METAL ABUNDANCES IN HOT WHITE DWARFS : PREDICTIONS OF THE DIFFUSION THEORY

Gérard Vauclair and Sylvie Vauclair

DAPHE, Observatoire de Meudon

1 - Introduction.

In the course of an exploration of the diffusion processes in white dwarfs, the role of the radiative acceleration has been investigated in detail and found to be quite important in hot white dwarfs (Vauclair, Vauclair and Greenstein, 1979; hereafter referred to as V^2G). In view of the increasing interest accorded to hot white dwarfs which become accessible to observations in the ultraviolet owing to satellites like IUE, it appeared quite relevant to obtain theoretical predictions of the effect of the diffusion of metals in hot white dwarfs. This short note is a summary of the results presented in more detail elsewhere (V^2G).

2- Radiative acceleration and equilibrium abundances for CNO in hot white dwarfs.

In the case of CNO, which abundances could be large in the atmosphere of the white dwarf progenitors, the radiative acceleration is affected by saturation effects. It is only when an element may be considered as a trace element that its radiative acceleration can be approximated by the expression given by Michaud et al. (1976):

$$g_{\mathrm{Rad}}^{\max} = 1.7\ 10^8\ \frac{T_{e4}^4\ R^2}{A\ T_4\ r^2} \qquad \mathrm{cm\ s^{-2}} \qquad (1)$$

where T_{e4} is the effective temperature in units of 10^4K, T_4 is the temperature in that same unit, R is the stellar radius and A the atomic mass of the diffusing atoms. This expression gives an estimate of the maximum radiative acceleration which could act on an element when its abundance decreases toward zero. Saturation effects reduce considerably the radiative acceleration compared to this maximum value ($g_{\mathrm{Rad}} << g_{\mathrm{Rad}}^{\max}$), as discussed by Michaud et al. (1976). A detailed calculation of the radiative acceleration taking into account individual lines is then necessary. This has been done for CNO for which all the lines originating from the ground state and the first excited level, whose oscillator strength exceeds $f = 10^{-3}$, were included(V^2G). The details of the calculations which lead to the expression of the radiative acceleration and of the diffusion velocity, taking into account the various stages of ionization simultaneously present, may be found in V^2G and are not repeated here. For our present purpose it is enough to say that an element will go up or down in the atmosphere according to the relative strengths of the forces which act on it: the radiative acceleration (g_{Rad}) acts upwards and the gravitational and thermal acceleration (g_{GT}) act downwards.An element for which $g_{Rad} > g_{GT}$ is pushed upwards by the radiative acceleration while it sinks downwards where $g_{Rad} < g_{GT}$. In hot white dwarfs , one finds an interesting situation where the maximum radiative acceleration (g_{Rad}^{max}) may exceed g_{GT} in a part of the envelope. This has important consequences for saturated elements like CNO . For a large abundance of CNO (let say the solar values for instance) the radiative acceleration due to saturated lines has the important property of varying as the inverse square root of the abundance. Consequently, if $g_{Rad} < g_{GT} < g_{Rad}^{max}$, the CNO abundance decreases as the radiative acceleration is not able to support a normal abundance of CNO. While the abundance decreases, g_{Rad} increases (as $n^{-1/2}$). The diffusion process stops when the abundances have reached the equilibrium values for which :

$$g_{Rad} = g_{GT} \tag{2}$$

Because of the $n^{-1/2}$ dependence of the radiative acceleration, the equilibrium abundance (n_e) is related to the original abundance (n_o), to the original radiative acceleration, computed for $n = n_o$ (g^o_{Rad}) and to g_{GT}, by the simple expression:

$$\frac{n_e}{n_o} = \left(\frac{g^o_{Rad}}{g_{GT}}\right)^2 \tag{3}$$

A symmetrical reasoning applies in the case where $g_{Rad}^{max} > g_{Rad} > g_{GT}$. Then the increase of the abundance results in a larger saturation in the lines and a reduction of g_{Rad}. The $n^{-1/2}$ dependence of g_{Rad} limits the overabundances to the values for which the balance between g_{Rad} and g_{GT} is achieved, as in the previous case. Of course, in the first case the equilibrium reached is an underabundance while it is an overabundance in the second case.

