

HST Spectroscopy of the Hottest White Dwarfs

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Summary. Spectral analysis needs the observation of lines of successive ionization stages in order to evaluate the ionization equilibrium (of a particular species) which is a sensitive indicator for the effective temperature (T_{eff}). Since stars with T_{eff} as high as 100 000 K have their flux maximum in the extreme ultraviolet (EUV) wavelength range and due to the high degree of ionization, most of the metal lines are found in the ultraviolet (UV) range. Thus, high-S/N and high-resolution UV spectra are a pre-requisite for a precise analysis. Consequently, we employed the Faint Object Spectrograph (FOS), the Goddard High Resolution Spectrograph (GHRS), and the Space Telescope Imaging Spectrograph (STIS) aboard the Hubble Space Telescope (HST) in order to obtain suitable data. We present state-of-the-art analyses of the hottest (pre-) white dwarfs by means of NLTE model atmospheres which include the metal-line blanketing of all elements from hydrogen to nickel.

1 INTRODUCTION

In the early eighties of the last century, the evolution of “H-normal” post-AGB stars has been quite well understood, e.g. Schönberner (1983) and Blöcker & Schönberner (1990) have presented evolutionary calculations for these stars. At that time, neither standard evolutionary calculations nor model atmospheres could explain observations of H-deficient post-AGB stars.

In 1979 the discovery of PG 1159–035, the H-deficient prototype of the GW Vir variables, had shown the inadequacy of theory: the optical spectrum exhibits broad and shallow absorption lines of highly ionized species, e.g. He II and C IV, indicating T_{eff} to be much higher than 100 000 K. At this temperature regime, the assumption of local thermodynamical equilibrium (LTE) is not valid and thus, adequate fully metal line-blanketed NLTE model-atmospheres were required – but not available.

In Sect. 2 we describe briefly our NLTE model-atmosphere code *TMAP*, which has been developed over the last two decades and has been successfully used for the analysis of hot, compact stars. Such analyses have continuously provided constraints for evolutionary theory and, vice versa, predictions from evolutionary calculations have inspired us to search for lines of unidentified species in UV spectra (e.g. Werner et al., 2004, 2005, 2007a,b, for Ne VII, F VI, Ar VII, and Ne VIII, respectively) provided by the HST and the Far Ultraviolet Spectroscopic Explorer (FUSE). The synergy effect of both satellites gave us

the opportunity to precisely analyze strategic lines from the complete UV range (from the H I Lyman edge to the optical) and to determine photospheric properties with hitherto unprecedented accuracy. In Sect. 3 and 4, we give representative examples for our analyses of H-deficient and H-normal post-AGB stars.

2 NLTE MODEL ATMOSPHERES

We use *TMAP*¹, the Tübingen NLTE Model Atmosphere Package (Werner, 1986; Werner et al, 2003; Rauch & Deetjen, 2003), for the calculation of plane-parallel, chemically homogeneous models in hydrostatic and radiative equilibrium. *TMAP* considers all elements from H to Ni (Rauch, 1997, 2003). In the analysis of LS V +46°21 (Sect. 4), e.g., 686 levels are treated in NLTE, combined with 2417 individual lines and about 9 million iron-group lines.

3 SPECTROSCOPY OF PG 1159 STARS

PG 1159 stars are so-called “born-again post-AGB stars” (Iben et al., 1983), i.e. after their departure from the asymptotic giant branch (AGB) and at already declining luminosity, they experienced a (very) late thermal pulse (He-shell flash) and returned to the AGB. During the born-again phase, the entire H-rich envelope ($10^{-4} M_{\odot}$) was convectively mixed (Herwig et al., 1999; Althaus et al., 2005) with the intershell material ($10^{-2} M_{\odot}$, located between He- and H-burning shells) and H is completely burned. The direct view on intershell matter (at the surface now) allows to conclude on details of nuclear and mixing processes in AGB stars. This is an important test for stellar evolutionary models (cf. Werner & Herwig, 2006).

