3. Model Atmospheres for White Dwarfs in Cataclysmic Variables

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Abstract.
We present our initial results of model calculations for hot, mass losing white dwarf primaries of cataclysmic variable systems. The models are calculated with PHOENIX 8.1 and include detailed NLTE effects, line blanketing as well as the effects of the wind on the model structure and the emitted spectrum. We present models for white dwarfs with a moderately strong wind, a "Nova" like model representing a very optically thick wind completely obscuring the white dwarf, and static white dwarf models for comparison. The models have effective (or model) temperatures in the range of a few 100K and solar abundances (for simplicity).

The properties of the synthetic spectra are sensitive to the model assumptions for both the extreme ultraviolet and ultraviolet spectral ranges. While NLTE effects for static white dwarfs are moderate, large and important NLTE effects are found in the wind models due to the lower densities of their line forming regions. In addition, the electron temperatures span an extremely wide range (from 30kK to more then 350kK for $T_{\text{eff}} = 200\,\text{kK}$) in the wind models.

3.1. Introduction
The white dwarf (hereafter, WD) primaries of cataclysmic variable (CV) systems are very different from field WDs. Their atmospheres contain high abundances of metals, introduced by the accretion of metal rich material from the secondary. The review by Ed Sion (this volume) gives an excellent overview of CV WDs during relatively quiet phases of CV evolution.

In this contribution, we consider WDs in the later stages of a thermonuclear event (e.g., a nova outburst). Taking novae as a paradigm, this is the phase when practically all of the usually observed light comes from the ejected nebula,
powered by the high-energy photons from the still active, and very hot, central source. In stark contrast to classical WDs, these objects lose mass through a wind driven by the high luminosity and the strong opacity of a large number of spectral lines. The wind will effect the spectrum and the physics of the nebula by changing the number of high energy photons emitted by the central source and thus its excitation. The effective temperatures in these WDs with winds can reach more than 200kK. The range of electron temperatures in the line forming regions will be large due to the large radial extension of the wind material. This means that NLTE effects will be much larger than in classical WDs and must be considered in great detail to correctly model the physics in these atmospheres.

The next section of the paper introduces the basic model assumptions for the three types of models that we discuss here and gives a brief description of the numerical techniques used in the simulations. We then present the results of preliminary calculations and show the differences in the emitted spectra for the different model types.

3.2. Model Construction

We consider three different models for the primaries of CVs:
Figure 2. Comparison of White Dwarf, White Dwarf+Wind and nova-type spectra for $T_{\text{eff}} = 200$ kK.

1. Static WD models. These correspond to classical WD models but with high metal abundances and higher temperatures. We have calculated these models mainly for comparison with the wind and nova-type models discussed below. Here, we use a gravity of $\log(g) = 8$ and solar abundances (mainly for simplicity) for the WD models.

2. The basic assumptions of our "Nova"-type models are the same as in Hauschildt et al. (1995). The expanding material is assumed to have a power law density of the form $\rho \propto r^{-N}$ with $N = 3$ for the models presented here. The velocity law is derived from the condition of constant mass-loss rate (in radius), $\dot{M} = 4\pi r^2 \rho v_{\text{max}}$, with a prescribed maximum velocity $v_{\text{max}}$ (we use here $v_{\text{max}} = 2000$ km s$^{-1}$, consistent with typical values observed in classical novae). We further parameterize the models with the "model temperature" $T_{\text{model}}$ through the relation $L = 4\pi R^2 \sigma T_{\text{model}}^4$, where $L$ is the luminosity of the model (here set to $L = 50,000 \, L_\odot$ for all models, the absolute value of the luminosity does not affect the spectra, see Pistinier et al. (1995); Hauschildt et al. (1995)). $R$ is the radius of the shell at $\tau = 1$ in the bound-free (hereafter, b-f) continuum at 5000Å. The model temperature is comparable to the effective temperature $T_{\text{eff}}$ in that it parameterizes the bolometric flux of the model at any time. It
Figure 3. The departure coefficients of O I–VI for the WD model with $T_{\text{eff}} = 200 \text{kK}$.

should never be confused with the effective temperature, which can only be defined for plane-parallel configurations (Hauschildt et al., 1995).

