White Dwarf Model Atmospheres: Synthetic Spectra for Supersoft Sources

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Abstract. The Tübingen NLTE Model-Atmosphere Package (*TMAP*) calculates fully metal-line blanketed white dwarf model atmospheres and spectral energy distributions (SEDs) at a high level of sophistication. Such SEDs are easily accessible via the German Astrophysical Virtual Observatory (*GAVO*) service *TheoSSA*. We discuss applications of *TMAP* models to (pre) white dwarfs during the hottest stages of their stellar evolution, e.g. in the parameter range of novae and supersoft sources.

Keywords. astronomical data bases: miscellaneous — stars: abundances, AGB and post-AGB, atmospheres, early-type, individual (V 4743 Sgr, V 1974 Cyg), novae, cataclysmic variables, winds, outflows — binaries: close — X-rays: binaries, bursts

1. Introduction

Novae in outburst may become the brightest sources of soft X-ray emission in the sky. During this so-called supersoft source (SSS) phase (some weeks or months after the outburst), it is possible to perform high-resolution and high-S/N spectroscopy with X-ray satellites like *Chandra* or XMM-*Newton*. These spectra require adequate NLTE model atmospheres for a reliable analysis.

A detailed analysis of such a nova, V 4743 Sgr, was recently presented by Rauch *et al.* (2010). They used plane-parallel, hydrostatic models calculated with the Tübingen NLTE Model-Atmosphere Package (*TMAP*†, Werner *et al.* 2003, Rauch & Deetjen 2003). Although the velocity field and the expansion of the nova's atmosphere was neglected, the overall slope of the continuum flux was well reproduced. Moreover, the strengths of prominent photospheric absorption lines (C V, C VI, N VI, N VII, O VII) as well as the strengths of absorption edges were in very good agreement with the observation (Figure 1, 2). Rauch *et al.* (2010) could e.g. show that the C/N abundance ratio was increasing from March to September 2003 (Figure 1).

2. Model Atmospheres for SSS

TMAP model atmospheres were successfully employed for spectral analyses of hot, compact stars. See Rauch & Werner (2010) and Rauch (2011) for a brief summary of this application to a variety of objects from post-AGB stars ($T_{\rm eff} \approx 100\,000\,{\rm K}$) to neutron stars in low-mass X-ray binaries ($T_{\rm eff} \approx 10\,000\,000\,{\rm K}$).

What do we need to analyze X-ray spectra taken during the SSS phase following a nova outburst reliably? The evolution of both stars has to be modeled, including e.g. stellar rotation, mass-loss history, common-envelope phase, and a long series of outbursts. Thus, 3-dimensional magneto-hydrodynamical calculations that follow the stars for a long time
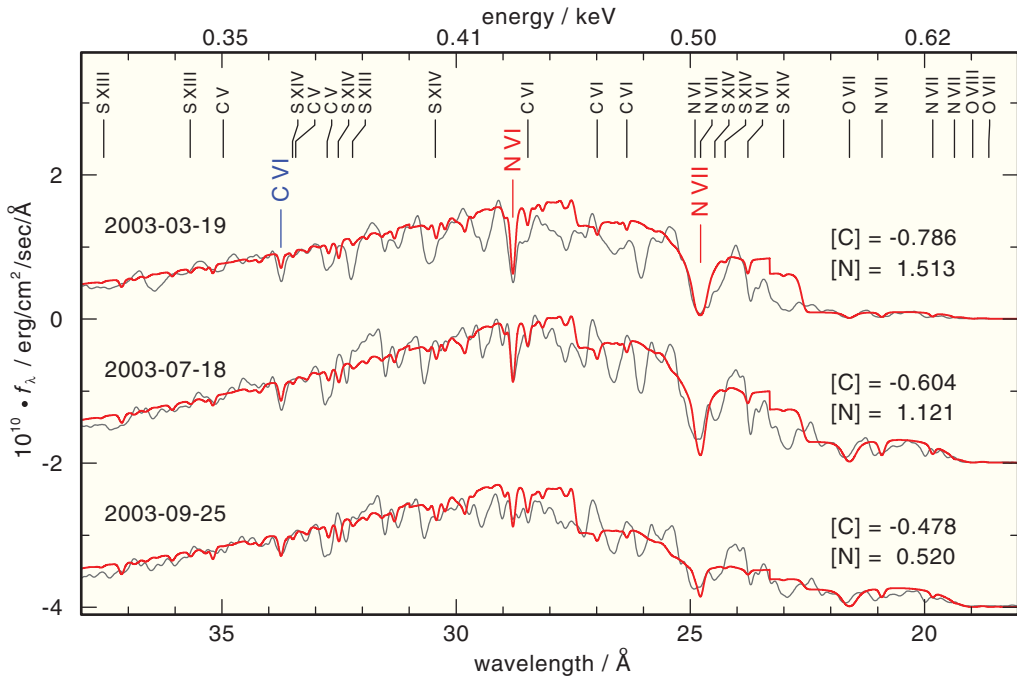
† http://astro.uni-tuebingen.de/~TMAP/TMAP.html