Our analyses of PG 1159 stars revealed that their abundances of He, C, N, O, Ne, Mg, F, Si, and Ar are in line with predictions from evolutionary models. These models show also a Fe depletion due to n-captures within the s-process. In three observations of PG 1159 stars with FUSE, no iron lines are detectable which gives a surprisingly large Fe-deficiency of 1 – 2 dex (Miksa et al., 2002). An inspection of STIS observations of the same objects (e.g. Jahn et al., 2007) shows that there is no increase of the Ni abundance and thus, it appears likely that the s-process has converted even Ni into trans iron-group elements. However, we do not have reliable atomic data to prove this. Other elements show deviations from theory, e.g. P appears roughly solar but the models predict a strong enhancement while S is expected to stay solar but shows large depletion (up to 2 dex). For a detailed review, see Werner & Herwig (2006).

¹ <http://astro.uni-tuebingen.de/~rauch/TMAP/TMAP.html>

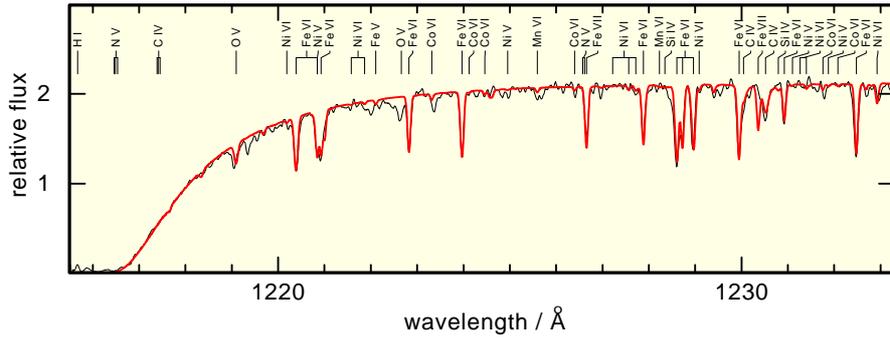


Fig. 1. Section of the STIS observation of LS V +46°21 compared to our final model. Identified lines are marked at the top.

4 SPECTROSCOPY OF LS V +46°21

LS V +46°21 is the central star of the closest known ($d = 130$ pc, $\varnothing = 1.6^\circ$) planetary nebula Sh 2–216. We have observed LS V +46°21 with STIS (5.5 ksec in 2000). The STIS observation shows more than 1000 absorption features (about 10% interstellar). 95% of these are identified. We have calculated the most detailed *TMAP* model-atmosphere ever (Rauch et al., 2007) in order to reproduce the observed spectrum (an example is shown in Fig.1). In the STIS observation, we identified Si v lines (cf. Jahn et al., 2007), Mg iv lines (for the 1st time in a post-AGB star), and Ar vi lines (for the 1st time in any star). Most of the determined abundances are in agreement with diffusion-model predictions (Chayer et al., 1995).

5 TMAP IN THE VIRTUAL OBSERVATORY

The HST with its UV spectroscopic capabilities has been crucial for these analyses and the development of *TMAP*. Hopefully, the Cosmic Origins Spectrograph (COS) will continue the work of its very successful precursors. The comparison of our synthetic spectra with the observations of hot, compact stars convinced us that theory works well and we have arrived at a high level of sophistication.

The spectral analysis, although to be done with sufficient care, has not to remain the field of specialists. Within the framework of *German Astrophysical Virtual Observatory* (GAVO, please note that the URLs given below will change to the GAVO portal² later) project, we provide grids of model-atmosphere fluxes (*TMAF*³) as well as a WWW interface (*TMAW*⁴) to calcu-

² <http://www.g-vo.org/portal/>

³ <http://astro.uni-tuebingen.de/~rauch/TMAF/TMAF.html>

⁴ <http://astro.uni-tuebingen.de/~TMAW/TMAW.shtml>

late individual *TMAP* model atmospheres without detailed knowledge about theory etc.

Since the reliability of synthetic spectra is strongly dependent on the accuracy of the atomic data which is used for their calculation, standard *TMAW* calculations use predefined model atoms which are provided within the Tübingen Model-Atom Database *TMAD*⁵.

While the use of the *TMAF* flux grids is the easiest way for a user of the Virtual Observatory, even individual analyses can easily be performed with appropriately adjusted model atoms.

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⁵ <http://astro.uni-tuebingen.de/~rauch/TMAD/TMAD.html>