THE SPECTRA AND COLORS OF COOL WHITE DWARFS

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Introduction

White dwarfs fall in two main categories (1) the group with H-rich atmospheres (DA) the most numerous, and (2) the group with He-rich atmospheres (DB, DC, DF, DG, λ4670). Calculations of element separation (via gravitational settling) and convective mixing in white dwarf models have been made by Koester (1976) and Vauclair and Reisse (1977) in order to understand the existence and maintenance of these distinct groups and to predict at what stage during the cooling of the white dwarf some connection may occur between the two groups. Over the last few years, Wickramasinghe, Bessell and Cottrell (Wickramasinghe et al., 1977; Cottrell et al., 1977; Bessell and Wickramasinghe, 1979; Bessell, 1978 and Wickramasinghe and Bessell, 1979) have investigated the properties of cool (T < 6000K white dwarfs observationally and theoretically. We have attempted to establish at what temperature mixing does occur in DA white dwarfs, whether cool white dwarfs could be confused with G, K and M dwarfs, and if one can discriminate spectroscopically cool He and H-rich white dwarfs. In this paper we will discuss the spectra and colors of the coolest (Te < 5000K white dwarfs and compare them with model atmosphere calculations.

Model Atmosphere Details

Model atmospheres were constructed using ATLAS5 modified as described in Wickramasinghe et al. (1977). For the H-rich models, gravities of log g = 8 (WD) and log g = 5 (dwarf) were considered, the temperature range was Te = 3500K - 6000K in 500K intervals, and the metal abundance Z ranged from 0 (solar) to -6, in steps of 1. Fewer He-rich models ($H/He = 10^5$) were constructed (Cottrell, 1978) and those with the smallest Z and the lowest Te are not very realistic because of the neglect of pressure ionization (Böhm et al., 1977), however the models do serve to emphasize the tremendous pressure that occur in such atmospheres and can show the probable line broadening in cool He-rich atmospheres.

Line Strengths in Dwarf and White-Dwarf Atmospheres

a) H-rich models.

Figure 1 shows the CaI 4226 and CaII 3933 line strengths for a grid of subdwarfs and DA white dwarfs. More detailed discussion of these computations will be presented elsewhere. The appearance of metal line spectrum is graphically shown in the computation of synthetic spectra (Wehrse, 1977) and in Figure 2 is shown computed spectra used to fit the observations of LP 701-29.

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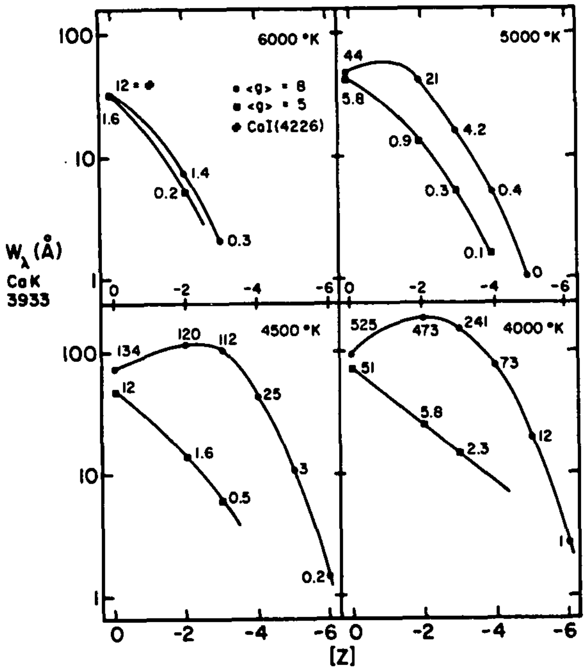

