New Developments in Hot White Dwarf Models

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A short history of EUV observations of white dwarfs is presented, and how they have forced us to use increasingly sophisticated theoretical models—starting from blackbody spectra up to the present generation of NLTE models which include the blanketing effect of millions of atomic lines.

1. Introduction

Observations of white dwarfs mark the beginning of extrasolar EUV astronomy and these objects continue to play a very important role as targets until today. About one third of all EUV sources found in the *ROSAT*/WFC (Pounds et al. 1993) as well as the *EUVE* (Bowyer et al. 1994) surveys are white dwarfs. This is very easy to understand: to be detectable in the EUV through the strongly absorbing interstellar hydrogen and helium the sources should not be too far away; to have enough photospheric flux at these wavelengths they should be hot. Both criteria are met by white dwarfs. Very simple estimates using the luminosity function of white dwarfs give the expected number of white dwarfs within 100 pc and hotter than 25,000 K as about 300; about 60 of these should be hotter than 60,000 K. This corresponds well with the typically 120 white dwarfs detected in the surveys. On the other hand, the nearest O-type star is at a distance of about 200 pc.

A second reason for the prominence of white dwarfs among EUV sources is provided by their peculiar chemical abundances. Most white dwarfs belong to the spectral type DA, which means that they show only the Balmer lines of hydrogen in the visible part of the spectrum. And hydrogen seemed indeed to be the only element present in these atmospheres, an assumption shown to be incorrect for the hottest of them only fairly recently through EUV observations. In a pure hydrogen photosphere the absorption coefficient decreases as λ^3 going from the Lyman absorption edge to the soft X-ray region, and, conversely, the radiation leaving the star comes from progressively deeper and hotter layers. As a consequence, the photospheric radiation of a pure hydrogen DA in the range 100–300 Å can be orders of magnitude larger than that of a blackbody of the same temperature. This effect is demonstrated in Fig. 1 for an effective temperature of 50,000 K.

The addition of helium, even at the level of 1/10 the solar value, changes the spectrum completely (Fig. 2). Now all flux below the He II groundstate absorption edge at 228 Å is completely suppressed, but the flux between 250 and 400 Å is still much higher than the corresponding blackbody flux. These two figures demonstrate that

- DA white dwarfs should be very powerful emitters of EUV radiation
- very small admixtures of helium, which would be completely invisible in the optical and UV, should be easily detectable in the EUV.

2. Early Observations and Interpretations

The first extrasolar EUV source detected was the DA white dwarf HZ43. It was observed by the Apollo-Soyuz extreme-ultraviolet telescope (Lampton et al. 1976). Between

S. Bowyer and R. F. Malina (eds.), Astrophysics in the Extreme Ultraviolet, 185–192.

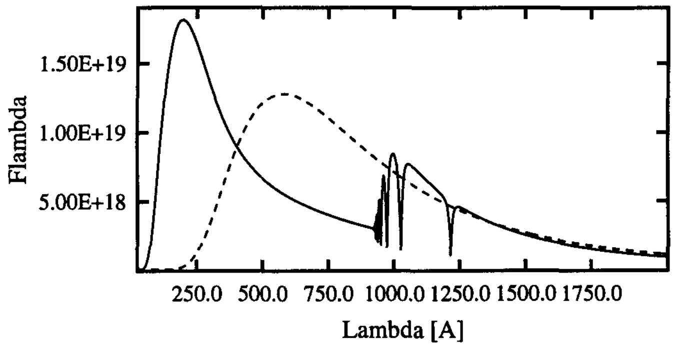

FIGURE 1. Comparison of a pure hydrogen white dwarf model atmosphere for $T_{\rm eff} = 50{,}000$ K, $\log g = 8$ with a blackbody spectrum of the same temperature

