Heavy-Metal Abundances in DO-Type White Dwarfs

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Abstract. Spectral lines of a variety of trans-iron elements were identified in high-resolution ultraviolet spectra of DO-type white dwarfs. Abundance determinations by means of non-local thermodynamic equilibrium stellar-atmosphere techniques have shown that, without exception, their abundances are unexpectedly strong supersolar, much higher than predicted by asymptotic-giant-branch nucleosynthesis calculations. We present our analyses and discuss the photospheric trans-iron element prominence.

1. Introduction

Hydrogen-deficient stars are a rosetta stone to understand stellar post-asymptotic giant branch (post-AGB) evolution. They experienced a final thermal pulse (FTP), either still on the AGB or directly after their descent from the AGB or only after they already entered the white-dwarf cooling sequence when their nuclear burning had completely ceased. In this so-called born-again star scenario, the stars are powered by their re-ignited helium-burning shell and evolve back to the AGB. A pulse-driven convection zone (Fig. 1), that is established during the TP brings intershell material (He-rich, formerly between H- and He-burning shell) to the stellar surface and, thus, the stars exhibit it in their emergent spectrum. A spectral analysis of such stars establishes invaluable constraints to AGB nucleosynthesis models and, thus, to stellar evolutionary theory.

In 2011, a H-deficient star, namely the DO-type white dwarf (WD) RE 0503−289 has been chosen by Ringat & Rauch as archetype for their Tübingen EUV Absorption (TEUV) tool in the framework of a German Astropyhsical Virtual Observatory (GAVO[1]) project performed at Tübingen. RE 0503−289 was discovered in 1993 in the ROSAT EUV bright source survey and, thus, scored high attention because almost no interstellar absorption contaminated its spectrum (e.g., Rauch et al. 2016b). In the course of a spectral analysis of far-ultraviolet (UV) observations, lines of ten trans-iron

[1]`http://g-vo.org`

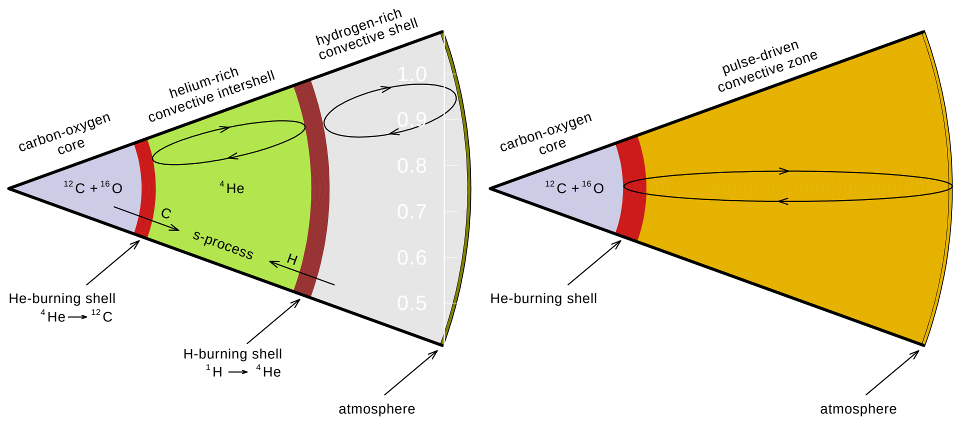

Figure 1. *Left:* Inner structure of an AGB star. *Right:* Inner structure of a VLTP star during the TP. Convection zones are indicated.

elements (TIEs), namely Ga, Ge, Kr, As, Se, Mo, Sn, Te, I, and Xe, were identified by comparison to data in the NIST[2] and Kelly[3] databases. These included the most prominent lines of these TIEs with laboratory measured wavelengths (Werner et al. 2012).

For RE 0503−289 (effective temperature $T_{\mathrm{eff}} = 70\,000 \pm 2000\,\mathrm{K}$, surface gravity $\log(g\,/\,\mathrm{cm/s^2}) = 7.5 \pm 0.1$, Rauch et al. 2016b), a spectral analysis based on non-local thermodynamic equilibrium (NLTE) model-atmosphere techniques is mandatory. For NLTE modeling, reliable transition probabilities are required, not only for those prominent lines that were identified in the observation but for the complete model atoms which are used in the model-atmosphere calculations.

