and Tapia, 1975). At somewhat cooler temperature Van Maanen 2 (at 5500 K) shows a rich spectrum with Ca, Fe and Mg lines (Greenstein, 1960, 1972 ; Böhm et al. 1972). At the very end of the cooling sequence the two white dwarfs W489 and LP701-29, at Te ≈ 4000 K have only Ca lines in their spectrum but the second one has an extremely blanketed spectrum (Dahn et al. 1978) and is perhaps the only one to have a hydrogen atmosphere (Cottrell, Bessell and Wickramasinghe, 1977).

Among these metallic white dwarfs, very few have been analyzed for abundance determinations. Detailed analysis has been made for two C2 white dwarfs by Grenfell (1974) : G47-18 and G99-37. The C/He abundance ratio was found to be 1.5 10^{-3} in G47-18 (Te ≈ 10 000 K) and $\sim 10^{-3}$ in G99-37 (Te ≈ 6300 K). In the second group of metallic white dwarfs, there are 4 stars for which abundance analysis has been performed : GD40, Ross 640, L745-46A and Van Maanen 2. The results of these analyses are summarized in Table 1. The Ca/He abundance ratios are available for the four stars. The correlation between the effective temperature and the Ca abundance is quite striking: the abundance decreases with decreasing temperature. However, with only four abundance determinations, we consider it premature to draw any conclusion. The Mg / He abundance ratio is available for two stars only. A third value should be shortly published for GD40 where the λ 2800 Mg II resonance line has been discovered by Greenstein. As for Fe / He, we rely only on the de-

TABLE 1

Metal abundance in cool metallic white dwarfs

Star	T_{eff}	Ca / He	Mg / He	Fe / He	Ref.
GD40	15 000	3(-8)	?	-	1
Ross 640	8 500	4(-10)	3(-8)	?	2,3
L 745-46A	7 800	4(-11)	-	-	3
Van Maanen 2	5 500	2(-11)	4(-10)	2(-10)	3
	5 800	2(-11)	7(-10)	4(-10)	4

References are :
1 : Shipman, Greenstein and Boksenberg, 1977
2 : Liebert, 1977b
3 : Wegner, 1972
4 : Grenfell, 1974

? means that the metal has been detected but that the abundance analysis is not yet available

- not detected.

terminations for Van Maanen 2, but another determination is possible in principle as Fe II lines have been discovered in Ross 640. For completeness we must add to these results the upper limits on metal abundances for the DC Stein 2051 B (Liebert, 1976) and the spectrum synthesis analysis of LP 701-29 (Cottrell, Bessell and Wickramasinghe, 1977) which led to global metallic under abundances of 10^{-3} of the solar abundances. The cool star G165-7 is currently being analyzed for abundance determination by Wehrse and Liebert (private communication).

Abundance analyses in metallic white dwarfs as well as upper limit estimates in DC white dwarfs are badly needed. In spite of this, considerable efforts have been devoted in understanding the origin of the metal abundances in white dwarfs and recent theoretical investigations will be discussed in the next sections.

II - Diffusion in white dwarfs.

The absence or the large deficiency of metals in white dwarfs has been for a long time attributed to the sedimentation of the elements in the strong gravitational field encountered at the surface of these objects. After the pioneering work of Schatzman (1958), this mechanism was studied essentially in connection with the problem of the separation of the white dwarfs into a H-rich and a He-rich sequence, by Strittmatter and Wickramasinghe (1971), Shipman (1972), Baglin and Vauclair (1973), D'Antona and Mazzitelli (1975), Böhm (1975), Koester (1976), Vauclair and Reisse (1977) and D'Antona and Mazzitelli (1979). The idea that the metals themselves take part in the sedimentation process and reappear in the photosphere at the cool end of the white dwarf sequence when convection zones become deep enough to dredge them up from the layers where they had primarily sunk, is expressed in a few papers (Weidemann, 1975; Hintzen and Strittmatter, 1975; Greenstein, 1976 ; Vauclair and Reisse, 1977). However, this generally accepted idea did not rely on detailed calculations of the diffusion processes.