The radiative acceleration on CNO and the g_{GT} term to which it must be compared have been computed in a series of hydrogen and helium envelope models (V^2G).We extract the 50 000K, 0.6 M⊙, hydrogen and helium models for illustration. Figure 1a shows the variation with depth of the radiative acceleration on C,N, and O in the hydrogen model. They are smaller than g_{GT}. However g_{Rad}^{max} for CNO (which is approximately equal to g_{Rad}^{max}(12)) is larger than g_{GT} in a substantial part of the envelope. In this part an equilibrium as previously defined is possible. The equilibrium abundances in this model are shown in figure 1b: while oxygen is probably deficient by more than a factor 100 compared to the sun, the deficiency of nitrogen and carbon should be less important (between 10 and 30). The equilibrium abundances are achieved on a diffusion time scale τ_D almost identical for C,N and O. τ_D is shown on figure 1b . In the outer layers

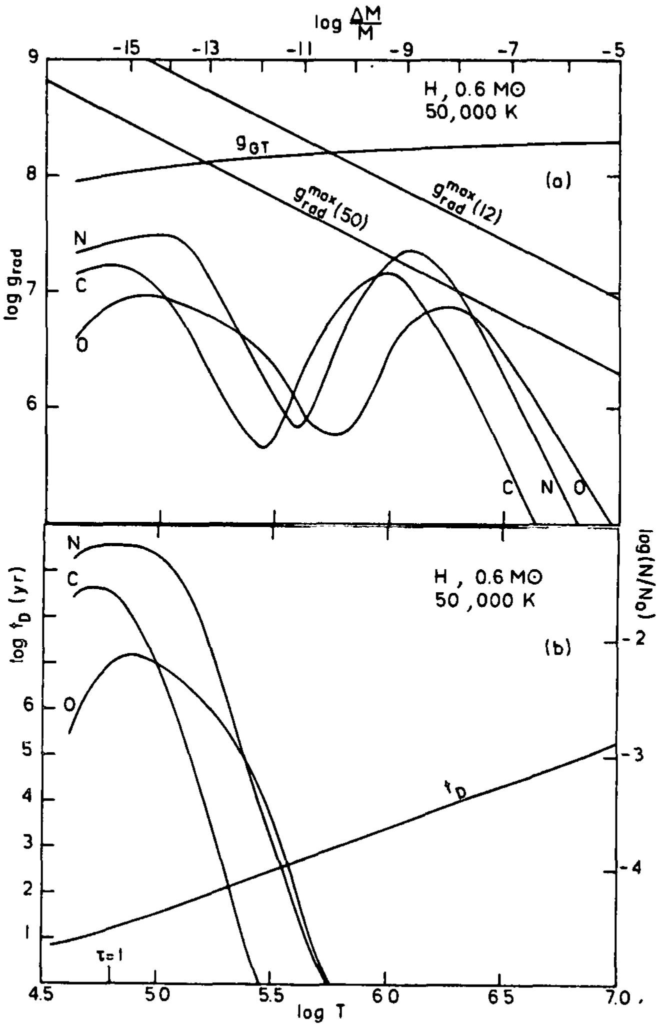

Fig.1: Radiative acceleration (a), equilibrium abundances and diffusion time scale (b) for CNO in hydrogen white dwarf. The curve marked $g^{max}_{rad}(50)$ is computed for an "average metal" with $A = 50$.

