White Dwarfs as Probes of Fundamental Physics: Tracers of Planetary, Stellar and Galactic Evolution
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What can ISM and non-photospheric highly ionised lines in white dwarf spectra reveal about the β CMa tunnel?

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Abstract. White dwarfs are useful objects with which to study the local interstellar medium (ISM). High ionisation state absorption features that cannot be attributed to the photosphere or the ISM have been observed along the line-of-sight to a number of white dwarf stars. Suggested origins of these lines include ionisation from past supernovae, stellar winds, circumstellar disks, photoionisation from nearby hot stars or also from the white dwarf itself. In this study we consider the origin of these non-photospheric highly ionised lines in two stars towards a rarefied region of the galaxy known as the extended β CMa Tunnel. We present preliminary results from our analysis of the first of these two stars.

Keywords. Interstellar medium, spectroscopy: white dwarfs, atmospheres: white dwarfs

1. Introduction

Space is not empty. Between stars there are many clouds of cool or warm (approx 50-10000 K) gas: the interstellar medium (ISM); those clouds within 10-20 pc of our solar system are typically called the local interstellar medium (LISM). When we observe distant stars with high resolution spectroscopes (R $\sim 10^5$) we must be aware of the potential for that starlight to travel through such ISM clouds and for additional absorption features to be formed by the atoms within.

Our solar system is situated inside a Local Bubble of hot ionised gas (approx 10^6 K) which spans approx 100 pc. The Local Bubble is relatively low density (approx 5×10^{-3} atoms cm^{-3}, Dupin & Gry 1998) and is proposed to have been caused by past supernovae (e.g., Maíz-Apellániz 2001). There is a further patch of rarefied space joining the Local Bubble to another similar bubble, called the β CMa Tunnel (e.g., Lallement *et al.* 2014). It is not known how this tunnel was formed or is maintained, as it does not have the characteristic bubble-like shape caused by a supernova (e.g., Fuchs *et al.* 2006).

Many sight lines have been studied (e.g., Dupin & Gry 1998; Welsh 1991) to determine the extent of the β CMa Tunnel, as shown in Figure 1. However, we have identified two nearby white dwarfs (d = 121 pc and 137 pc respectively) that appear to have very low line-of-sight hydrogen column densities, similar to the tunnel. As they are physically

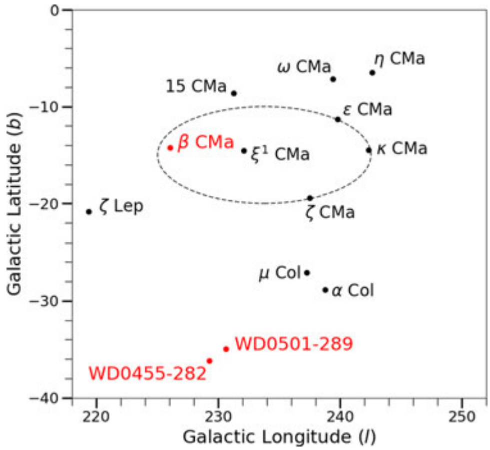

Figure 1. Updated plot of Fig. 1. of Welsh (1991) using data from SIMBAD (Wenger *et al.* 2000) showing sight lines from a study of the β CMa Tunnel. Also included are the positions of the stars in our study.

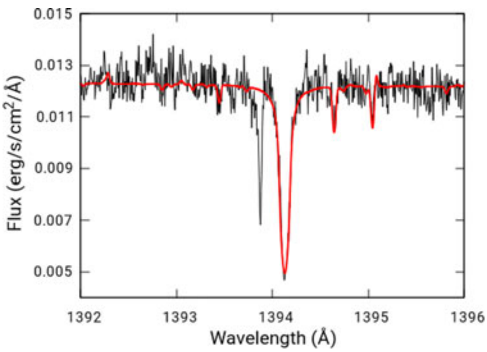

Figure 2. Example of a Si IV absorption profile featuring the photospheric component (modelled as red solid line) and an extra non photospheric but high ionisation state line at $\sim$1393.8 Å.

close together (approx 17 pc), we have a rare opportunity to investigate the effect of their Strömgren spheres. We pose two questions. Are these stars part of an extension of the β CMa Tunnel and are they interacting with it?