Such detailed computations in white dwarfs just appeared in the last few months. Four different teams have faced the problem with different approaches and methods : Alcock and Illarionov (1979a), D'Antona and Mazzitelli (1979a), Fontaine and Michaud (1979), Vauclair, Vauclair and Greenstein (1979). These papers will be referred to as AI, DM, FM and V^2G respectively. It is not the place here to describe these papers in detail. They all study with various degree of sophistication the diffusion of one or more metals, among C, N, O, Mg, Ca, in various models of hydrogen and / or helium envelopes. The interested readers may find in the above cited papers the assumptions and expressions used for the diffusion coefficients, velocities and time scales. They do not need to be repeated here. The important result they all find is that, for any realistic choice of the white dwarf mass, the diffusion time scales for metals are always short compared to the evolutionary time scales.

Table 2 summarizes the diffusion time scales for C, N, O, Mg and Ca as computed by V^2G for 0.6 $M_{\odot}$ cool hydrogen and helium white dwarfs of various effective temperatures. These time scales are computed at the bottom of the convection zone. The diffusion time scales are much shorter in hydrogen envelopes than in helium ones of similar temperature. This is due to the fact that the convection zones extend deeper in the helium envelope than in the hydrogen one. In the helium envelope the convection zone reaches its maximum depth at 10 000 K for the considered 0.6 $M_\odot$ model. The diffusion time scales are maxima at that temperature and decrease at lower temperature as the bottom of the convection regresses towards the surface. The maximum diffusion time scales are shorter than 10^5 y, which should be compared to the age of a 10^4 K, 0.6 $M_\odot$, C/O core white dwarf which is about 6.10^8 y according to the available evolutionary sequences.

TABLE 2
Diffusion time scales in 0.6$M_\odot$ white dwarfs (in years)
(from Vauclair, Vauclair, Greenstein, 1979)

a) Hydrogen envelopes :

T_e	C	N	O	Mg	Ca
10 000	11	9.3	7.7	5.5	3.4
7 500	6.3(2)	6.3(2)	5.9(2)	3.6(2)	4.9(2)

b) Helium envelopes :

T_e	C	N	O	Mg	Ca
15 000	3.0(3)	2.9(3)	2.7(3)	2.4(3)	1.9(3)
10 000	5.1(4)	3.2(4)	1.7(4)	2.7(4)	1.1(4)
7 500	3.0(4)	2.5(4)	1.5(4)	1.2(4)	5.3(3)

How these diffusion time scales vary with the white dwarf masses, and what is the uncertainty due to the model used for the envelope (chemical composition, equation of state, convection theory) may be partly seen by comparing the previous results with those obtained for the envelopes by FM, given in Table 3. Their diffusion time scales are estimated at a fractional mass $q = 10^{-4}$, 10^{-5}, $10^{-6.2}$ for 0.406, 0.612

TABLE 3
Diffusion time scales in helium envelopes (from Fontaine and Michaud, 1979)

Parameters	C	O	Ca
$M/M_\odot = 0.406$ $T_e = 9000$ K	3.2(7)	2.5(7)	7.0(6)
$M/M_\odot = 0.612$ $T_e = 10000$ K	4.0(6)	3.1(6)	7.1(6)
$M/M_\odot = 0.885$ $T_e = 11000$ K	3.8(5)	2.7(5)	4.5(4)

and 0.885 $M_{\odot}$ respectively, for the effective temperature at which the convection zone reaches its maximum depth. Due to the use of different chemical composition and equation of state, they find longer time scales than V^2G but still much shorter than the evolutionary time scales. The diffusion time scale for carbon estimated in a 0.4 $M_{\odot}$, 10 000 K helium envelope by DM is in agreement with the time scale derived by FM. Diffusion time scales could become comparable or longer than the evolutionary time scales only in lower mass white dwarfs, a case which has been considered by AI. However, the convection zones are so deep in such low mass white dwarfs that the validity of the diffusion coefficient calculation in degenerate matter must be questioned (Fontaine, this meeting). Nevertheless, the deficiency of metals in all white dwarfs led AI to the conclusion that such low mass white dwarfs do not exist in nature because their original abundances could not be reduced by diffusion.