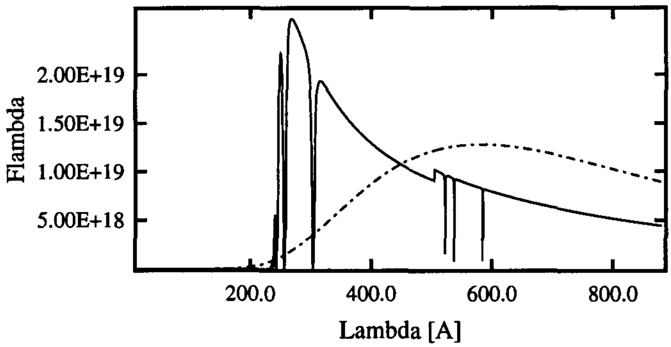

FIGURE 2. A similar comparison as in Fig. 1, except for a He/H ratio of 0.01 in the model atmosphere.

very simple theoretical spectra, like power law and blackbody, a blackbody of 110,000 K was found to give the best fit to the observations. This is much higher than the photospheric temperature of HZ43—a modern value is 49,000 K (Napiwotzki et al. 1993)—but the discrepancy is easily understood in light of the discussion in the preceding section.

White dwarf model atmosphere calculations were first used to interpret the same observations by Auer & Shipman (1977). The effective temperature in their analysis depended on the *assumption* about the helium abundance, which could not be determined independently from the data, and ranged from 55,000 K (no photospheric helium) to 70,000 K for a helium abundance of 1/100 the solar value (the upper limit compatible with the absence of the He II 4686 Å line.

The EUV radiation observed from a white dwarf photosphere depends on a large number of parameters: effective temperature, surface gravity, solid angle of the star, photospheric He/H ratio or abundances of other elements, interstellar column densities of H I, He I, and He II. Observations in the EUV have never been detailed enough to determine all of these parameters, and it is therefore necessary to include in the analysis all available information from other spectral ranges. Even then, the information gained from the EUV up to the *EXOSAT* experiment has been rather limited.

3. Observations and Status Up to 1988—Pre *ROSAT* and *EUVE*

About 20 DA white dwarfs were observed by *EINSTEIN* and *EXOSAT*, in part through different filter bands giving a limited spectral information. While some of the objects could be explained with simple, pure hydrogen model atmospheres, many others, especially among the hotter DA showed clear indications of additional absorbers in the photosphere. The most natural assumption at that time seemed to be helium, and the observations have been used by a number of groups to determine He abundances in these DA (Kahn et al. 1984; Petre et al. 1986; Jordan et al. 1987; Paerels & Heise 1989). It was already known that theoretically He was not expected in the atmospheres, because it should diffuse rapidly towards the deeper layers and radiative levitation is not effective enough to support it (e.g., Vennes et al. 1988).

A possible solution to this problem was the assumption that the pure hydrogen layer is extremely thin. Because of the decrease of hydrogen absorption in the EUV the underlying He could become visible in the EUV, whereas in the optical and UV the star would appear as a pure hydrogen object. The next step in the refinement of the theoretical atmosphere models and the first step beyond simple, classical LTE atmospheres, was therefore to include this diffusion equilibrium H/He stratification consistently in the computations (e.g. Jordan and Koester 1986). These theoretical models were equally able to interpret the *EINSTEIN* and *EXOSAT* observations—it was not possible to distinguish between homogeneous He/H mixtures and a stratified atmosphere with a thin hydrogen layer on top of the helium and a transition zone as calculated from the diffusion equations (Koester 1989). The signature of helium on the spectrum is quite distinct in the two cases; nevertheless, with only two very broad bandpass measurements available, it was always possible to fit the observations and determine either He/H, or the thickness of the hydrogen layer as parameter of the model.

The only exception, where an interpretation of the absorption by helium was not possible, was the *EXOSAT spectrum* of Feige24. In this case Vennes et al. (1989) showed that the spectrum could be reproduced with a rather ad hoc mixture of heavy elements ("metal soup"). Vennes (1992) also demonstrated that similar mixtures of heavy elements could explain the observations of a few other hot DA.