where an equilibrium is possible, it is achieved on a time scale shorter than 10^3 years, which is considerably shorter than the age of a 50 000K white dwarf (10^7 y). The results for the 50 000K helium envelope are shown on figures 2a,b. In helium envelopes, the radiative accelerations are larger than in hydrogen ones, mainly because of the larger width of the lines. In this particular model, one encounters the case where $g_{GT} < g_{Rad} < g^{max}_{Rad}$ for N and marginally for C, while $g_{Rad} < g_{GT} < g^{max}_{Rad}$ for O. Nitrogen and carbon could be overabundant at equilibrium in contrast with the hydrogen atmosphere, while oxygen remains underabundant. The overabundance of N should not exceed a factor of 5 and C is supported just at the solar abundance. Oxygen should be deficient by a factor of 10. These equilibrium abundances should be achieved on time scales shorter than 100 y. Let us emphasize that whether N and C will accumulate in the atmosphere or leave the star in the form of a selective wind may be settled only after a more careful calculation of the radiative forces at small optical depth can be made. The boundary conditions need also to be more precisely defined and for this one must solve the problem of the interaction of the white dwarf with its surrounding. However, these calculations suggest that ,if white dwarf progenitor atmospheres do contain CNO, the radiative forces are able to support a substantial fraction of them in hydrogen atmospheres and could even support an abundance equal to or larger than the solar abundance of C and N in helium atmospheres at high enough effective temperatures.

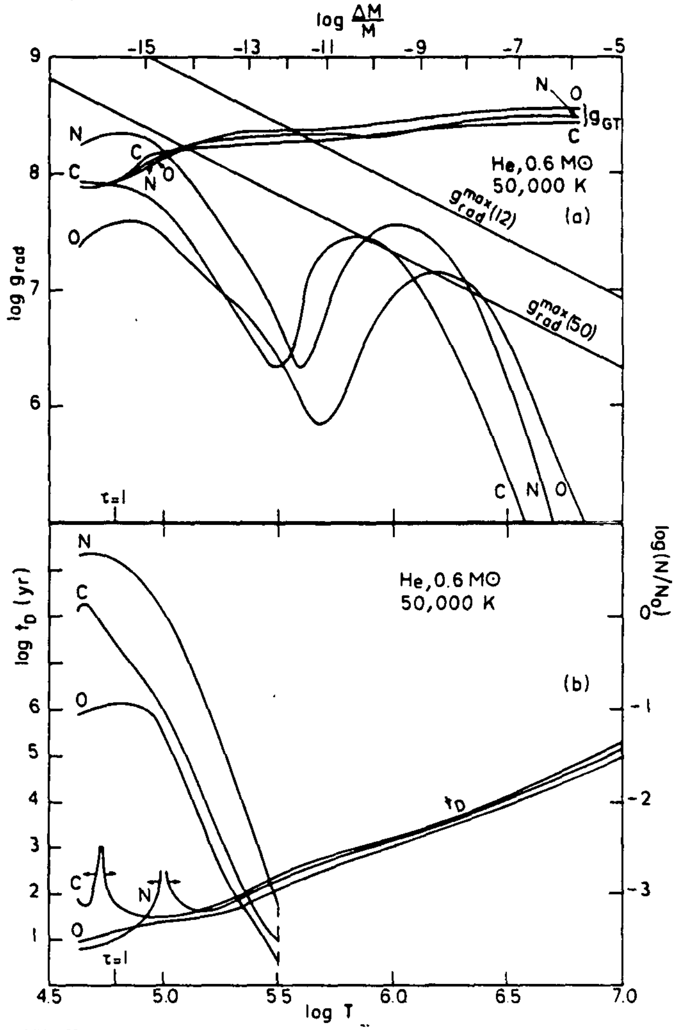

Fig.2 : Radiative acceleration (a), equilibrium abundances and diffusion time scale (b) for CNO in helium white dwarf.

3 - Conclusion.

