WHITE DWARF STARS: EVOLUTION OF THE ENVELOPE COMPOSITION

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ABSTRACT. Over the last several years, evidence has been unfolding that the surface abundances of white dwarfs may evolve as the stars cool. It is possible that some post-AGB stars enter the white dwarf sequence with far less hydrogen and helium than predicted by standard theory of the quenching of shell sources, and with atmospheres dominated by C and O. The interplay of diffusion and episodes of convective mixing may lead first to He-rich atmospheres, then H-rich, and finally He-rich again.

1. INTRODUCTION

White dwarf stars divide into two well-recognized atmospheric composition groups, those with hydrogen-dominated and helium-dominated abundances. This distinction has long been recognized by the division of the spectra into the DA (showing hydrogen lines) and non-DA, the DO-DB-DQ-DC spectra showing respectively He II, He I, carbon or no spectral features. Ten years ago the general view was that these groups form two separate evolutionary sequences, preceded by similar sequences of hydrogen- and helium-rich planetary nebula nuclei (PNN) and hot subdwarfs. In the standard theory of the asymptotic giant branch (AGB) phase of stellar evolution, active hydrogen- and helium-burning shells are not sustainable after the layer masses are reduced below a few times 10^{-4} $M_\odot$ for hydrogen and the order 10^{-2} to 10^{-3} $M_\odot$ for helium. It is possible for the hydrogen layer to be lost from the star entirely, especially in the form of a late helium shell flash. Thus, the standard theory predicts the star to finish its evolution with a hydrogen layer mass either of the order 10^{-4} $M_\odot$ or zero.

In the last several years, however, a revolution has taken place which threatens to overturn completely this standard picture. The following is intended as a brief review of the evidence which caused a reappraisal of the likely layer masses of hydrogen and helium with which the dying stars become white dwarfs. We discuss the evidence for thin hydrogen layers in Section 2, and the much more recent case for thin helium layers in Section 3. This report is partly an abbreviated adaptation of the review paper presented at the IAU Symposium 145 in Bulgaria (Liebert 1991), especially in Section 2, where many important citations have been omitted due to lack of space. Section 3 includes an important update.

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2. THIN HYDROGEN LAYERS

A number of observed characteristics now indicate that most, if not all, DA stars have hydrogen layer masses many order of magnitude less than the order 10^{-4} $M_\odot$ predicted by stellar evolution theory. Fontaine and Wesemael (1987) were the first to make this case in a comprehensive manner, using evidence from stars ranging from the hottest to fairly cool white dwarfs.

First, with one interesting exception, the hottest DA white dwarfs and hydrogen-rich planetary nebula nuclei (PNN) of similarly high surface gravities appear to have temperatures of 60-75,000 K, while hydrogen-poor white dwarfs and high gravity PNN exist with Teff ranging from 80,000 K to 170,000 K (see references in Section 3).

Second, most of the hot DA stars show evidence for generous trace abundances of helium. Since there seems to be no plausible physical mechanism capable of supporting the measured amounts of helium at the surfaces of these quiescent, high-gravity stars, several authors have proposed that the outer envelopes are stratified, having only ultrathin outer hydrogen layers between $10^{-13.3}$ to 10^{-15} $M_\odot$. It is plausible that this small amount of hydrogen previously could have been mixed deeper into the envelopes of the stars so that the surfaces of the hotter progenitors were hydrogen-poor.

Third, there are no helium-atmosphere DO-DB stars known between about 27,000 K to 47,000 K. While the statistical significance of this claim was challenged several years ago, the new stellar discoveries and redeterminations of the temperature scales have only strengthened the result, which appears to require that all DO and PG1159 stars evolve into objects with H-rich atmospheres.

Fourth, in the temperature range 12-27,000 K, a DB sequence accounts for about 25% of all white dwarfs. There is again a plausible explanation for the change in the dominant surface constituent, provided the original hydrogen layer masses are small. Convective mixing of an outer helium layer reaches maximum efficiency near about 30,000 K. If an initial outer hydrogen layer has $< 10^{-14.9}$ $M_\odot$, the mixing of the underlying helium layer might engulf the hydrogen, turning the DA into a DB star.