The main absorption features we expect to see in the white dwarf spectra are from the photosphere itself. H-rich white dwarfs contain broad hydrogen lines, and if sufficiently hot ($>30{,}000$ K) we would also expect highly ionised photospheric metal lines in the UV spectra. If lines are formed in the photosphere then they will share a similar velocity - the photospheric velocity. However, in spectra of high enough resolution we might also see absorption lines from lower ionisation state metals; these lines originate from ISM clouds that the starlight has traversed, and are low ionisation states because the clouds are far cooler than the stellar photosphere. The ISM metal lines would have a velocity depending on the motion of the ISM cloud, thus not usually a similar velocity to that of the photosphere.

Some high ionisation lines can be present in spectra, which do not appear to originate in the stellar photosphere, as their velocities do not match the photospheric velocity. This is illustrated in Figure 2, showing a photospheric Si IV line (black), with a non-LTE stellar atmospheric model overlaid (red), and a second Si IV feature not accounted for

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by the photospheric model. There are a number of proposed mechanisms for creating these ionised features including ionisation from past supernovae, stellar winds, circumstellar disks, ancient planetary nebulae, photoionisation from nearby hot stars, and photoionisation from the observed star (Strömgren sphere).

2. Overview

We have identified two white dwarfs, WD 0455-282 and WD 0501-289 (see Figure 1) in the vicinity of the known β CMa Tunnel. The focus of this work is WD 0455-282. WD 0455-282 is a Teff $\approx$ 60,000 K, log g $\approx$ 7.90, H-rich white dwarf (e.g., Preval *et al.* 2019). Preval *et al.* (2019) observed WD 0455-282 with the Hubble Space Telescope (HST) using the Space Telescope Imaging Spectrograph (STIS; e.g., Riley *et al.* 2019) in the high resolution grating (R $\approx$ 114,000, see Figure 3). Due to its high temperature we detect highly ionised photospheric metal lines. We also detect lines from low ionisation states which must be due to the ISM, as well as highly ionised non-photospheric absorption lines of unknown origin. We use XSPEC (e.g., Arnaud 1996) for this analysis, specifically the built in Gaussian function GABS, to fit the absorption profiles as this accounts for the saturation of any lines.

Silicon. For the silicon ions we assess the likelihood of them arising from the same cloud. If they do, the ionisation states should have comparable Doppler width, b (km/s), values as this is a property of the cloud's temperature and turbulence. First we analyse the Si IV profiles (bottom middle and right panels of Figure 3). We can see they each have a single component and so we used a single Gaussian in each case. As these lines are a doublet, we also fit them together with the wavelength ratio fixed. Results of our models are given in rows 2-3 and 4 of Table 1, respectively. An issue with modelling the Si III profile (bottom left panel in Figure 3) is that it contains many blended components, meaning Gaussian lines need adding to reduce the chi square to an acceptable value. This in turn increases the error; so far a good fit has not been found. Lastly there are two Si II lines available (top middle and right panels of Figure 3). Si II 1260 Å presents a similar issue as the Si III profile. The weaker Si II 1304 Å has only two components in its profile, however the error found for this fit is nearly 100% (row 1 of Table 1). On inspection we found in our models that the continuum is not flat as should be expected. Following discussion with the XSPEC code author, we believe this to be a systematic error, and are taking steps to correct this before using the code further. Overall we cannot draw conclusions from these results, as the errors in some cases are too high.

Carbon. Due to the continuum issues we can only discuss the other results qualitatively. Take for example the C II 1334 Å profile (top left panel in Figure 3) which visibly appears to contain over four Gaussian components. To check this, we modelled the profile with increasing numbers of Gaussian features until a reduced chi square close to unity was obtained. First, one Gaussian absorption per side of the profile was used, which, as expected, did not fit well visibly or give a good reduced chi square value. Using two Gaussian features per side improves the fit, as has been suggested by others (e.g., Preval *et al.* 2019). However, the reduced chi square value using a fit of four Gaussian features in total is still not close to unity. Adding a fifth component to the red-shifted side yields a good reduced chi squared value.

