21st European Workshop on White Dwarfs
Castanheira, Vanderbosch, Montgomery, eds.
July 23–27, 2018, Austin, Texas, USA

High-Precision Atomic Physics Laboratories in Space: White Dwarfs and Subdwarfs

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Abstract

Stellar atmospheres are prime laboratories to determine atomic properties of highly ionized species. Reliable opacities are crucial ingredients for the calculation of stellar atmospheres of white dwarfs and subdwarfs. A detailed investigation on the precision of many iron-group oscillator strengths is still outstanding. To make progress, we used the Hubble Space Telescope Imaging Spectrograph to measure high-resolution spectra of three hot subdwarfs that exhibit extremely high iron-group abundances. The predicted relative strengths of the identified lines are compared with the observations to judge the quality of Kurucz's line data and to determine correction factors for abundance determinations of the respective elements.

1 Introduction

"Rubbish in, rubbish out" ultimately describes the results of any astrophysical code, as sophisticated as it may be if the input is inaccurate, rudimental, or approximate. In case of non-local thermodynamical equilibrium (NLTE) stellar atmosphere modeling, the crucial ingredient is the atomic data. Since the occupation numbers of all atomic levels treated in NLTE have to be calculated in detail via the rate equations (Werner & Dreizler, 1999), e.g., reliable transition probabilities are required, not only for those few lines that are identified in an observation but for the complete model atoms that are considered in the model-atmosphere calculations.

Sources for atomic data are beside standard data bases like, e.g., the atomic spectra database[1] of the National Institut for Standards and Technologies (NIST), the extended line lists provided by Kurucz[2] (Kurucz, 1991, 2011) or the Opacity Project[3] (Seaton et al., 1994). These databases, however, are far from being complete.

When Werner et al. (2012b) newly discovered lines of ten trans-iron elements, namely Ga, Ge, As, Se, Kr, Mo, Sn, Te, I, and Xe in the far-ultraviolet spectrum of the hot, helium-rich, DO-type white dwarf RE 0503−289 (effective temperature $T_{\rm eff} = 70\,000 \pm 2000\,{\rm K}$, surface gravity $\log\,(g\,/\,{\rm cm\,s^{-2}}) = 7.5 \pm 0.1$, Rauch et al., 2016b), it was only possible to measure the Kr and Xe abundances because oscillators strengths for the ionization stages VI - VII were only available for these species. This initiated a campaign to calculate transition probabilities and oscillators strengths for trans-iron elements (Table 1). The newly calculated data is provided by our Tübingen Oscillator Strengths Service (TOSS).

So far, the quality of the oscillator strengths of the elements with atomic numbers $Z \geq 20$ is only evaluated in part, e.g., for Sc III - VIII (Massacrier & Artru, 2012), Xe VI (Rauch et al., 2015b), and Mo V-VI (Rauch et al., 2016a). A critical evaluation of lines of the iron-group (IG, namely Ca - Ni) elements ist still outstanding. To make progress, we use high-resolution and high signal-to-noise (S/N) ultraviolet (UV) spectra of two super metal-rich sd(O)B-type stars (Edelmann, 2003), namely EC 11481−2303 and PG 0909+276 (Wild & Jeffery, 2017), and of the He-sdO Feige 110 (Rauch et al., 2014b) which is a primary flux standard of the *Hubble Space Telescope* (*HST*). The difference of about 18 000 K in $T_{\rm eff}$ between these stars (Table 2) allows us to investigate on ionization stages III-VI of the iron-group elements.

Although UV spectra obtained with the *International Ultraviolet Explorer* (*IUE*) and the *Far Ultraviolet Spectroscopic Explorer* (*FUSE*) of these stars are available, their low S/N and insufficient resolution as well as the high number of IG lines and the strong contamination by interstellar line absorption hampers the identifica-

[1] `https://www.nist.gov/pml/atomic-spectra-database`
[2] `http://kurucz.harvard.edu/atoms.html`
[3] `http://cdsweb.u-strasbg.fr/topbase/TheOP.html`