Our conclusion at the present time is that in single white dwarfs whose average mass is between 0.6 $M_{\odot}$ and 0.8 $M_{\odot}$ (Shipman, 1979) the diffusion time scales are comfortably shorter than the evolutionary time scales. There is presently no indication of any mass difference between helium and hydrogen white dwarfs (Shipman, 1979) so that this conclusion holds for both composition populations. By the time the convection zones reach their maximum depth in both hydrogen and helium envelopes, the metals have diffused to much deeper layers. Consequently, the idea that the competition between convective mixing and diffusion could explain the observations of metals in cool white dwarfs is not supported by these recent results.

Before concluding this section a few remarks about the uncertainties affecting these computations must be made. Among these uncertainties one must consider 1) the uncertainty in the value of the diffusion coefficient itself as soon as the gas is highly degenerate at the bottom of the convection zone, 2) the estimate of the importance of the thermal diffusion compared to the gravity term ; in their calculations FM and V^2G did show that the use of the conventional Chapman and Cowling (1970) formulation leads to a thermal diffusion comparable or even larger than the gravity and AI retain only this thermal diffusion term in the diffusion velocity, 3) the ionization of heavy metals in degenerate matter ; this third point is linked to 2) because the thermal diffusion is proportional to the square of the electric charge of the diffusing particle. These uncertainties are not discussed in detail here because some recent improvements will be reported later in this meeting (Fontaine). However, we do not think that the general features of the diffusion processes in white dwarfs will be drastically different from the one we have described.

III - λ 4670 stars

The existence of the two groups of metallic white dwarfs described in section I clearly demonstrates that some physical process(es) must compete with diffusion to maintain or to provide the observed metals. We showed in section 2 that convective mixing is not able to dredge up the metals which had previously diffused downwards because the diffusion time scales are much shorter than the evolutionary time scales. However, for the carbon white dwarfs, it looked legitimate to consider as a possible mechanism the convective mixing between the helium envelope and the carbon/oxygen core. It is believed from evolutionary calculations that the single white dwarfs are the end products of the evolution of stars of intermediate masses ($1 < M/M_{\odot} < 5$) whose ultimate core composition results from helium burning (mostly carbon and oxygen) (Weidemann, 1975). As one could expect oxygen to be more concentrated toward the center and carbon toward the edge of the core this mechanism was tempting as it would explain the large C/O abundance ratio claimed to characterize λ 4670 by Bues (1973). However, as the C/O abundance ratio could also be normal and the star still appear as a typical λ 4670, according to Grenfell (1974), this is not really a restriction and the convection could dredge up oxygen as well as carbon, would the core be homogeneously mixed. The main restriction for this mechanism to work is that the mass of the helium envelope must be smaller or equal to the maximum mass which may become convectively unstable in a helium envelope. Otherwise, the interface between the helium envelope and the carbon core would be too deep to be reached by the convection zone. Relying upon evolutionary calculation arguments, D'Antona and Mazzitelli (1979a, b) suggest that the remaining helium envelope past the last nuclear burning event in the white dwarf progenitor should be more massive than the maximum mass of the helium convection zone in the white dwarf stage. However, the possibility that a smaller mass helium envelope could exist and could be mixed by convection with the carbon core was considered by DM and Vauclair and Fontaine (1979).

They found that, whatever the convective instability criterion used in the variable mean molecular weight interface (Schwarzschild or Ledoux), the mixing takes place. Only low mass white dwarfs ($M/M_{\odot} < 0.4$) become carbon rich by this mechanism in the effective temperature range appropriate for the λ 4670. The results of the mixing should always be pure carbon except for the very special case where the helium envelope has a mass almost equal to the maximum mass the helium convection zone could have. There is no reason for such an adjustment of the helium envelope mass and no evidence that the carbon white dwarfs as a group have a smaller mean mass than other helium white dwarfs or DA (Shipman, 1979).