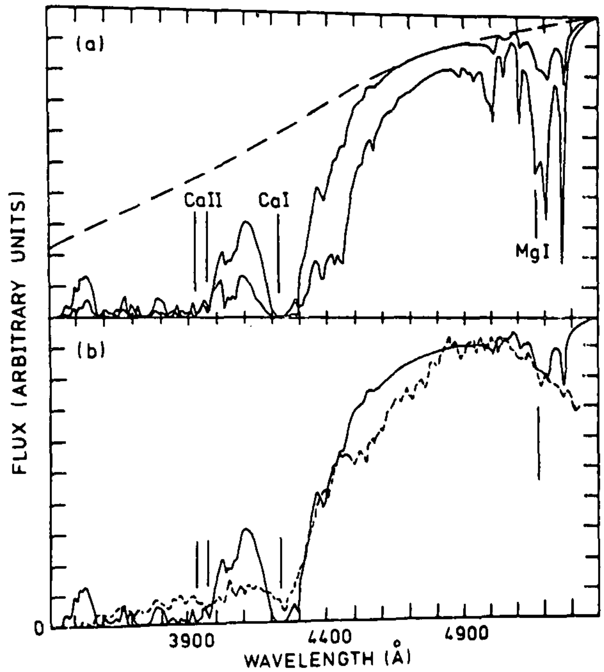

Figure 1. CaII H & K and CaI 4226 line strengths for log g = 8 and log g = 4 models with different metal abundances.

Figure 2. a) Two synthetic spectra with parameters Te = 4000K log g = 8, Z = -2, -3 (upper curve). The dashed line is the continuum for the line-free Z = -3 model.

b) Observations (Dahn et al., 1978) (dashed line) compared with synthetic spectrum with parameters Te = 4000K log g = 8, Z = -3.

From Figure 1 it can be seen that at a given effective temperature, a low gravity (main sequence) star would have a K line of similar strength to that of a white dwarf of lower metal abundance, although for the atmospheres with high Z the degree of ionization is markedly different. However, for some ranges of Te and Z the ionization equilibrium will not differ, and an H-rich WD and very low Z could have CaI and CaII lines of similar strength to a subdwarf of a different temperature. In these cases continuum colors such as (R-I), or the existence of Balmer lines should resolve the conflict. At even lower Z the electron pressures become extremely low, and only weak and shallow CaII H and K lines will appear (Shipman, 1977). Thus H-rich WD and Z < -6 could have spectra like DK or DC stars.

b) He-rich models.

As a result of the much lower opacities in the He-rich atmosphere compared to the H-rich case, the gas pressures are significantly higher. These high pressures cause the extreme line broadening seen in the synthesized spectra shown in Figure 2. However, the ionization equilibrium of these models is almost certainly unrealistic because we have neglected pressure ionization which is important for He-rich models cooler than 5000 (Böhm et al., 1977), consequently the neutral lines are too strong. But the greater pressure broadening of lines in the He-rich model which distinguishes an He-rich atmosphere from an H-rich atmosphere of the same temperature is not affected by this assumption.

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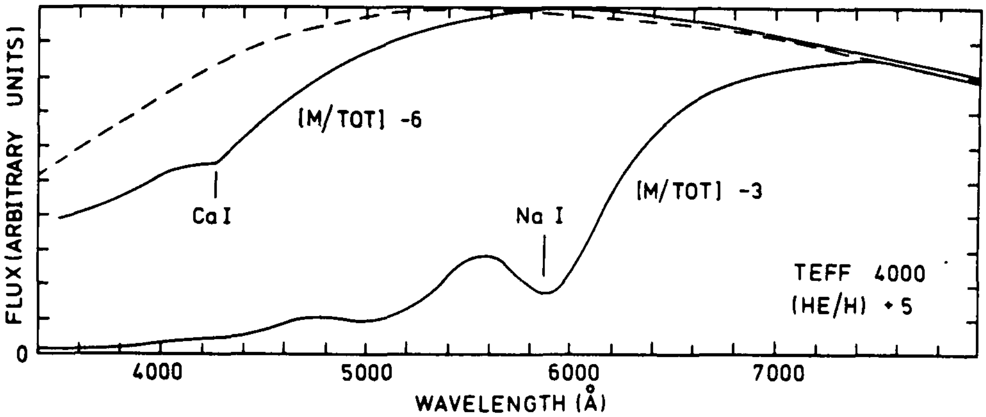