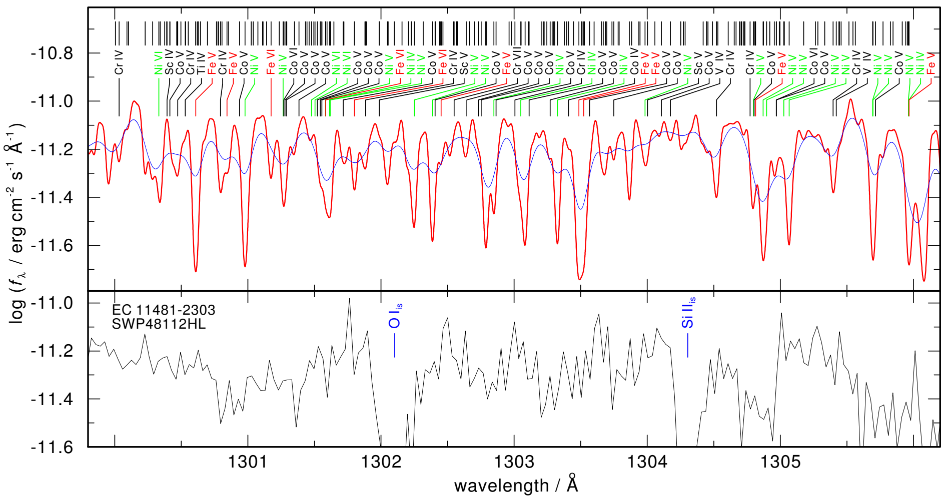

Figure 1: *Top panel*: Theoretical spectra for EC 11481−2303 calculated with Kurucz's so-called POS lines (observed, POSitively identified, Kurucz, 2011) in a small wavelength interval close to the maximum sensitivity of *STIS* with E140M convolved with Gaussians to match the resolving power of *STIS* ($R = \lambda/\Delta\lambda = 45\,800$; red, thick line) and *IUE* ($R = 10\,000$; blue, thin). The marks indicate all POS lines, those with $\log gf$ values ≥ 0.01 are identified; *Bottom*: High-resolution *IUE* observation (SWP 48112 HL), "is" denotes interstellar lines. The poor S/N hampers line identifications.

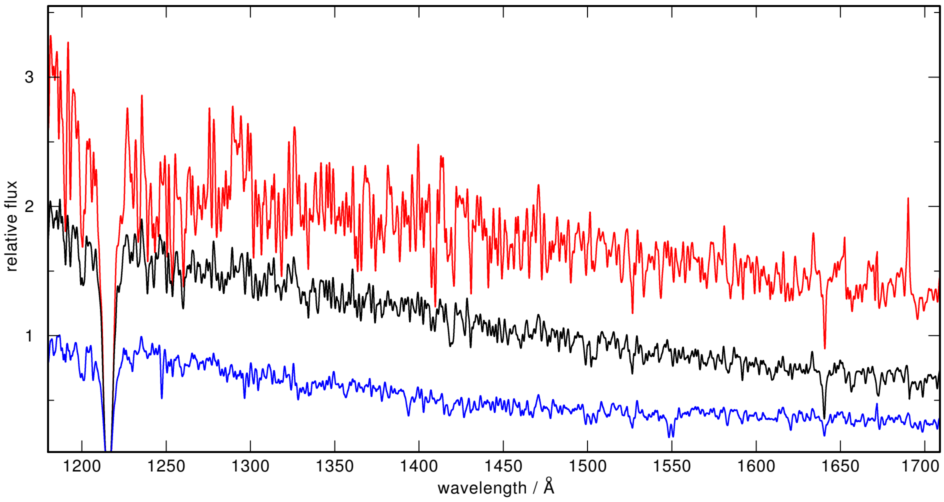

Figure 2: *STIS* spectra of EC 11481−2303 (red), Feige 110 (black), and PG 0909+276 (blue), smoothed with a Gaussian of 1 Å (FWHM) and shifted for clarity. Ly α1215 Å and He II λ1640 Å are prominent, besides presumably thousands of IG lines.

tion of isolated IG lines (Figure 1). Therefore we used the *Space Telescope Imaging Spectrograph* (*STIS*) aboard *HST* in the wavelength range of 1140−1709 Å to obtain high-resolution spectra (grating E140M) with an S/N of about 30−50 that is necessary for our purpose. The three spectra are shown in Figure 2, each one is expected to feature ≥ 2000 IG absorption lines.