It is interesting to note that for the carbon white dwarfs the two mechanisms which could have explained them require low stellar mass. On one hand the convective mixing of helium with the carbon core requires masses lower than $\sim 0.4\ M_{\odot}$. On the other hand the dredging up of the sedimented carbon originally present in the outer layers requires a carbon diffusion time scale comparable to the evolutionary time scale : this requirement could be fulfilled in low mass white dwarfs. However, let us remark that :

1) In the first case one should observe pure carbon white dwarfs unless nature mysteriously manages to adjust the mass in the helium outer envelope as previously discussed.

2) In the second case, the diffusion of other metals would also be slowed down and the convection zone would dredge up these metals in addition to carbon. One could expect to see them in the spectra of these stars. Up to now the λ 4670 have not revealed anything other than carbon features in their visible spectra.

For some time it has been claimed that carbon white dwarfs as a group could have a different velocity distribution than the other groups of white dwarfs, characteristic of a halo population (Wegner, 1975 ; Sion and Liebert, 1977). However, Humphreys et al. (1979) pointed out that blanketing by carbon bands could have seriously biased the sample towards large motion stars and would have led to an overestimate of their tangential velocities. This reasoning relies on the argument that 1) tangential velocities are derived from measured proper motions and distances computed via photometric parallaxes, 2) the calibration of M_V-(B-V) is generally used to derive these photometric parallaxes, 3) blanketing due tne C_2 bands affects the (B-V) color index in such a way as to overestimate the luminosity and so the distance of the white dwarfs, and consequently their tangential velocities. This argument was used by Sion, Fragola and O'Donnell (1979), who found that carbon white dwarfs cannot be attached to a particular population but represent a mixed population. From this point of view there is no population argument in favor of the carbon stars having a low mass halo progenitors and presumably smaller masses than the average white dwarfs. However, this is still a controversial matter. A recent investigation (Durret and Vauclair, unpublished) ahows that the effect of the blanketing due to the C_2 bands on the calibration of the M_V-(B-V) relation could have been overestimated. In the case of G47-18 which has the strongest bands and in which one could expect the maximum effect we find that both B and V magnitudes are equally affected by blanketing : the B color being affected by the λ 4670 band and the V color by the λ 5060 band. In this particular case we find no global effect on the (B-V) color. G47-18 was excluded from the M_V-(B-V) calibration given in Sion et al. on the basis of this presumed strong blanketing effect. As we find no effect at all, it is legitimate to put G47-18 on the M_V-(B-V) calibration. If the calibration is correct, G47-18 must fit the relation which fits the six other stars with trigonometric parallaxes. This is not the case : the Sion et al. calibration would predict G47-18 more than 1 magnitude brighter.

These considerations show that the carbon white dwarfs as a group are still poorly known from an observational point of view and poorly understood from a theoretical point of view. No convincing link with other stars in a previous evolutionary phase leading to a surface composition similar to the λ 4670 white dwarfs has been established. R Cor Bor stars have been found too rare to be considered as possible progenitors of the λ 4670 (Sion et al. 1979). One must keep in mind that in this line of reasoning, which consists in looking for stars of similar surface composition as λ 4670 progenitors, one makes the assumption that this composition must be somehow unaffected by evolution. The previous discussions demonstrated on the contrary that diffusion in the outer layers of white dwarfs is a very efficient mechanism. Consequently, if one finds an evolutionary link between carbon rich stars in a late stage of evolution and carbon wnite dwarfs one must also find the mechanism which precludes downward diffusion of carbon.

IV - Diffusion and accretion.