Although Werner et al. (2012) used the Tübingen Model-Atmosphere Package, a state-of-the-art NLTE code (Werner et al. 2003; Rauch & Deetjen 2003; Werner et al. 2012), to calculate plane-parallel atmospheres in hydrostatic and radiative equilibrium, an abundance analysis was hampered because they had only sufficient atomic data for Kr and Xe available and determined abundances of -4.3 ± 0.5 and -4.2 ± 0.6 (logarithmic mass fractions, about 2.7 and 3.6 dex oversolar), respectively (Fig. 2).

2. Atomic Data

The discovery of TIE lines in the spectrum of RE 0503−289 (Werner et al. 2012) and the lack of adequate atomic data initiated a campaign to calculate transition probabilities and oscillator strengths (Table 1). The Tübingen Oscillator Strengths Service (TOSS) was constructed as part of the activities of GAVO to provide easy access to weighted oscillator strengths and transition probabilities. With the newly calculated data, abundance determinations for all TIEs with hitherto identified lines became possible (Fig. 2). Their extreme overabundances are the result of radiative levitation (Rauch et al. 2016a). The complete spectrum of RE 0503−289 (cf., Hoyer et al. 2017) is shown via the GAVO

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[2] `http://www.nist.gov/pml/data/asd.cfm`