Figure 3. Synthetic spectra for He-rich white dwarfs with Te = 4000K log g = 8, Z = -3 and -6. The dashed line corresponds to the line free continuum for the Z = -3 model. The positions of CaI 4226 and NaI 0 are indicated. In reality, these neutral lines will not be so strong because of the neglect of pressure ionization.

Colors of Cool White Dwarfs

Table 1 contains the line-free broad-band colors for the white dwarf models. The subdwarf colors are discussed in Bessell and Wickramasinghe (1979). The (R-I) colors for the Z = 0 WD models are similar to those for subdwarfs (Z = -3) of the same temperature, but as Z is lowered, the continuum color becomes bluer. Moreover, the low Z H-rich models cooler than 5000K show little change in (R-I) with lowering temperature and never get redder than a 5000K subdwarf, due to the effect of dominating H_2 dipole opacity. The hotter (6000 - 7000K) He-rich models are bluer than the H-rich models of the same temperature He^- being bluer than H^-. But when the pressure induced H_2 dipole opacity becomes dominant in the H-rich models, the (R-I) colors become similar. Below 4500K the He models are redder.

TABLE 1

LINE-FREE COLORS WHITE DWARFS (log g = 8)

Te	He/H	Z	u-b	b-y	U-B	B-V	$(R-I)_K$
6000	-1	0	0.81	0.37	-.45	0.45	0.21
	-1	-2	1.00	0.42	-.34	0.54	0.21
5500	-1	-3	1.18	0.50	-.22	0.64	0.27
	-1	-5	1.20	0.50	-.21	0.58	0.27
5000	-1	-3	1.29	0.54	-.15	0.70	0.31
	-1	-5	1.30	0.54	-.14	0.71	0.30
4500	-1	0	1.52	0.66	0.00	0.86	0.43
	-1	-3	1.48	0.62	-.03	0.82	0.37
4000	-1	0	1.79	0.77	0.18	1.02	0.53
	-1	-3	1.57	0.67	0.03	0.88	0.40
	-1	-6	1.51	0.63	-.01	0.82	0.33
3500	-1	-4	1.59	0.67	0.05	0.88	0.36
	-1	-6	1.57	0.66	0.03	0.86	0.34
5500	5	-3	0.76	0.33	-.49	0.40	0.11
4000	5	-3	1.52	0.64	0.00	0.84	0.38
	5	-5	1.48	0.61	-.03	0.80	0.35

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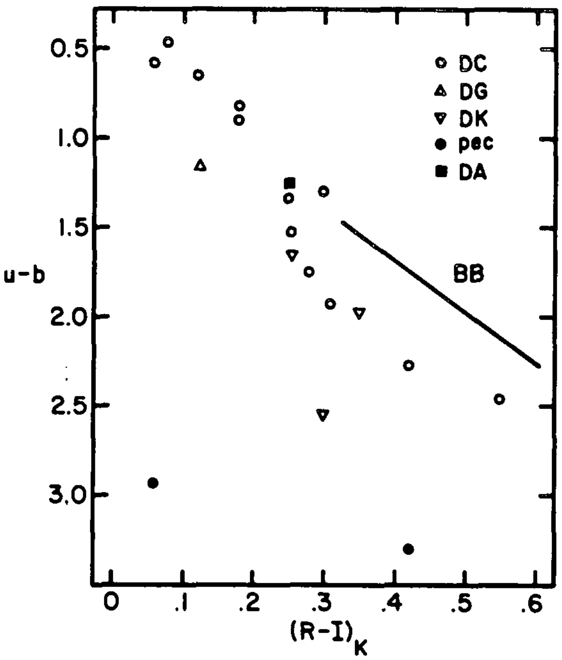
Mould and Liebert (1978) have also computed colors for cool WD models and predict that cool H-rich WD should have a large infrared deficiency because of the H_2 dipole opacity. They have attempted to discriminate between H and He-rich atmospheres on the basis of their J-H, and V-K colors. This technique appears very promising, but is critically dependent on the assumption that there is no H contamination in the He atmospheres.

