HST and FUSE Spectroscopy of the DAO-type Central Star LS V+4621

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Abstract. The DAO-type white dwarf LS V+4621 is the hydrogen-rich central star of the possible planetary nebula Sh 2-216. We have taken high-resolution, high-S/N ultraviolet spectra with STIS aboard the HST and FUSE in order to constrain its photospheric parameters. A detailed spectral analysis by means of state-of-the-art NLTE model-atmosphere techniques is presented which includes the determination the individual abundances of iron-group elements.

1. A brief history of Sh 2-216 and LS V+4621

Sharpless 2-216 (Sh 2-216) has been discovered as a “curious emission-line nebula” [Fesen, Blair, & Gull 1981]. At a distance of \( d = 130 \) pc [Harris et al. 1997], it is the closest possible planetary nebula (PN) known with an apparent diameter of 100'. Sh 2-216 has experienced a mild interaction with the interstellar medium (ISM; Tweedy, Martos, & Noriega-Crespo 1995). From its distance and proper motion, Kerber et al. (2004) have determined that it has a thin-disk orbit of low inclination and eccentricity.

LS V+4621 has been identified as the exciting star of Sh 2-216 by proper motion measurements [Cudworth & Reynolds 1985]. Tweedy & Napiwotzki (1992) have demonstrated that LS V+4621, which is the brightest (\( m_V = 12.67 \)) DAO white dwarf (WD 0439+466) known, has the properties (\( T_{\text{eff}} = 90 \) kK, \( \log g = 7 \) (cgs), He/H = 0.01 by number) to ionize the surrounding nebula.

2. On the Balmer-line problem in LS V+4621

Napiwotzki (1992, 1993), Napiwotzki & Schönberner (1993), and Napiwotzki & Rauch (1994) have reported that a problem (BLP) exists to reproduce lines of the Balmer series (with NLTE model atmospheres) simultaneously at a given \( T_{\text{eff}} \) in hot DA white dwarfs. Bergeron et al. (1993) found (in LTE calculations for DAO WDs) that the BLP is reduced by the consideration of metal-line blanketing, and Bergeron et al. (1994) could show clearly that the presence of heavy metals is the source of the BLP – in other words, pure hydrogen models are not well suited for the spectral analysis of hot DA WDs in general.
Werner (1996) calculated NLTE model atmospheres for LS V+46 21 based on parameters of Tweedy & Napiwotzki (1992) and introduced C, N, and O (at solar abundances) in addition. Surface cooling by these metals as well as the detailed consideration of the Stark line broadening in the model-atmosphere calculation has the effect that the BLP almost vanishes in LS V+46 21. Later, Kruk & Werner (1998) could demonstrate that these model atmospheres reproduce well HUT (Hopkins Ultraviolet Telescope) observations of LS V+46 21 within 912 – 1840 Å at $T_{\text{eff}} = 85$ kK and $\log g = 6.9$.

3. UV observations

Spectral analysis by model-atmosphere techniques needs observations of lines of subsequent ionization stages in order to evaluate the ionization equilibrium (of a particular species) which is a sensitive indicator of $T_{\text{eff}}$. Since stars with $T_{\text{eff}}$ as high as $\approx 90$ kK have their flux maximum in the EUV wavelength range and due to the high degree of ionization, most of the metal lines are found in the UV range. Thus, high-S/N and high-resolution UV spectra are a prerequisite for a precise analysis. Consequently, we employed HST/STIS (Space Telescope Imaging Spectrograph aboard the Hubble Space Telescope) and FUSE (Far Ultraviolet Spectroscopic Explorer) in order to obtain suitable data.

A STIS spectrum (1144 – 1729 Å, exposure time 5.5 ksec, resolution = 0.06 Å) was taken in 2000 and was processed by the standard pipeline data reduction. A FUSE observation (905 – 1195 Å, 67.6 ksec, 0.05 Å) was performed in 2003/2004 and reduced by J.W.K. (Feb 2005).

4. Evolutionary models

For the evolution of LS V+46 21 standard evolutionary models for hydrogen-rich post-AGB stars, e.g. Schönberner (1983) and Blöcker & Schönberner (1990) are appropriate. Recently, new evolutionary calculations for DA WDs with a thin hydrogen envelope have been presented by Althaus et al. (2005). These evolutionary calculations are used to compare with and to determine stellar masses, luminosities, and post-AGB ages (see Ziegler et al. 2007, for details).

5. Spectral analysis

The plane-parallel, static, and chemically homogeneous models used in this analysis are calculated with TMAP, the Tübingen NLTE Model Atmosphere Package (Werner et al. 2003). H+He+C+N+O+Mg+Si are considered with “classical” model atoms (cf. Rauch 2003). For Ca+Sc+Ti+V+Cr+Mn+Fe+Co+Ni individual model atoms are constructed by IRONIC (Rauch & Deetjen 2003), using a statistical approach in order to treat the overwhelmingly large number of atomic levels and line transitions by the introduction of “super-levels” and “super-lines”. In total 531 levels are treated in NLTE, combined with 1761 individual lines and about 9 million iron-group lines, taken from Kurucz (1996) as well as from the OPACITY and IRON projects (Seaton et al. 1994; Hummer et al. 1993).
5.1. The STIS spectrum

The STIS spectrum has a very good S/N (> 50, Fig. 1) and allows to identify about 95% of all spectral features (photospheric as well as interstellar absorptions). We were able to identify some Si v lines (Fig. 1), which allow to use the Si iv/Si v ionization equilibrium (Sect. 3) for our analysis (cf. Jahn et al. 2007). Moreover, we could identify Mg iv lines (Fig. 1) – up to our knowledge – for the first time in these objects (cf. Ziegler et al. 2007).