[3] `http://www.cfa.harvard.edu/ampcgi/kelly.pl`

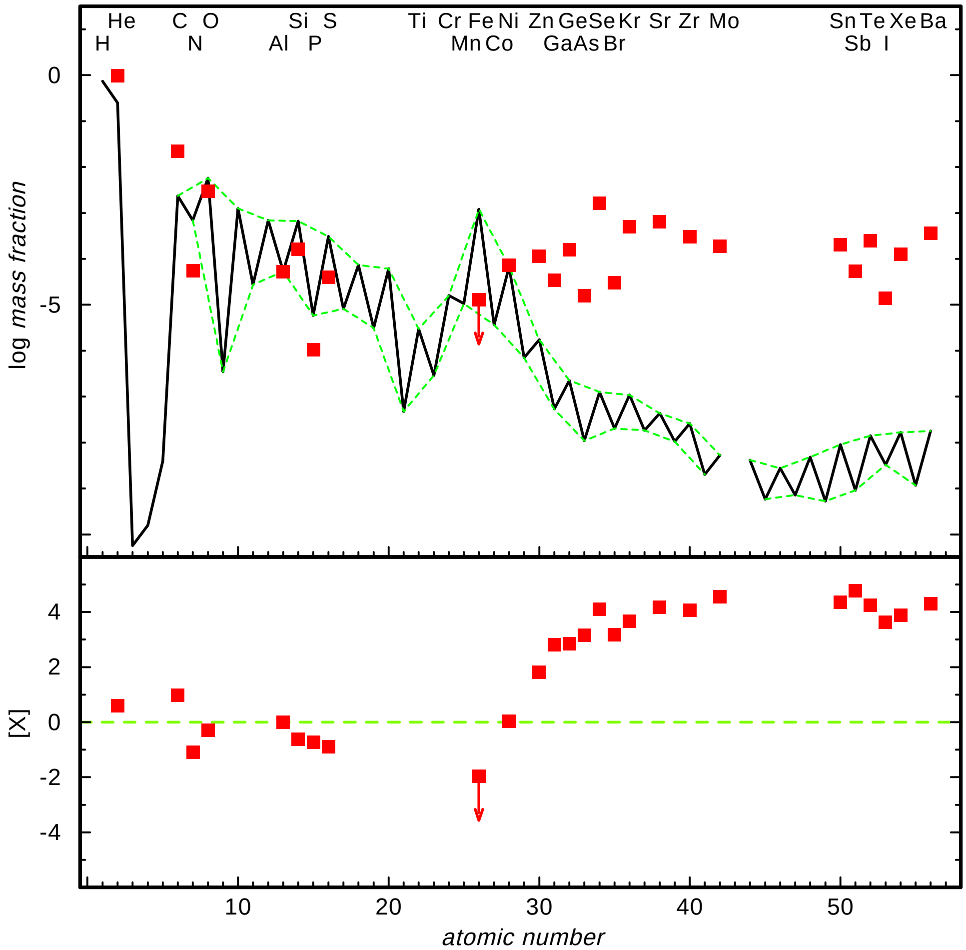

Figure 2. Solar abundances (Asplund et al. 2009; Scott et al. 2015b,a; Grevesse et al. 2015, thick line; the dashed lines connect the elements with even and with odd atomic number) compared with photospheric abundances of RE 0503−289 (Dreizler & Werner 1996; Rauch et al. 2012, 2014a,b, 2015a,b, 2016a,b; Werner et al. 2018). The abundance uncertainty is about 0.2 dex in general. The arrows indicate upper limits. Top panel: Abundances given as logarithmic mass fractions. Bottom panel: Abundance ratios to respective solar values, [X] denotes log (fraction / solar fraction) of species X. The dashed, green line indicates solar abundances.

Tübingen VISualization Tool (TVIS, `http://astro.uni-tuebingen.de/~TVIS/objects/RE0503-289`).

3. Is RE 0503−289 a unique object?

Rauch et al. (2016a) performed diffusion calculations to demonstrate that the extreme TIE overabundances in RE 0503−289 are the result of efficient radiative levitation. We observed three related objects close to the location of RE 0503−289 in the $\log T_{\rm eff}$ – $\log g$ plane (Fig. 3), namely PG 0109+111, PG 1707+427, and WD 0111+002. While

Table 1. Ions with recently calculated oscillator strengths.

Atom	Ions	Reference
Zn	IV - V	Rauch et al. (2014a)
Ga	IV - VI	Rauch et al. (2015b)
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)
Mo	IV - VII	Rauch et al. (2016a)
Te	VI	Rauch et al. (2017b)
I	VI	Rauch et al. (2017b)
Xe	IV - V, VII	Rauch et al. (2015a, 2017a)
Ba	V - VII	Rauch et al. (2014b)

RE 0503−289 is located directly on the so-called PG 1159 wind limit (dashed line in Fig. 3, calculated with $\dot{M} = 1.29 \times 10^{-15} L^{1.86}$ from Bloecker 1995; Pauldrach et al. 1988). PG 1707+427 lies towards higher $T_{\rm eff}$ and PG 0109+111 and WD 0111+002 towards higher $\log g$ even right of the full line that indicates where the photospheric carbon abundance is reduced by a factor of 0.1 by gravitational settling (cf., Unglaub & Bues 2000).

The detailed spectral analysis presented by Hoyer et al. (2018, based on HST/COS UV spectra) shows equally strong TIE abundance enhancements for PG 0109+111 and WD 0111+002 (Fig. 4) and, thus, the TIE abundance enhancement due to radiative levitation is most likely a common phenomenon. In contrast, no TIE line has been identified in the spectrum of PG 1707+427. Probably the stellar wind is still too strong in this star and prevents efficient diffusion.

4. Conclusions and remarks

TIE abundance determinations are crucial indicators for AGB nucleosynthesis, establishing constraints on the slow neutron-capture (s-) process. In objects close to the PG 1159 wind limit, radiative levitation wipes out any information about AGB abundances and are, thus, useless to investigate on AGB yields of TIEs. Much better suited for this purpose are objects with a stellar wind strong enough to continuously bring post-FTP intershell matter to the stellar surface (like in the case of PG 1707+427). The predicted TIE abundances are then of the order of one dex above the solar values (Karakas & Lugaro 2016). To measure these, much better UV spectra with signal-to-noise ratios above 300 are required.

