LOW MASS HYDROGEN ENVELOPES AND THE DB GAP

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INTRODUCTION

The existence of a gap in the distribution of helium atmosphere white dwarfs at the effective temperature interval 30,000 K $\leq T_e \leq$ 45,000 K is well documented (Wesemael, Green and Liebert 1985; Liebert et al 1986; Green and Liebert 1987).

To explain the presence of this gap and other variations of the non-DA to DA ratio, it has been proposed (Fontaine and Wesemael 1987; Liebert, Fontaine and Wesemael 1987) that the helium-rich PG 1159 stars are the progenitors of essentially all white dwarfs. Some minute quantity of hydrogen of total mass, M_H, is assumed to be mixed in the outer helium envelope, and settle upward as the star cools from the PG 1159 stage. Eventually enough hydrogen is at the surface to make the star appear a DA. The star has to become DA before it cools down to ≈ 45,000 K and cools to ≈ 30,000 K as a DA. At this temperature, depending on M_H, the underlying helium convection zone may break into the hydrogen layer, diluting it and making the star a DB.

In order to test this hypothesis, envelope models for a 0.6 solar mass white dwarf have been computed for T_e's between 15,000 K and 80,000 K. The envelopes are mixtures of hydrogen and helium in diffusive equilibrium.

THE PHYSICAL MODEL

To calculate the envelope structure, the stellar radius and effective temperature are taken from the evolutionary models of Koester and Schönberner (1986) for a 0.6 solar

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mass helium envelope white dwarf. The He/H ratio is specified at optical depth 10^{-3} and the stellar structure equations integrated inwards. The composition structure is determined by assuming that each species is in diffusive equilibrium due to balance between gravity, partial pressure gradients, radiative forces, and induced electric fields. Thermal diffusion has been not been included as it has been shown to be negligible in white dwarfs by Paquette et al (1987). Convective mixing is treated as a diffusive mixing process for which the diffusion coefficient is obtained from mixing length theory. Radiation forces on separate species are included by assuming a gray opacity law. The equation of state is based on Eggleton et al (1973) and Los Alamos radiative opacities for H/He mixtures are used. Full details of the calculations will be given elsewhere. However, because the results are sensitive to the treatment of convection, the mixing length theory employed is briefly discussed below.

In a convection zone, the structural gradient, ∇, is given in terms of the adiabatic gradient, ∇_a, and radiative gradient, ∇_r, by

$$\nabla = (\nabla_r + \sigma \nabla_a) / (1 + \sigma)$$

σ is a dimensionless quantity equal to the growth rate of small perturbations multiplied by t_{th}, the thermal time scale of a convective element of size equal to the mixing length, l, which is proportional to the pressure scale height. In radiative zones, $\sigma = 0$. The convective mixing diffusion coefficient is $\sigma\, l^2 / t_{th}$.

σ is the largest solution of

$$s^2 + s + A = 0$$

where

$$A = \frac{2}{3} (t_{th}/t_{dyn})^2 \left.\frac{\partial \ln \rho}{\partial \ln T}\right|_P (\nabla - \nabla_a)$$

and t_{dyn} is the dynamical time scale. This equation can be derived from equations in MacDonald (1983). Convection occurs if $A < 0$.

RESULTS AND CONCLUSIONS

The He/H ratio by mass at the photosphere (optical depth 2/3) is used to characterize whether a white dwarf is a non-DA or a DA. This quantity is plotted against T_e for three values of M_H in figures 1 and 2. The heading of each figure gives the mixing length ratio used. The lines are labelled by the logarithm of M_H in solar masses.

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Figure 1
Mixing Length Ratio = 1