Other elements. We can also take the velocities measured for all the ISM lines (Si II, O I, N I) and see if any of the projected velocities of LISM clouds match the values. The LISM models of Redfield & Linsky (2008) suggest that the so called Blue Cloud lies along this sight line. However, the projected velocity of 12.56 ± 1.03 km/s does not match the preliminary velocities measured in this analysis.

Table 1. Measurements of silicon ionisation states presenting the $\sim 25\,\mathrm{km\,s^{-1}}$ component.

Silicon line	Velocity ($\mathrm{km\,s^{-1}}$)	Doppler width ($\mathrm{km\,s^{-1}}$)
Si II 1304	26.05 ± 0.99	2.64 ± 2.04
Si IV 1393	25.63 ± 0.43	3.79 ± 0.67
Si IV 1402	24.82 ± 1.26	4.69 ± 2.91
Si IV doublet[1]	25.28 ± 0.49	4.99 ± 0.94
		5.02 ± 0.95

Notes: [1]Modelling was repeated fixing the wavelength ratio at its known value.

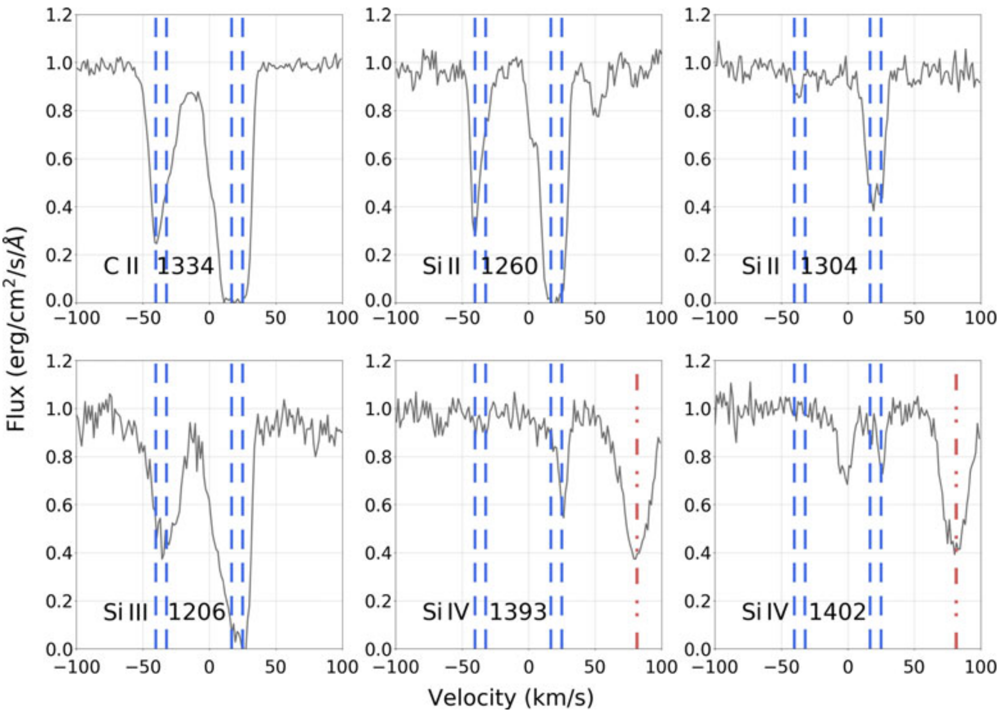

Figure 3. Absorption profiles of the carbon and silicon towards WD 0455-282, shown in velocity space. The photospheric velocity is shown by the vertical red dot-dash line, and the four component velocities reported in Preval *et al.* (2019) are shown in blue dashed lines.

3. Implications

Local space. It is important to understand how ISM along sight lines can influence our stellar spectra. Despite being a rarefied region of space, there could be as many as five non-photospheric components contributing to the absorption profiles seen in WD 0455-282, of which some or all could be due to intervening ISM clouds. As well as this, we see high ionisation states in the spectra which are not due to the photospheric. This latter point, coupled with the low neutral hydrogen column density towards this star could indicate an extension to the known β CMa Tunnel.

Stellar feedback. Analysis of ISM temperatures and composition is important for understanding how stellar material is fed back into the galaxy. The aim of this analysis is to test mechanisms for producing the components we see in this, and similar, spectra, to understand the existence of the β CMa Tunnel.

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