3. The WD+wind models use a parameterized wind velocity law of the form $v(r > R_\star) = v_\infty (1 - R_\star/r)^{\beta}$ in the outer part of the atmosphere with a smooth transition into the nearly hydrostatic atmosphere of the WD itself. In this expression, $R_\star$ is the radius of the WD (the location where the static WD would have its photosphere) and $v_\infty$ is the velocity of the material at infinite distance from the WD. For the models presented here we use $\beta = 0.8$, $v_\infty = 1000 \text{ km s}^{-1}$ and assume a mass-loss rate of $M = 10^{-6} \text{ M}_\odot /\text{yr}$.

**General Model Assumptions** For model calculations, we use our multi-purpose stellar atmosphere code PHOENIX. PHOENIX (version 8.1, Hauschildt et al., 1996; Hauschildt, Baron, & Allard, 1997) uses a special relativistic spherical radiative transfer for nova models and an equation of state (EOS) which includes more than 300 ions of 39 elements (with up to 26 ionization stages each). The temperature correction is based on a variation of the Unsöld-Lucy method that has been modified to include NLTE and scattering. This algorithm converges very quickly and is highly stable.
Figure 4. The departure coefficients of O I–VI for the WD+Wind model with $T_{\text{eff}} = 200$ kK.

We solve the radiative transfer equation consistently for lines and continua (allowing for arbitrary overlaps) with the method discussed in Hauschildt (1992) and Hauschildt et al. (1995) rather than employing the Sobolev approximation. Hauschildt et al. (1995) and Baron et al. (1996) have shown that this simpler method cannot be used in nova atmospheres due to the large number of overlapping lines as well as the strong coupling between lines and continua. Such complications require that the multi-level NLTE rate equations be solved self-consistently and simultaneously with the radiative transfer and energy equations, and the equations must include the effects of both line blanketing and expansion of the nova atmosphere.

In the calculations presented in this paper, we use a selection of the full set of NLTE species we currently have available, namely H, He I–II, Mg II, Ca II, Ne I, C I–IV, N I–VI, O I–VI, S II–III, Si II–III, and Fe I–III (for a complete list of NLTE species available in PHOENIX 8.1 see Hauschildt et al., 1997). Note that we do not use the NLTE treatment for Li I, Na I, Co I–III and Ti I–III because these species are not important in nova atmospheres and treating Co and Ti in NLTE would considerably increase the CPU time for the model calculations with little improvement. We thus include a total of 3922 NLTE levels and 47061 NLTE primary lines in the calculations presented here, details
are given in Hauschildt (1993); Hauschildt & Baron (1995); and Hauschildt et al. (1997).

The large number of transitions that have to be included in realistic models of these atmospheres require an efficient method for the numerical solution of the multi-level NLTE radiative transfer and model calculation problem. Simple approximations, such as the Sobolev method, are very inaccurate in situations in which lines overlap strongly and make a significant pseudo-continuum contribution (weak lines), as is the case for nova and supernova atmospheres (Hauschildt et al. 1996 and Baron et al. 1996). Classical techniques, such as complete linearization or the Equivalent Two Level Atom method, are computationally prohibitive. In addition, we are modeling moving media (e.g., stellar winds, novae and supernovae), so that approaches such as Anderson’s multi-group scheme (Anderson, 1989) or extensions of the opacity distribution function method (Hubeny & Lanz, 1995) cannot be applied because of the velocity dependent coupling of different wavelengths. Methods that are based on partial linearization schemes and the use of superlevels tend to be numerically less stable, and frequently encounter convergence problems because of the highly non-linear and non-local couplings that dominate these atmospheres.

Both the secondary NLTE and LTE background lines (see below) are treated with a direct opacity sampling method. We do not use pre-computed opacity sampling tables, but instead dynamically select the relevant LTE background lines from master line lists at the beginning of each iteration and sum the contribution of every line, within a search window, to compute the total line opacity at arbitrary wavelength points. The latter feature is crucial in NLTE calculations in which the wavelength grid is both irregular and variable from iteration to iteration due to changes in the physical conditions. This approach also allows detailed and depth dependent line profiles to be used during the iterations. To make this method computationally efficient, we employ modern numerical techniques, e.g., vectorized and parallel block algorithms with high data locality (Hauschildt, Baron, & Allard, 1997), and we use high-end workstations or parallel supercomputers (Hauschildt, Baron, & Allard, 1997; Baron & Hauschildt, 1997) for the model calculations.