4. Accumulating Evidence Against Helium

High resolution *IUE* spectra had since a long time shown the presence of weak metal lines (C IV, Si IV, N V, Fe V, Ni V) in some hot DA white dwarfs, which was also confirmed later by HST/FOS and HST/GHRS spectra (Bruhweiler & Kondo 1981,1983; Tweedy 1991; Sion et al. 1992; Vennes et al. 1992; Vidal-Madjar et al. 1994; Holberg et al. 1993; Werner and Dreizler 1994). It was not always easy to distinguish between interstellar, circumstellar, and photospheric lines, but in several cases a photospheric origin was clearly established. The real breakthrough, however, came only with EUV observations. A rocket observation of G191-B2B (Wilkinson et al. 1992) showed a number of metal features in the EUV, but no helium. And, finally, the analysis of a large number of DA white dwarfs observed with the Wide Field Camera on *ROSAT* (Barstow et al. 1993) demonstrated convincingly that for several objects the absorption in the EUV could not be caused by helium, neither in a homogeneous mixture nor in a stratified atmosphere. Another very significant result of this study was that all DA below a certain temperature threshold of about 40,000 K could be explained by pure hydrogen atmospheres, whereas almost all hotter objects showed additional absorption. This result was confirmed with larger samples and in much more detail by Jordan et al.(1994), Wolff et al. (1995a,b), and Finley (1995).

It thus became obvious that the next step in the development of white dwarf model atmospheres would have to be the inclusion of EUV bound-free and line absorption by heavy elements up to iron and nickel, typically in the ionization stages of III–VIII, a task which would have been next to impossible a few years ago.

5. LTE Model Atmospheres and Atomic Data

The situation concerning the availability of necessary atomic data has been greatly improved by the calculations of the Opacity Project (Seaton et al. 1992). Photoionization cross sections for all important elements up to iron are available in the TOPBASE database at the CDS. Unfortunately, at present the lowest ionization state for iron is III, and other iron peak elements (especially Ni) are completely missing, so that for these hydrogen-like estimates have to be used.

An invaluable database for the bound-bound transitions are the line lists compiled by Bob Kurucz over many years and distributed on CDROM (Kurucz 1991, 1992). They contain more than 40 million atomic lines, mostly of the iron group elements. The absorption by these lines is not only important for the calculation of a detailed synthetic spectrum, but also for the structure of the model atmosphere, that is the blanketing effect of all these lines has to be taken into account. The large amount of data, and the complexity of handling it poses challenges to the calculation of white dwarf atmosphere models, which we have not had to face in this field before. The two general methods discussed in the literature to solve this problem in the context of LTE models are Opacity Distribution Functions (ODF) and Opacity Sampling (OS). Rather than repeating this discussion here, I will present a short description of my own atmosphere codes. These codes, or models calculated with it, have been widely used by our own group in Kiel as well as by others (Finley, Barstow, Gemmo, O'Donoghue, Saffer, Kepler, Robinson, and others).

The calculations proceed in three steps

- Calculation of an opacity table for a given chemical composition. This is by far the most expensive calculation in the case of LTE atmospheres, and it is therefore economically reasonable to separate this step from the calculation of the model structure. The typical size of these tables is 600 temperature/pressure pairs and 35,000–75,000 wavelengths. This large number of wavelength values, which in the EUV corresponds to spacings of 0.005 to 0.015 Å, is necessary because we use Opacity Sampling. The code steps through the complete lists of photoionization cross sections (from the Opacity Project) and then through the complete Kurucz line lists, at each wavelength adding the contribution of the lines, as long as they are stronger than a predefined threshold. Calculation of such a table takes about 24 hrs on a typical workstation, and we have therefore developed a number of shortcuts, e.g., calculating tables for different mixtures from precalculated tables for individual elements, etc. The typical size of such a table is 30 MB.
- Calculation of the atmospheric structure. This uses the standard assumption of LTE atmospheres and includes convection, if the stratification is unstable. The numerical method is the Feautrier method with variable Eddington factors, and the only unusual feature is the large number of wavelength points (up to 75,000) necessary to model the blanketing effect as accurately as possible.
- The final step is the calculation of a detailed synthetic spectrum for a fixed model structure. In the case considered here the spectrum provided by the previous step is