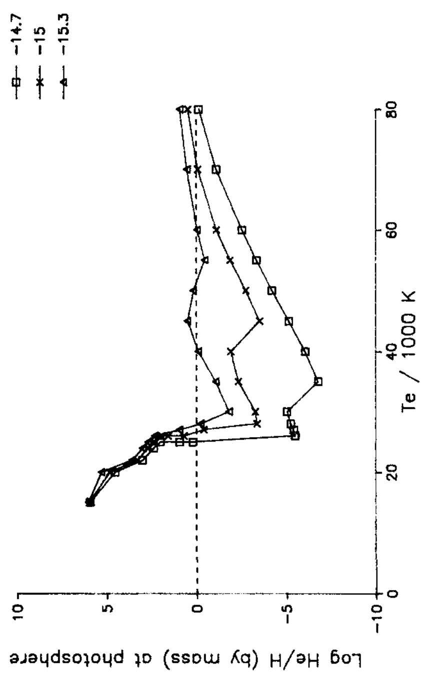


Figure 2
Mixing Length Ratio = 2

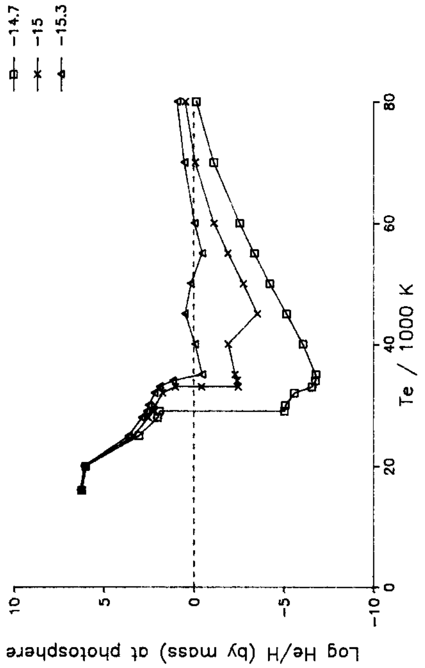


Figure 3
Mixing Length Ratio = 1

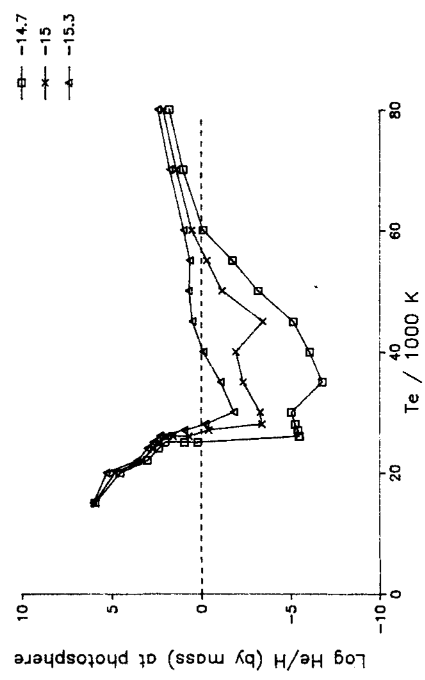
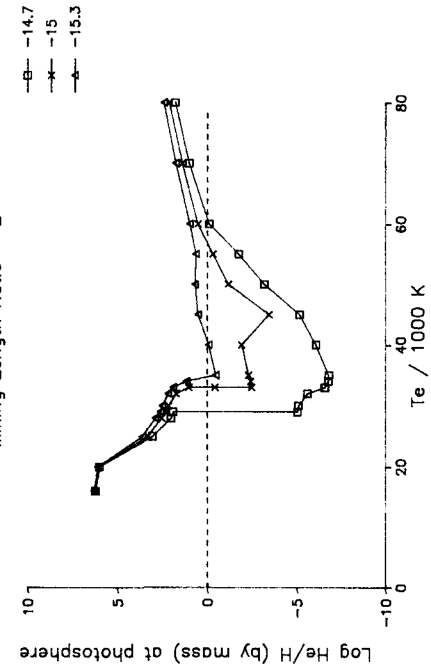


Figure 4
Mixing Length Ratio = 2



It is readily apparent that for $M_H \approx 10^{-15}$ solar masses, the photospheric He/H ratio undergoes significant changes as the star evolves. Levitation of helium by radiation forces, important at high effective temperatures, decreases as the star cools resulting in an increase in photospheric hydrogen. A small surface helium convection zone sets in at an effective temperature that is dependent on M_H. Since the presence of hydrogen tends to suppress the helium convection zone, the larger the amount of hydrogen, the cooler the star has to be before convection sets in. Convective mixing dredges up helium and the He/H ratio increases slightly before decreasing again. A deep helium convection zone develops when $T_e \approx 30,000$ K, rapidly transforming hydrogen-dominated atmospheres into helium-dominated atmospheres.

So far it has been assumed that the envelopes have had sufficient time to come into diffusive equilibrium as the star cools. To check this assumption, gravitational settling time scales for trace hydrogen have been computed as a function of depth for pure helium envelope models. By equating age with the gravitational settling time scale, the depth from which hydrogen will have floated to the surface can be found. If hydrogen is initially mixed no deeper than $\approx 10^{-6}$ solar masses from the surface, the envelope will be in diffusive equilibrium before the star has cooled to 80,000 K. Otherwise, not all the hydrogen has had time to float to the surface and the equilibrium models will underestimate the photospheric helium abundances. The results of an attempt to quantify this effect are shown in figures 3 and 4 for hydrogen initially mixed in the outer 10^{-5} solar masses of the envelope.

Given the uncertainties in convection theory, it can be seen from the figures that it is possible to construct evolutionary sequences that give the gap. The best model has mixing length ≈ 2, and a minimum allowed value of $M_H \approx 2\ 10^{-15}$ initially mixed in the outer 10^{-5} to 10^{-4} solar masses of the envelope.

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