The most promising mechanism able to compete with diffusion in producing the observed metals in white dwarf atmospheres in accretion, AI, FM and V^2G suggest that the metals observed in white dwarf atmospheres are indeed evidence of the equilibrium reached between accretion and diffusion. The accreted interstellar matter is diluted into the surface convection zone and metals diffuse through the bottom of the convection zone towards the interior. The time dependence of the abundance of any particular species may be expressed as a function of the abundance of the species in the accreted material, the accretion time scale and the diffusion time scale. Relevant equations may be found in Vauclair and Vauclair (1978) and V^2G. However, the diffusion time scales are so short in white dwarfs that the abundances can always be considered to have reached their equilibrium values. When this equilibrium is reached there are as many atoms of one species coming into the convection zone by accretion as are going out by diffusion.

The equilibrium abundances have been estimated in V^2G for C, N, O, Mg, and Ca in a few hydrogen and helium 0.6 $M_\odot$ models. Their results are summarized in table 4.

TABLE 4

Metal equilibrium abundances produced by accretion and diffusion in $0.6M_\odot$ white dwarfs per g s^{-1} of accreted material

a) He envelopes.

T_e	C / He	N / He	O / He	Mg / He	Ca / He
15 000	2.0(-18)	6.5(-19)	3.4(-18)	1.5(-19)	8.0(-21)
10 000	5.3(-18)	1.1(-18)	3.2(-18)	2.6(-19)	6.7(-21)
7 500	2.6(-18)	7.0(-19)	2.4(-18)	9.5(-20)	2.7(-21)

b) H envelopes.

T_e	C / H	N / H	O / H	Mg / H	Ca / H
10 000	9.0(-16)	2.5(-16)	1.2(-15)	4.1(-17)	1.7(-18)
7 500	7.1(-17)	2.5(-17)	1.3(-16)	4.0(-18)	3.6(-19)

Let us remark the variation of the equilibrium abundances with effective temperature : there could be an increase or a decrease of the abundance depending on the element one considers and the effective temperature range. The qualitative variation of the Ca/He abundance ratio with T_e is in agreement with the few observations available (see section 1) for helium atmospheres. To understand these variations we must keep in mind that both the accretion and the diffusion are affected by dilution in the convection zone in such a way as to make the equilibrium abundance independent of the convection zone mass. Only the abundance in the accreted material, the rate of accretion, and the diffusion flux through the bottom of the convection zone may vary the equilibrium abundance. The mass ratio between the diffusing atoms and the main constituent, and the charge of the diffusing ions appear in the expression for the diffusion velocity (FM, V^2G). Consequently the diffusion flux at the bottom of the convection zone varies with effective temperature, reflecting variations in radius, temperature, density, ionization stages, at that level. The convection zone plays a role not by the mass it contains but by the physical conditions at its lower boundary. This was also emphasized by AI. The uncertainties affecting the diffusion velocity calculation (see section 2) also affects the correlation one can find between abundances and effective temperature.

Other important effects may alter the correlation between the observed abundances and the effective temperature : the accretion rate itself may depend on the effective temperature of the star and the chemical composition of the accreted material may also depend on the temperature of the star. The first point was made long ago in a series of paper by Mestel (1954), Schatzman (1955) and Schlüter (1955) who showed that the existence of a HII region around hot stars would considerably reduce the accretion rate. Later Talbot and Newman (1977) computed the accretion rate on stars surrounded by such a HII region. V^{2}G used both Mestel's (1954) and Talbot and Newman's (1977) results to evaluate the density of interstellar matter which would produce the accretion rate needed to explain the metal abundances in cool white dwarfs. They find that, while Mestel's (1954) results required too large interstellar matter densities, the Talbot and Newman (1977) calculation would predict correct order of magnitude accretion rates for reasonable values of the interstellar matter densities. For instance Ca and Mg abundances in Ross 640 could be accounted for with an accretion rate of $2.3\ 10^{11}$ g s^{-1} ($\sim 3\ 10^{-15}\ M_\odot$ / y) which is achieved in the Talbot and Newman (1977) model with a density of $\sim$ 10-100 cm^{-3}, for a stellar velocity of $\sim$ 20-50 km s^{-1}. This must be considered as only indicative, as the chemical composition of the accreting material was chosen to be similar to the interstellar matter standard composition. There could also be an effect of the stellar radiation on the chemical properties of the interstellar matter around the star. The chemical composition of the accreted material could differ from the composition of the interstellar medium far from the star. This point has been developed by Alcock and Illarionov (1979b). They showed that the accreting material undergoes chemical fractionation. Grains of various composition evaporate at different distances from the stellar surface, depending on their chemical properties and on the surface temperature of the star. The constituent atoms after evaporation accrete onto the star at different rates depending on the distance from the star where their parent grains evaporate. Consequently, the chemical composition of the accreted material may be rather different from the composition of the interstellar matter.