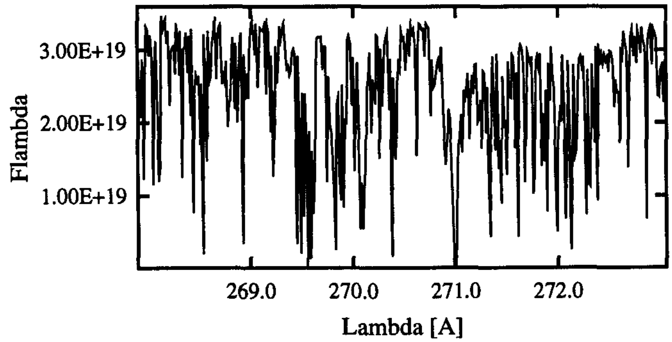

FIGURE 3. Arbitrary 5 Å section of a DA model with metals, $T_{\text{eff}} = 52{,}500$ K, $\log g = 7.5$, using about 5,000 bound-bound absorption edges and 9,500,000 atomic lines calculated individually with detailed profiles.

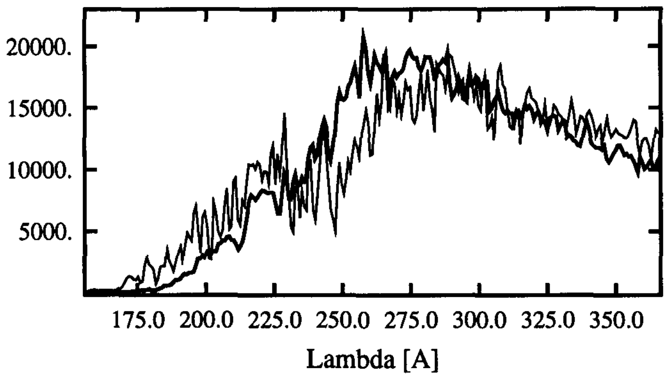

FIGURE 4. Comparison of the *EUVE* spectrum of G191-B2B (thick line) with an LTE model (thin line), using only abundances derived from UV observations as described in the text.

already detailed enough for a comparison with most observations, so the effect of this step is only to add a few more wavelength points, use more sophisticated broadening theories for the H and He lines, and change output formats.

Fig. 3 shows the result of such a model calculation for $T_{\text{eff}} = 52{,}500$ K and $\log g = 7.5$, which has included about 5,000 bound-free edges and 9.5 million lines.

The aim of this paper is not a spectral analysis of individual objects, so I will present only one comparison of models with the best studied of all white dwarfs, G191-B2B. If we take the metal abundances as determined from the UV (e.g. Vidal-Madjar et al. 1994), the interstellar column densities from the *HUT* observations (Kimble et al. 1993), and the solid angle from fitting the models at the V magnitude, we arrive at the comparison of Fig. 4. This is not a perfect fit, and not the final result, but considering the fact that the only free parameter we are left with is the effective temperature, the good agreement is very encouraging. The effective temperature for this model is 52,500 K, which is significantly lower than T_{eff} determined from optical spectra with pure H atmospheres (57,000–60,000 K). This result should not be a surprise: compared to a pure H atmosphere the energy flux in the EUV of G191-B2B is decreased by orders of magnitude, leading to a very significant backwarming effect in the visible. And indeed, our calculations show that the Balmer line spectrum for the metal-rich 52,500 K model in Fig.3 is practically indistinguishable from that of a pure H model at $T_{\rm eff}$ = 57,500 K. In other words, the blanketing effect in this temperature range, and for the rather extreme metal abundances as in G191-B2B, can amount to 5,000 K or more.