Fifth, the pulsational properties of the ZZ Ceti DA stars in the 11-13,500 K range are best explained by thin hydrogen layers. Were the hydrogen layer masses as thick as stellar evolution theory predicts, the blue edge of the instability strip cannot be explained, and the red edge cannot be attributed to convective mixing.

Finally, we note that the fraction of DA's among cooler stars (< 11,000 K) appears to be considerably smaller, suggesting that many of the DA stars are converted to non-DA atmospheres by convective mixing. However, it must be acknowledged that many unanswered questions remain concerning the cooler stars. In particular, we do not fully understand the helium abundances in DA stars too cool to show spectral lines of helium.

3. LOW MASS HELIUM LAYERS

In the last section, we noted that the very hottest of the degenerate stars with log g > 7 turn out to be nearly all non-DA stars -- DO stars near 80,000 K, and the even hotter "PG1159" stars for which the prototype is the pulsating star PG1159-035. We had noted that the He-rich PNN appear to be logical progenitors for these stars. Indeed, the hot DO stars have helium-dominated and hydrogen and CNO-poor atmospheres in a manner qualitatively similar to the much cooler DB white dwarfs. In contrast, recent abundance analyses for the hotter PG1159 stars and a related object have been real surprises, as reviewed below.

In contrast to most white dwarfs, the PG1159 stars show spectra exhibiting a variety of high-excitation ions. He II, C IV and O VI transitions have been found as strong absorption features in optical and UV spectra of these objects, and some of these lines show central emission reversals. N V, N IV, and O V features have also been seen. Given the high temperatures and the complexity of these spectra, it was apparent that non-LTE atmospheres coupled with careful treatments of the CNO ions and line profiles were required for an adequate abundance analysis. Two teams of researchers from Kiel and Munich, Germany, have developed the necessarily physics for analysis of these stars and of some higher-luminosity PNN counterparts.

Werner, Heber and Hunger (1991) published the first detailed analysis of four PG1159 stars. They found that the stars have Teff in two groups near 100,000 K and 140,000 K, and that all have log g near 7, consistent with the conclusion that are approaching final degenerate radii. Surprisingly, the abundances of carbon (48% by mass) and oxygen (15%) are of the same order as helium (32%) in the atmospheres of these four stars. Now Werner (1991) has analyzed the related object H1504+65, an object showing lines of C IV and O VI, but with no obvious He II. For this star he finds Teff = 170,000 $\pm$ 20,000 K, and log g = 8 +/- 0.5, making this the hottest star ever analyzed by model atmospheres techniques. Strikingly, its surface abundances are equally divided (by mass fraction) between carbon and oxygen, while being virtually devoid of hydrogen and helium (the latter < 1%). H1504+65 appears to be a "bared" CO degenerate core!

The derived abundances of carbon and oxygen are orders of magnitude higher than those predicted for diffusive equilibrium, including selective radiative acceleration mechanisms. The fact that helium may be a minority constituent in the atmospheres of four PG1159 stars, while being virtually absent in the hotter H1504+65, changes our view of how these stars evolve. Werner, Heber and Hunger (1991) point out that hydrogen-poor PNNs may experience a Wolf-Rayet phase of enhanced mass loss, during which time they may lose most of the outer helium layer. After they enter the white dwarf sequence above 100,000 K, they presumably have retained enough helium mixed into layers much deeper than the atmosphere to evolve with gravitational diffusion into DO white dwarfs with helium-dominated atmospheres (< 80,000 K). However, as noted in Section 2, enough hydrogen is also retained to later form an ultrathin but optically-thick "DA" atmosphere (> 30,000 K). At lower temperatures, the convective mixing may again convert the star to a helium-dominated DB atmosphere.

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