Figure 1. Comparison of flux-calibrated *Chandra* observations of the nova V 4743 Sgr (in thin black) with synthetic spectra (H+He+C+N+O+Ne+Mg+Si+S + Ca−Ni opacities considered in modeling, $T_{\mathrm{eff}} = 720\,000$ K, $\log g = 9$, cf. Rauch *et al.* 2010). Positions of line transitions are marked at top. $v_{\mathrm{rad}} = -2300$ km/sec was applied to the models to match the C VI and N VI resonance lines. [X] denotes log (abundance/solar abundance). For clarity, the July and September observations are artificially shifted in flux.

are definitely the best choice. In addition, 3D NLTE radiation transfer, accounting for the expanding atmosphere and mass loss not only during the outburst, clumping in the ejected matter, etc. is necessary. This should be combined with 3D photoionization modeling to describe the surrounding gas and dust. Although all these state-of-the-art ingredients are already available, their combination and application to an individual nova system is still a dream.

In the case of V 4743 Sgr, Ness *et al.* (2003) measured a blueshift ($v_{\mathrm{rad}} = -2000$ km/sec) in the *Chandra* spectrum. This strong evidence for expansion was found in the SSS spectra of other novae as well (Ness 2010). A new version of the multi-purpose model-atmosphere code *PHOENIX* (Hauschildt & Baron 1999) accounts for this expansion (van Rossum & Ness 2010). These models predict typical wind effects that are already known from the UV wavelength range in cooler post-AGB stars. In the relevant parameter range for SSS, the model flux for $\lambda < 30$ Å ($E > 0.41$ keV) is increasing with increasing mass-loss rate and absorption edges of C VI (25.30 Å), N VII (18.59 Å), and O VII (16.77 Å) become weaker. From these results, one has to conclude that, of course only in case of higher mass-loss rates ($>10^{-8}$ M$_\odot$/yr), spectral analyses of SSS based on hydrostatic model atmospheres tend to overestimate T_{eff} and metal abundances.

The question remains, *why do the static TMAP models reproduce the observations that well* (Figure 2)*?* The answer may be very simple – the strong mass-loss phase of V 4743 Sgr is over. Obviously, there are no P Cygni line profiles observed and thus, the "wind-blown" material around V 4743 Sgr is not dense enough to provide the emission. The matter in the line of sight is still moving towards us and thus, we see blueshifted, pure
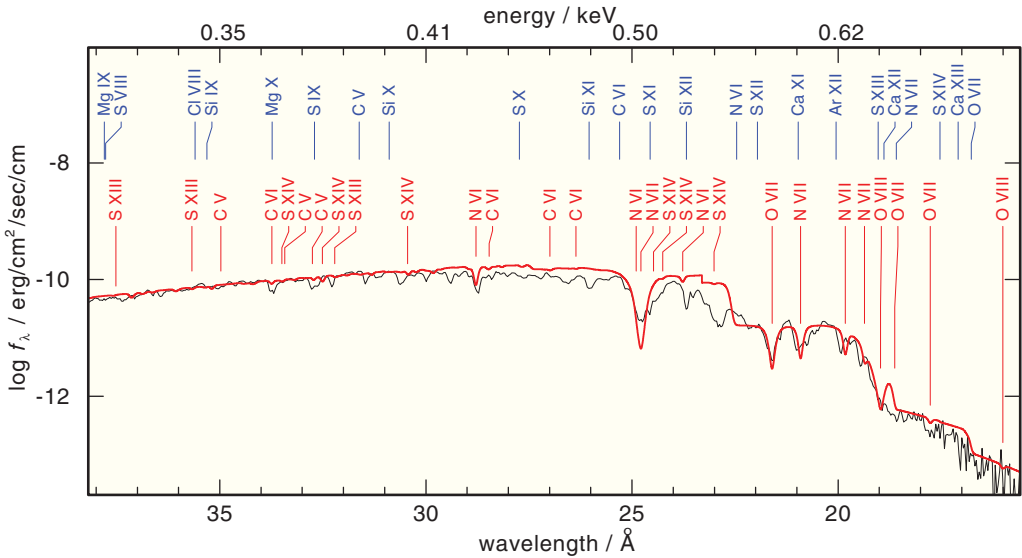
Figure 2. Comparison of flux-calibrated XMM-*Newton* observations of V 4743 Sgr (April 2003) with the final model (H+He+C+N+O+Ne+Mg+Si+S + Ca-Ni, $T_{\rm eff} = 740\,000\,{\rm K}$, $\log g = 9$) of Rauch *et al.* (2010). Positions of ground-state thresholds are marked at top (blue), those of line transitions just below (red).