When one invokes accretion to explain the metals observed in white dwarfs, which almost all have helium atmospheres, the questions of the fate of the hydrogen in the accreted matter naturally arises. It has been suggested that if hydrogen accretes on a helium white dwarf, a hydrogen atmosphere would rapidly form even with a very low accretion rate (D'Antona, Mazzitelli, 1975 and DM). However, many physical processes may inhibit hydrogen accretion or even expel hydrogen from the stellar surface. Michaud and Fontaine (1979) extending the results of Montmerle and Michaud (1976) showed that in an envelope dominated by helium, the electric field needed to preserve the electrical neutrality of the stellar gas is strong enough to repel protons contained in the accreted material. As soon as a corona exists around the star, an electrically neutral wind of protons and electrons should leave the corona. The existence of a helium corona around helium white dwarfs has been discussed by Böhm and Cassinelli (1971) and Muchmore and Böhm (1978). Such a corona may be energetically fed by the accoustic flux driven in the convection zone and by the energy released in the accretion process. Consequently any proton accreted by a helium white dwarf would either never reach the surface of the star, or be diluted in the convection zone. It would then be rapidly ejected outwards by the combined effect of the pressure gradient and of the electric field and then conveyed back to the interstellar matter through a corona-wind complex.A search for such coronae, either mixed in composition or separated (a hydrogen corona surrounding a helium corona) would be extremely useful.

V - Conclusion. Metal abundances in hydrogen white dwarfs *vs.*helium white dwarfs.

According to section IV,for a similar accretion rate, we expect larger metal abundances in a hydrogen white dwarf than in a helium white dwarf of similar effective temperature. We must understand then why metallic absorption lines are seen mainly in helium white dwarfs as this seems in contradiction with the theoretical predictions. At this point however, one must note that the cool white dwarf LP701-29 has been claimed to have a hydrogen atmosphere with a metal abundance reduced by 10^3 compared to the sun. This was inferred from a spectrum synthesis analysis by Cottrell et al. (1977). This star is still unique at the time of writing. Some more similar stars are probably to be discovered. However, hotter stars so far found to show metals have a helium atmosphere.

In the visible, the bound-free of H^- (Geltman, 1962) dominates the opacity in the hydrogen atmospheres while He^- opacity (Mc Dowell, Williamson and Myerscough, 1966) dominates in the helium atmospheres. The much larger continuum opacity in the hydrogen atmosphere is probably responsible for the non-visibility of the metallic lines (V^2G). To check this, NLTE calculations of the formation of the resonance lines of CaII and MgII in hydrogen atmospheres have been undertaken (Freire and Vauclair, in preparation). Preliminary results are available for a 10 000 K log g = 8 hydrogen model made available to us by Koester (private communication), CaII is approximated by 3 levels and MgII by 2 levels. A range of calcium / hydrogen and magnesium / hydrogen abundance ratios similar to the Ca / He and Mg / He abundance ratios observed in the helium metallic white dwarfs has been explored. Table 5, summarizes our results for the CaII K line (λ 3933.7 Å). For each value of Ca / H, we indicate the optical depth in the continuum, τ_c, at the line center wavelength, at which the line is supposed completely formed (i.e. optical depth unity in the line), the central depth of the line d_c ($d_c = 1 - I\lambda_o / I_c$ where $I\lambda_o$ and I_c are the intensities at the line center in the line and in the continuum respectively) and an approximate value of the equivalent width W. For both the small abundance and large abundance limits, our values are only indicative. For Ca / H = 2.10^{-8} (10^{-2} the solar value) the line forms very high in the atmosphere : the optical depth at the line center is unity for $\tau_c = 2.4\ 10^{-4}$. The model used does not extend to small enough optical depth to correctly compute the line strength. It is why we have limited the abundance to this value. For Ca / H = 2.10^{-11} (10^{-5} the solar value) the line is not completely formed at the bottom of the atmosphere model provided by Koester (τ_c = 200) : the optical depth at the line center is only equal to 0.54. The model has to be extended downwards. The equivalent widths listed in table 5 are quite small. For comparison, let us recall that in GD40, the CaII K line has an equivalent width of 2.5 Å (Shipman, Greenstein, Boksenberg, 1977) and in Ross 640 both H and K Ca II lines have an equivalent width of 34 Å (Liebert, 1977b), for Ca / He abundance ratios of 3.10^{-8} and 4.10^{-10} respectively.