6. NLTE Versus LTE Models for White Dwarfs

NLTE effects are known to be very important for the very hot PG1159 and similar objects above 100,000 K (e.g. Werner et al. 1991). Almost all EUV sources, however, are DA white dwarfs at much lower temperature, and for these NLTE effects had been considered to be unimportant, with the exception of the Hα line core. This view has been challenged only recently with the necessity of considering metal absorbers in the EUV, because first NLTE calculations have predicted large effects on the ionization balance of the heavy elements.

As described in the previous section, even in LTE models the inclusion of so many metal lines is a challenging problem. To calculate occupation numbers and the blanketing effect consistently in NLTE is a formidable task, which would have been impossible just a few years ago. New, very powerful numerical techniques and ingenious ways of handling huge sets of atomic data had to be developed to make this possible. There are currently only two groups capable of providing such calculations for white dwarfs: Klaus Werner and coworkers in Kiel, and Ivan Hubeny and coworkers at NASA/Goddard. Both groups have very recently given detailed descriptions of their codes (Werner & Dreizler 1995; Hubeny & Lanz 1995). Although the implementations are different in the two codes, the two major ideas which have made these calculations feasible are common in both

- The use of "Approximate Λ-Operators". This idea goes back to Cannon (1973) and Scharmer (1981), and has been further developed by the Kiel group (Hamann 1985, Werner & Husfeld 1985, Werner 1986).
- The introduction of "superlevels" and "superlines" goes back to Anderson (1985). The enormous number of levels and transitions of the iron group elements is reduced by orders of magnitude, and thus made tractable, by grouping many individual levels into superlevels with combined energies, statistical weights, and transition probabilities.

Both groups have calculated grids of metal line blanketed NLTE white dwarf atmospheres and published first applications. Both groups also claim significant NLTE effects on the ionization balance of the metals, leading to substantial differences between NLTE and LTE model predictions for the EUV continuum flux as well as line strengths (see e.g., Dreizler & Werner 1993; Lanz & Hubeny 1995).

There is no doubt that the ultimate goal must be to apply the correct physical description, that is the NLTE calculations. Only with real NLTE calculations will it be possible to determine and justify the ranges of parameters, where the much simpler LTE calculations will be sufficient, and the groups taking on this immense task deserve our strongest encouragements. We are, however, still a long way from this goal; at present, in spite of all the improvements of the past few years, there are still many compromises that have to be made in NLTE calculations; there are also still many uncertainties in the atomic data, which may influence the final results. It is my personal view, that at the moment it is not at all clear, which compromises are more severe: neglecting NLTE effects, or the limited detail in the treatment of levels and transitions in the NLTE models. I. Hubeny, for example, showed at this meeting, that by including 300,000 atomic lines instead of 30,000 a model came much closer to the observations of G191-B2B (and also to the LTE model!).

The present generation of NLTE models has not yet been very successful in the interpretation of *EUVE* spectroscopic observations; in my experience the LTE models seem to be closer to the truth at the moment.

7. Outlook: What Is the Next Step?

Gravitational separation would lead to a very fast depletion of heavy elements in the atmospheres of hot DA—the timescales are of the order of a few years only. If they are still present, there must be forces at work counteracting the influence of gravitation, and the most likely effect is selective radiation pressure on ions, which have strong absorption lines in regions of high stellar radiation flux. Recent calculations of this effect have been performed for stellar *envelopes* (Chayer et al. 1994, 1995), leading to the prediction of a single value for an element abundance at $\tau_{Rosseland} = 2/3$. However, the conditions (e.g. ionization stage of elements) vary considerably within the stellar atmosphere, and we have to expect not a homogeneously mixed atmosphere, but rather one in which some elements accumulate in certain layers. This distribution of elements in turn will influence the distribution of the photons over wavelength at that depths, and the complete problems can only be solved in a self-consistent way, considering at the same time the equilibrium solution of the diffusion equations including radiation pressure *and* the condition of radiative equilibrium for the atmosphere.

Such calculations do not yet exist, but will ultimately be necessary—probably even for the NLTE case—if we really want to understand the EUV observations. Work in this direction is currently underway in Kiel, and probably at other institutions as well.

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