2 Spectral analysis and preliminary results

To calculate synthetic spectra for our three programme stars, we employ the *Tübingen Model-Atmosphere Package* (TMAP, Werner et al., 2012a; Rauch & Deetjen, 2003) that can calculate plane-parallel NLTE model atmospheres in radiative and hydrostatic equilibrium. NLTE modeling is mandatory due to the high T_{eff} of our stars (Table 2).

Unlike few thousands of lines from light metals, the IG elements have of hundreds of thousands of levels and hundreds of millions of lines. The reason for the rapid increase in line number is the electron configuration of the IG elements, where the 3d and 4s shells are partly filled. To include all lines but still not to exceed the maximum number of NLTE levels (that *TMAP* is capable to consider), a statistical approach using the *Iron Opacity and Interface Code* (*IrOnIc* Rauch & Deetjen, 2003) combines all atomic levels of an ion to

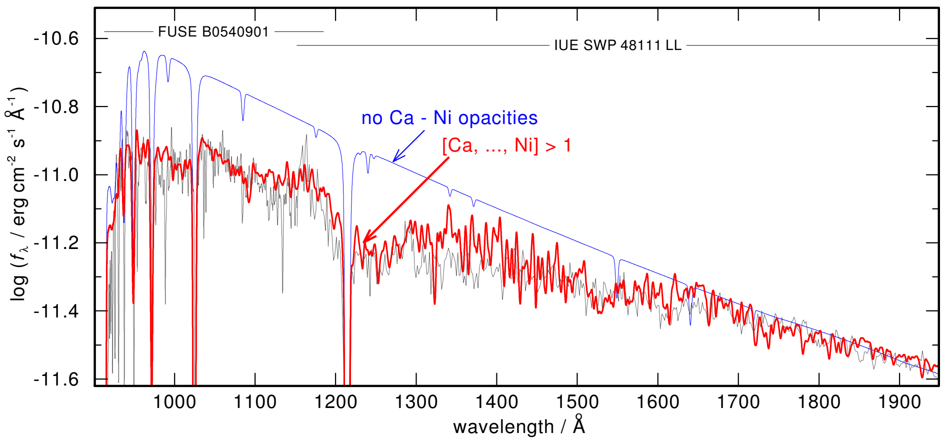

Figure 3: Observed UV spectrum of EC 11481−2303 compared with a model considering HHeCNO (blue) and HHeCNO+IG elements with IG abundances $\geq 10\times$ solar abundances (red, Ringat & Rauch, 2012)

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Table 1: Recently calculated transition probabilities.

Element	Ions	Reference
Zn	IV - V	Rauch et al. (2014a)
Ga	IV - VI	Rauch et al. (2015a)
Ge	V - VI	Rauch et al. (2012)
Se	V	Rauch et al. (2017b)
Kr	IV - VII	Rauch et al. (2016b)
Sr	IV - VII	Rauch et al. (2017b)
Zr	IV - VII	Rauch et al. (2017a)
Tc	II - VI	Werner et al. (2015)
Mo	IV - VII	Rauch et al. (2016a)
Te	VI	Rauch et al. (2017b)
I	VI	Rauch et al. (2017b)
Xe	IV - VII	Rauch et al. (2015b, 2017a)
Ba	V - VII	Rauch et al. (2014c)

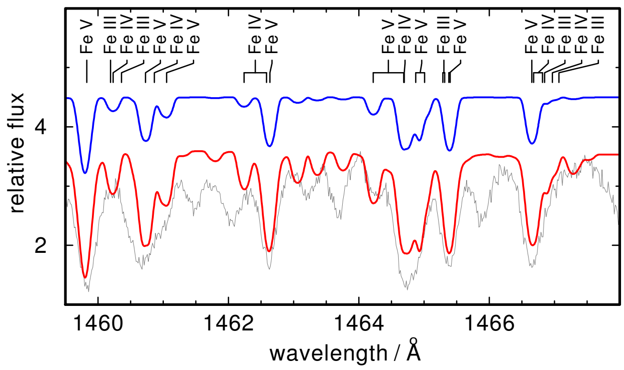

Figure 4: Part of the *STIS* spectrum of EC 11481−2303 (grey), compared with a HHeCNOFe *TMAP* spectrum (red). The blue line shows Fe lines only, with identification marks at top. The synthetic spectra are convolved with a rotational profile ($v_{\rm rot} = 25\,{\rm km/s}$) and a Gaussian (FWHM of 0.05 Å) to account for *STIS*'s resolution.