From a detailed comparison of H i Ly α with the observation, we determined \( N_{\text{HI}} = 8.5 \pm 0.1 \cdot 10^{19} \text{ cm}^{-2} \). Given this value, the Galactic reddening law of Groenewegen & Lamers (1989) yields \( E_{\text{B} - \text{V}} = 0.021 \). We achieve the best match to the continuum slope with \( E_{\text{B} - \text{V}} = 0.065 \pm 0.04 \). This is in agreement with the result of \( E_{\text{B} - \text{V}} = 0.1 \) that Kruk & Werner (1998) derived from the anal-
ysis of a HUT spectrum. We determined a photospheric radial velocity of \( v_{\text{rad}} = 20.4 \pm 0.4 \, \text{km sec}^{-1} \). This is significantly higher than the values of 11.9 km sec\(^{-1}\) and 11.1 km sec\(^{-1}\) measured from IUE (International Ultraviolet Explorer) spectra by Tweedy & Napiwotzki (1992) and Holberg, Barstow, & Sion (1998), respectively. Such a large difference is possible if the object has not been located in the middle of the IUE aperture (Holberg priv. comm.). The higher \( v_{\text{rad}} \) will have some influence on the calculation of the Galactic orbit of LS V+4621 (Sect. 1.) and hence, investigation on the interaction of Sh 2-216 with the ISM.

As an example for the spectral analysis, we have selected a section between 1330 and 1137 Å in order to demonstrate that we can fit Fe \( \text{v} \), Fe \( \text{vi} \), and Fe \( \text{vii} \) lines simultaneously (Fig. 2). Because of the sensitivity of the ionization balance, this allows to determine \( T_{\text{eff}} \) within very small error limits.

5.2. The FUSE spectrum

![Figure 3. FUSE spectrum of LS V+4621 compared with our final model at two different reddenings. For clarity, observation and model fluxes are smoothed with a Gaussian of 1 Å (FWHM).](image)

The FUSE spectrum of LS V+4621 is heavily contaminated by interstellar absorption features (Fig. 3). Our final model fits to the observation at wavelengths < 1090 Å better with a higher reddening (\( E_{B-V} = 0.1 \)). Some of this difference in continuum slope can be explained by the interstellar H\(_2\) opacity, but an increase in the interstellar extinction appears to be necessary.

The analysis of the FUSE spectrum and an investigation on the interstellar absorption is presented in more detail by Ziegler et al. (2007, and these proceedings).

6. Conclusions

From the \( \text{N iv} - \text{N v} \), \( \text{O iv} - \text{O v} \), \( \text{Si iv} - \text{Si v} \), and \( \text{Fe v} - \text{Fe vii} \) ionization equilibria, we were able to determine \( T_{\text{eff}} = 95 \pm 2 \, \text{kK} \) with – for these objects – unprecedented precision. Since this is a prerequisite for reliable abundance
determinations, their error limits (Fig. 4) are also relatively small. The former determined surface gravity of log $g = 6.9$ [Traulsen et al. 2005] has been confirmed.

The derived abundance pattern (Fig. 4) gives evidence for an interplay of gravitational settling (e.g. the He and C abundances are strongly decreased by a factor of $\approx 0.15$) and radiative levitation (iron-group elements show an up to $\approx 6 \times$ solar increased abundance).

In our metal-line blanketed NLTE model atmospheres which include the opacity of 16 species from H to Ni (Sect. 5.), the BLP (Sect. 2) vanishes in the available medium-resolution optical spectra (at $S/N \approx 30$) – now adequate high-resolution and high-$S/N$ optical spectra are desirable in order to investigate if there are still remaining problems.

The reddening of $E_{B-V} = 0.065 \pm 0.04$ towards LS V+4621 is much higher than expected from the Galactic reddening law (Sect. 5.1) possibly because of additional reddening due to dust in the nebula Sh 2-216.

7. Future work

State-of-the-art NLTE spectral analysis has arrived at a high level of sophistication. However, it is hampered by the lack of reliable atomic data for metal lines. We are able to identify/reproduce about 95% of all spectral lines in the STIS spectrum of LS V+4621 and it is likely that unidentified lines (e.g. in Figs. 1) simply stem from the most prominent ions as well, but their wavelengths are not sufficiently well known. E.g. for Fe vii, [Kurucz 1996] provides only 22 laboratory measured (POS) lines and 1952 lines with theoretical line positions (LIN lines). This situation is even worse for other ions (Fe vi: 224 and 58664, respectively) and species. Thus, it should be a challenge for atomic physics to provide properly measured atomic data (also for highly ionized elements) which will then strongly improve future spectral analyses.

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