In the calculations we present in this paper, we have have included a constant statistical velocity field, $\xi = 50 \text{ km s}^{-1}$, which is treated like a microturbulence. The choice of lines of species not explicitly treated in NLTE (hereafter, LTE background lines) is dictated by whether they are stronger than a threshold $\Gamma \equiv \chi_l / \kappa_c = 10^{-4}$, where $\chi_l$ is the extinction coefficient of the line at the line center and $\kappa_c$ is the local b-f absorption coefficient. This typically leads to about $2 \times 10^6$ LTE background lines. The profiles of these lines are assumed to be depth-dependent Voigt profiles (for strong lines) or Gaussians. We have verified in test calculations that the details of the LTE background line profiles and the threshold $\Gamma$ do not have a significant effect on either the model structure or the synthetic spectra. However, the LTE background lines are included because their cumulative effect can change the structure and the synthetic spectra. In addition, we include about 2000 photo-ionization cross sections for atoms and ions (Verner & Yakovlev 1995).
3.3. Preliminary Results

If Fig. 1 we show synthetic spectra for various models with $T_{\text{eff}} = 200\,\text{kK}$. The WD and WD+winds spectra are similar (with the exception of the emission lines), mostly because the wind part of the model is not very optically thick and thus does not change the overall spectrum too much. The effects of a very optically thick wind are obvious in the comparison to the “Nova” spectrum. Its pseudo-continuum has a very different shape than the WD and WD+winds model spectra because of the stronger re-processing of the photons by the wind. In the UV, the absolute differences are enormous (cf. Fig. 2). The effects of the wind in the WD+winds model are easily visible in the line profiles and the model is distinct from the static WD model. The “Nova” spectrum shows much weaker emission lines and only weak, if any, P Cygni absorption components. It is interesting to note that the WD+winds NLTE line-blanketed model shows more UV flux than its continuum, LTE counterpart whereas the “Nova” model shows the opposite behavior. This is caused by the different effects of line blanketing (and successive photon degradation) cause by the two types of winds.

The NLTE departure coefficients, $b_i$, are extremely different for the static and the “wind” models. In Figs. 3 and 4 we show the oxygen $b_i$ for the $T_{\text{eff}} = 200\,\text{kK}$ WD and WD+winds models. In the static WD model, the $b_i$ are relatively small (between 0.5 and 1.2), indicating moderate NLTE effects on the oxygen line formation, mostly due to the relatively high collision rates in the dense static WD atmosphere. In the WD+winds model, however, the departure coefficients are typically between $10^{-4}$ and $10^4$, indicating much more severe NLTE effects. This happens because the lines form now in a much lower density wind environment rather than in the high density WD atmosphere. The presence of the velocity field also introduces larger departures from LTE by increasing the overlap between different lines and by “leaking” high energy photons into red-ward spectral regions, thereby driving the radiative rates even farther from their LTE values.

3.4. Summary and Discussion

Our preliminary model calculations show that there are observable differences between models for various scenarios for the evolution of the central white dwarfs in CV just after the explosive phase of the outburst. The physics of both wind model types (a WD+winds model and a “Nova” like model) is extremely complex. The radial extension of the WD+winds model at $T_{\text{eff}} = 200\,\text{kK}$ is close to a factor of 1000, the electron temperatures increase by a factor of 10 from the outermost to the innermost point in the model “atmosphere,” and the pressures (or densities) change by a factor of $10^8$ in the line forming regions, with many lines forming throughout a significant fraction of that region. Lower densities in the line forming regions of the wind models cause much larger NLTE effects compared to the static WD models. The large temperature gradient causes the simultaneous presence of several ionization stages of some elements (notably CNO, Ne, Mg) in the line forming region, making NLTE calculations even more complex.

The calculations we have presented here are the first steps towards fully detailed models. Improvements will include more NLTE species and lines for higher ionization stages as well as a self-consistent treatment of the velocity field.
in the wind as function of the radiation field in the atmosphere. The latter will allow much more accurate derivation of the mass loss rates etc. from observed spectra. Furthermore, these models will be able to accurately model the X ray spectra of a variety of objects.

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