absorption lines. An approach like presented by Rauch *et al.* (2010) appears well justified. It is possible that accretion already takes place and changes the C/N abundance ratio (Section 1).

3. *TheoSSA* - SSS Model Spectra on Demand

TheoSSA† is a registered Virtual Observatory‡ (*VO*) service developed by the German Astrophysical Virtual Observatory *GAVO*¶. It provides access to SEDs at three levels: 1) pre-calculated SED grids for a fast comparison with observations, 2) SEDs with individual parameters (and provided standard model atoms from the Tübingen Model-Atom Database, *TMAD*‖) can be calculated†† without knowledge of the model-atmosphere code, 3) SEDs with individual parameters and self-constructed model atoms can be calculated by experienced users. *TheoSSA* was firstly based on *TMAP* models only but it is prepared for SEDs from any other stellar model-atmosphere code.

Pre-calculated grids of SEDs for SSS (cf. Rauch & Werner 2010) are also easily accessible in *VO*-compliant form via *TheoSSA*'s WWW interface‡‡. In case of any request, we will calculate new grids with different abundances.

In addition, some SED grids for SSS ($T_{\rm eff} = 0.55 - 1.05\,{\rm MK}$, Rauch & Werner 2010) are available converted into tables¶¶ for the direct use within *XSPEC*‖‖.

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† Theoretical Stellar Spectra Access
‡ http://www.ivoa.net
¶ http://www.g-vo.org
‖ http://astro.uni-tuebingen.de/~TMAD/TMAD.html
†† http://astro.uni-tuebingen.de/~TMAW/TMAW.shtml
‡‡ http://dc.g-vo.org/theossa
¶¶ http://astro.uni-tuebingen.de/~rauch/TMAF/flux_HHeCNONeMgSiS_gen.html
‖‖ http://heasarc.gsfc.nasa.gov/docs/xanadu/xspec

4. Conclusions

Spectral energy distributions for SSS (calculated with *TMAP*) are easily available via *TheoSSA* – use them! Blackbody energy distributions generally have – at the same temperature – a much lower peak intensity (about a factor of three in the parameter range of SSS, Rauch *et al.* 2010) and the flux maximum is located towards lower energies (about a factor of two). Thus, "spectral analyses" based on blackbodies yield wrong results.

There are novae that are observed in their SSS phase where the impact of mass-loss is not significant. For these objects, analyses based on static model atmospheres like *TMAP* provide reliable results within typical error ranges (Rauch *et al.* 2010). In case of prominent P Cygni line profiles, however, a code like *PHOENIX* has to be employed.

A time series (about all three months) of V 4743 Sgr X-ray observations has shown that the white dwarf's surface is extremely hot (T_{eff} higher that $500\,000\,\text{K}$) for at least half a year (Rauch *et al.* 2010). The phase of increasing T_{eff} appears important because the mass-loss rate will be presumably higher and, hence, expanding model atmospheres can be used to study wind properties.

A time series of X-ray spectra on a short time scale (about weekly) starting at an early outburst phase like taken e.g. for Nova V 1974 Cyg with IUE† (cf. González-Riestra & Krautter 1998) is highly desirable. Since *Chandra* and XMM-*Newton* will unfortunately not work forever, such spectra have to be taken in the very near future. The development of appropriate, reliable model atmospheres is already on the way.

Acknowledgements

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† International Ultraviolet Explorer