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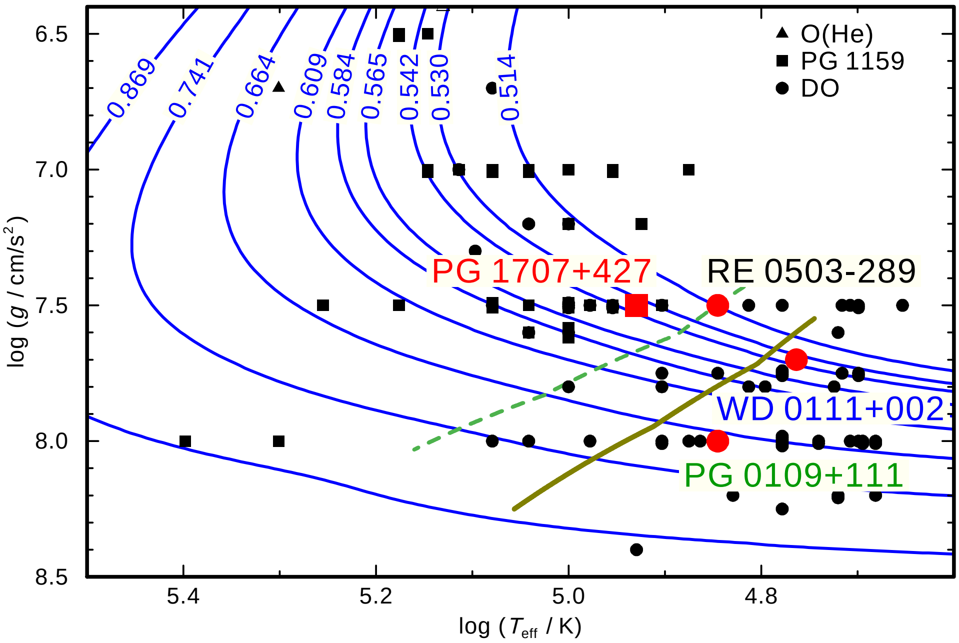

Figure 3. Location of RE 0503–289 and related objects in the $\log T_{\rm eff}$ – $\log g$ plane. Evolutionary tracks for H-deficient WDs (Althaus et al. 2009) labeled with their respective masses in $M_{\odot}$ are plotted for comparison. Transition limits predicted by Unglaub & Bues (2000) are indicated (see text for details).

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References

Althaus, L. G., Panei, J. A., Miller Bertolami, M. M., García-Berro, E., Córsico, A. H., Romero, A. D., Kepler, S. O., & Rohrmann, R. D. 2009, ApJ, 704, 1605. `ArXiv\e-prints:0909.2689`

Asplund, M., Grevesse, N., Sauval, A. J., & Scott, P. 2009, ARA&A, 47, 481. `ArXiv\e-prints:0909.0948`

Bloecker, T. 1995, A&A, 299, 755

Dreizler, S., & Werner, K. 1996, A&A, 314, 217

Grevesse, N., Scott, P., Asplund, M., & Sauval, A. J. 2015, A&A, 573, A27. `ArXiv\e-prints:1405.0288`

Hoyer, D., Rauch, T., Werner, K., & Kruk, J. W. 2018, A&A, 612, A62. `ArXiv\e-prints:1801.02414`

Hoyer, D., Rauch, T., Werner, K., Kruk, J. W., & Quinet, P. 2017, A&A, 598, A135. `ArXiv\e-prints:1610.09177`