One would like to check the previous theoretical predictions by observations. The questions which then arise are: 1) What are the lines expected at these high temperatures for CNO? Are they in the wavelength range reachable from existing satellites? 2) What are the strengths of these lines? Are they detectable with the presently available resolution? We are not able at the present time to answer question 2 as we did not do the calculations, but we can answer question 1. We base our discussion on the possibility offered by IUE satellite to observe in the ultraviolet in the range 1150 Å -1950 Å with the short wavelength spectrograph and in the range 1900 Å- 3200 Å with the long wavelength spectrograph. In the hydrogen atmosphere, carbon is mainly in the form of CIV (62% at Rosseland mean optical depth unity) while CIII contributes 3.5%

and CV, the noble gas, 3.4% Nitrogen is mainly in the form NIV (86%), NIII contributes only 8.5% and NV 4.7%. OIV dominates also with 81% while OIII contributes 16% and OV only 2% The ionization of CNO is only slightly different in the helium atmosphere. The lines due to these ionization stages which are in the wavelength covered by IUE are numerous. Those originating from the ground state and the first excited level were introduced in the calculation of the radiative acceleration presented here as they were presumed to have a stronger effect. However, as far as detection in the spectrum is concerned, we must also consider as potentially detectable those originating from higher levels. From a survey of the Wiese et al. (1966) tables one can infer that carbon could be detected through the following lines: λ1175.7Å originating from the first excited level of CIII, $\lambda\lambda$1247.4, 2296.9, 3170.1Å from higher levels of CIII, λ1549.1Å, the resonance line of CIV and other lines of CIV from higher levels at $\lambda\lambda$2524.4, 2595.1, 2698.4Å. A line of CV at λ2273.9Å is also in the range covered by IUE. However it originates from the first level of a noble gas configuration which should have a very small population. Nitrogen could be detected through the lines of NIII at $\lambda\lambda$1184, 1750, 1805, 1885, 1908, 1920 and 2063Å which all come from higher levels than the first excited one, the line of NIV at λ1718.5Å, the resonance line of NV at λ1240 Å and the λ3161Å line from a higher level. Oxygen could be detected through the lines of OIII at $\lambda\lambda$2455, 2558, 2601, 2678, 2691, 2983, 3002, 3041, 3081 and 3127Å, the lines of OIV at $\lambda\lambda$2505, 3066, 3197Å, the lines of OV at $\lambda\lambda$1371, 3058, 3144Å none of which were included in the radiative acceleration by V^2G as they originate from high levels. It is anticipated that resonance lines should be the strongest: λ1549Å of CIV and λ1240Å of NV appear as the best candidates to look for. Unfortunately the wavelength region of the resonance line of NV is probably dominated by Lyα (1215Å) in hydrogen atmospheres: the NV line should be in the wing of Lyα .

IUE spectrographs have been designed to achieve a resolution of 6Å in the short wavelength range and 8Å in the long wavelength range. Calculation of the line strength in model atmosphere is now necessary to check the visibility of the above mentionned CNO lines. Greenstein and Oke (1979) have recently reported IUE observations of white dwarfs. While both Wolf 1346 (EG139) and +73°8031 (EG144) are too cool (21000K and 15000K respectively) to be compared to our theoretical predictions, the hot DA HZ43 (EG98) and the DO HZ21 (EG86) are much hotter (60000K and 50000K respectively). Our theoretical results are quite relevant for a comparison with the observations of these two hot white dwarfs. Greenstein and Oke (1979) found no evidence for metallic lines in any of them. However, in an earlier discussion of the IUE spectrum of HZ43 (Heap et al. 1978) a fine structure near 1720Å was detected and temptatively ascribed to NIV.

REFERENCES

Heap, S.R., Boggess, A., Holm, A., Klinglesmith, D.A., Sparks, W., West, D., Wu, C.C., Boksenberg, A., Willis, A., Wilson, R., Macchetto, F., Selvelli, P.L., Stickland, D., Greenstein, J.L., Hutchings, J.B., Underhill, A.B., Viotti, R., Whelan, J.A.J. 1978, Nature, 275, 15.
Greenstein, J.L., Oke, B. 1979, Ap.J. (Letters), 229, L141.
Michaud, G., Charland, Y., Vauclair, S., Vauclair, G. 1976, Ap.J., 210, 447.
Vauclair, G., Vauclair, S., Greenstein, J.L. 1979, Astr.Ap., in press.
Wiese, W.L., Smith, M.W., and Glennon, B.M. 1966, Nat. Bur. Stand. Ref. Data Ser. (USA), vol. 1, No. 4.