TABLE 5

Ca II K line strength in a 10 000 K hydrogen white dwarf

$\frac{\mathrm{Ca}}{\mathrm{H}}$	τ_c	d_c	W Å
2.(-8)	2.4(-4)	.82	.30
2.(-9)	5.0(-3)	.73	.18
2.(-10)	1.3(-1)	.43	.12
2.(-11)	2.1(2)	.07	.10

The same conclusions apply to the Mg II resonance lines. Table 6 summarizes our results. The Mg / H abundance ratios range between 10^{-3} and 10^{-6} of the solar value. The same restriction as for the CaII K line applies for the large abundance limit. The lines form higher in the atmosphere than the smallest optical depth of the model. Clearly for large calcium and magnesium abundances one has to consider the formation of the resonance lines at very small optical depth where NLTE effects are important. It will not be possible to do that until we understand the physical environnement of the white dwarfs. The discussion of section IV showed that we would expect approximately 200 times more Ca and Mg in a hydrogen white dwarf than in a helium white dwarf of similar effective temperature

TABLE 6

Mg II resonance lines strength in a 10 000 hydrogen white dwarf

$\frac{\mathrm{Mg}}{\mathrm{H}}$	τ_c	d_c	W Å
3.(-8)	2.8(-6)	.97	.40
3.(-9)	2.5(-4)	.89	.20
3.(-10)	6.8(-2)	.60	.10
3.(-11)	2.(2)	.12	.08

if they are both subject to the same rate of accretion. The present calculation suggests that in spite of their larger abundances the metals could remain more difficult to detect in the H atmospheres than in He atmospheres, at the present resolution of the spectroscopic observations. That hydrogen atmospheres could store more metals than helium ones is nevertheless suggested by observation. In the only case where one believes to have detected metals in a cool hydrogen white dwarf (LP701-29) their deficiency is 100 times less pronounced than in the helium white dwarf Van Maanen 2, which has not a very different temperature. The extreme physical conditions in the hydrogen atmosphere of LP701-29 which is among the coolest white dwarfs presently known

($\sim$ 4000 K), or a large accretion rate could explain why metallic lines are observed in this case (in spite of the strong blanketing) while they are not detected in hotter hydrogen atmospheres.

We reach the conclusion that a self-consistent picture of the white dwarf chemical evolution emerges. Accretion and diffusion must be the two basic mechanisms responsible for the occurence of metals in the atmospheres of cool white dwarfs. Many efforts are still to be devoted to improve our understanding of these mechanisms and more stars should be analyzed for abundance determinations. From the theoretical viewpoint we still have to understand more precisely how accretion occurs : how metals may accrete from interstellar matter and grains while hydrogen remains around the star. The processes which prevent hydrogen from penetrating into helium rich envelopes have to be studied in more detail. Some of them have been invoked : coronae, winds, electric fields. It may well be that they are all linked together in tne global mechanism which describes the interaction of the stars with their environment.

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