In Figures 4 and 5 are plotted the (u-b) and (R-I) colors and scans for some of the reddest known white dwarfs. Few of the stars are redder than the limiting (R-I) for H-rich models (see also Liebert et al., 1979). Many of the stars show evidence for violet and blue deficiencies compared to black bodies, continuum models or other stars with the same (R-I); however, except for G 165-7 and LP 701-29 no blanketing from resolved lines is apparent in the spectra. Because of the extreme line broadening (e.g. Figure 3) expected in cool He-rich atmosphers it is likely that those stars with the heavily suppressed blue continua are He-rich stars with Z ≃ -6.



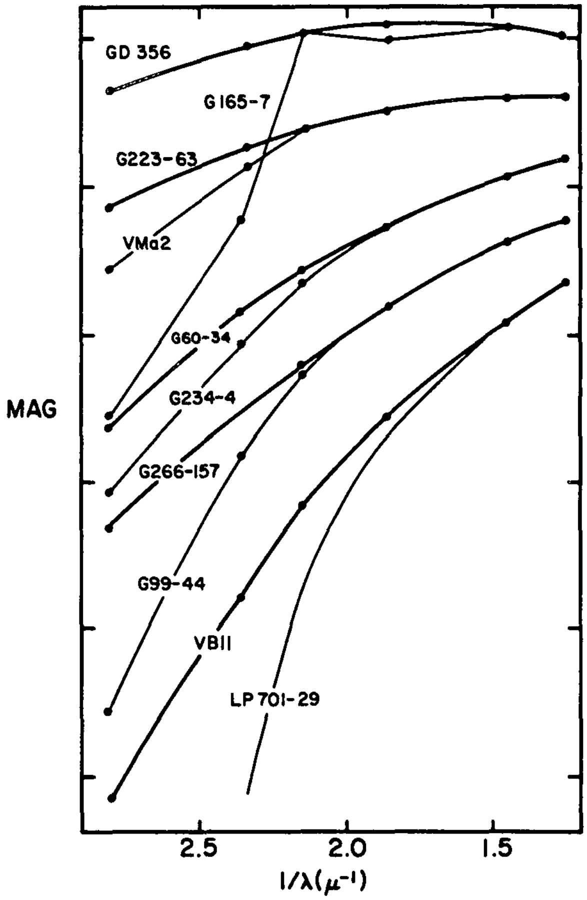


Figure 4. (μ-b) versus $(R-I)_K$ colors for some white dwarfs. Colors for some of the stars have been transformed from Greenstein (1976).

Figure 5. Continuum colors for white dwarfs from Greenstein (1976). The scan for LP 701-29 is adopted from Dahn et al. (1978).

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Deficiencies in the Computed Data

The greatest uncertainties in the models lie in the equations of state appropriate for the extrememly high pressures anticipated in the cool H and He rich models. We touched upon this earlier with regard to the pressure ionization which was not considered in the cool He-rich models. But it could also be important in the cool H-rich models and alter the numbers of H_2 molecules and ionized H atoms that are computed. This in turn could increase the H^- opacity at the expense of the H_2 dipole opacity and result in redder colors for the cool H-rich models.

Another uncertainty is in the H_2 dipole opacity itself. Mould and Liebert (1978) conclude that there is no theoretical justification for decreasing this opacity source, but it will be valuable to have accurate J-H, H-K colors of the cool white dwarfs to assess whether or not this opacity formulation does appear valid.

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