Karakas, A. I., & Lugaro, M. 2016, ApJ, 825, 26

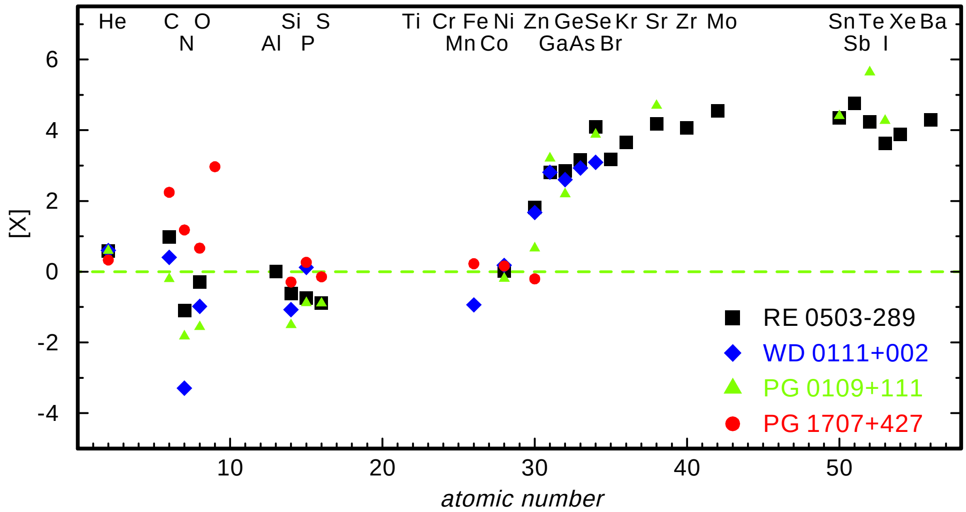

Figure 4. Photospheric abundances of RE 0503−289 and three related objects. The dashed horizontal line indicates solar abundances.

Pauldrach, A., Puls, J., Kudritzki, R. P., Mendez, R. H., & Heap, S. R. 1988, A&A, 207, 123
Rauch, T., & Deetjen, J. L. 2003, in Stellar Atmosphere Modeling, edited by I. Hubeny, D. Mihalas, & K. Werner, vol. 288 of Astronomical Society of the Pacific Conference Series, 103. `ArXiv\e-prints:0403.239`
Rauch, T., Gamrath, S., Quinet, P., Löbling, L., Hoyer, D., Werner, K., Kruk, J. W., & Demleitner, M. 2017a, A&A, 599, A142. `ArXiv\e-prints:1611.07364`
Rauch, T., Hoyer, D., Quinet, P., Gallardo, M., & Raineri, M. 2015a, A&A, 577, A88. `ArXiv\e-prints:1504.01991`
Rauch, T., Quinet, P., Hoyer, D., Werner, K., Demleitner, M., & Kruk, J. W. 2016a, A&A, 587, A39. `ArXiv\e-prints:1512.07525`
Rauch, T., Quinet, P., Hoyer, D., Werner, K., Richter, P., Kruk, J. W., & Demleitner, M. 2016b, A&A, 590, A128. `ArXiv\e-prints:1603.00701`
Rauch, T., Quinet, P., Knörzer, M., Hoyer, D., Werner, K., Kruk, J. W., & Demleitner, M. 2017b, A&A, 606, A105. `ArXiv\e-prints:1706.09215`
Rauch, T., Werner, K., Biémont, É., Quinet, P., & Kruk, J. W. 2012, A&A, 546, A55. `ArXiv\e-prints:1209.0642`
Rauch, T., Werner, K., Quinet, P., & Kruk, J. W. 2014a, A&A, 564, A41. `ArXiv\e-prints:1403.2183`
— 2014b, A&A, 566, A10. `ArXiv\e-prints:1404.6094`
— 2015b, A&A, 577, A6. `ArXiv\e-prints:1501.07751`
Scott, P., Asplund, M., Grevesse, N., Bergemann, M., & Sauval, A. J. 2015a, A&A, 573, A26. `ArXiv\e-prints:1405.0287`
Scott, P., Grevesse, N., Asplund, M., Sauval, A. J., Lind, K., Takeda, Y., Collet, R., Trampedach, R., & Hayek, W. 2015b, A&A, 573, A25. `ArXiv\e-prints:1405.0279`
Unglaub, K., & Bues, I. 2000, A&A, 359, 1042
Werner, K., Deetjen, J. L., Dreizler, S., Nagel, T., Rauch, T., & Schuh, S. L. 2003, in Stellar Atmosphere Modeling, edited by I. Hubeny, D. Mihalas, & K. Werner, vol. 288 of Astronomical Society of the Pacific Conference Series, 31. `ArXiv\e-prints:0209.535`
Werner, K., Rauch, T., Knörzer, M., & Kruk, J. W. 2018, A&A, 614, A96. `ArXiv\e-prints:1803.04809`
Werner, K., Rauch, T., Ringat, E., & Kruk, J. W. 2012, ApJ, 753, L7