(typically) seven superlevels and the respective lines to superlines. This strongly reduces the number of NLTE levels. *IrOnIc* uses Kurucz's line lists as an input, considering so-called LIN and POS lines. While POS lines have been measured experimentally and can be used for line identification, the LIN lines include quantum mechanically calculated lines in addition and are used for model-atmosphere calculations only.

The element abundances of EC 11481-2303 have already been determined by Ringat & Rauch (2012), but with the new high-resolution *STIS* spectrum, we are able to precisely adjust these abundances. We calculated individual atmosphere models for each IG element. Each model consists of the elements HHeCNO, and in addition one IG element. The abundances that we determined confirm the results of Ringat & Rauch (2012), showing very low C and O abundances, and remarkably high Fe, Co, and Ni abundances of $\approx 10 - 1000\times$ the solar values (Table 3). Although we still can find only upper limits for some elements, other elements clearly show hundreds of absorption lines. It seems that Fe, Co, and Ni are primarily responsible for the depressed UV flux, and therefore can be used to model the spectrum very well. In Figure 4, we show a part the of EC 11481−2303 spectrum compared with a *TMAP* spectrum. Most of the Fe lines fit the spectrum well, while the gaps will probably be filled by the other IG elements.

Our analysis is still ongoing. However, with the high-quality spectra of *STIS*, we will be able to identify line per line, element per element, and we will provide a correction table for the oscillator strengths of the IG elements to improve model-atmosphere calculations and abundance analyses.

Table 2: Parameters of our three program stars.

	T_{eff} / K	$\log(g\,/\,\mathrm{g/cm^2})$	He/H mass ratio	distance / pc[d]
EC 11481−2303[a]	55 000±5 000	5.8±0.3	0.01±0.01	291±7
Feige 110[b]	47 250±2 000	6.0±0.2	0.11±0.05	268±6
PG 0909+276[c]	37 290± 640	6.1±0.2	0.87±0.04	267±8

[a] Ringat & Rauch (2012). [b] Rauch et al. (2014b). [c] Wild & Jeffery (2017).
[d] calculated with parallaxes from Gaia DR2 (`https://gea.esac.esa.int/archive`).

Table 3: Photospheric abundances of EC 11481−2303. [X] denotes $\log(\mathrm{abundance/solar\ abundance})$ of element X. The abundance uncertainty is ± 0.2 dex.

Element	Mass Fraction	[X]
H	9.45×10^{-1}	0.11
He	9.38×10^{-3}	−1.42
C	$< 4.64 \times 10^{-8}$	< -4.71
N	4.40×10^{-4}	−0.20
O	$< 5.60 \times 10^{-6}$	< -3.01
Ca	$< 2.78 \times 10^{-2}$	< 2.66
Sc	$< 2.65 \times 10^{-3}$	< 4.75
Ti	$< 5.62 \times 10^{-3}$	< 3.28
V	$< 2.50 \times 10^{-3}$	< 3.94
Cr	5.09×10^{-3}	2.51
Mn	1.84×10^{-4}	1.24
Fe	4.52×10^{-2}	1.57
Co	6.91×10^{-3}	3.28
Ni	2.81×10^{-2}	2.62

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Acknowledgements

AL is supported by the German Aerospace Center (DLR, grant 50 OR 1704) and LL by the German Research Foundation (DFG, grant WE 1312/49-1) and by the Studentship Programme of the European Southern Observatory. Financial support from the Belgian FRS-FNRS is also acknowledged. PQ is research director of this organization. The TOSS (`http://astro-uni-tuebingen.de/~TOSS`) service was constructed as part of the Tübingen project of the German Astrophysical Virtual Observatory (GAVO, `http://www.g-vo.org`). This research has made use of NASA's Astrophysics Data System and the SIMBAD database, operated at CDS, Strasbourg, France.