Metal Abundances in Hot DO White Dwarfs: RE 0503–289 and KPD 0005+5106

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Abstract. The relatively high abundance of carbon in the hot DO white dwarf RE 0503–289 indicates that it is a descendant of a PG 1159 star. This is corroborated by the recent detection of the extremely high abundances of trans-Fe elements which stem from s-process nucleosynthesis in the precursor AGB star, dredged up by a late He-shell flash and possibly amplified by radiative levitation. On the other hand, the hottest known DO white dwarf, KPD 0005+5106, cannot have evolved from a PG 1159 star but represents a distinct He-rich evolutionary sequence that possibly originates from a binary white dwarf merger.

1. Trans-Iron Elements in White Dwarfs

The presence of elements beyond the iron group in white dwarfs was first proved by Vennes et al. (2005). They discovered Ge in three hot \( T_{\text{eff}} = 56,000–58,000 \text{ K} \) DA white dwarfs (GD 246, Feige 24, G191–B2B) with roughly solar abundance. Subsequently, Chayer et al. (2005) detected Ge, As, Se, Sn, and I in two cool \( T_{\text{eff}} = 49,500 \text{ K} \) DOs (HD 149499B and HZ 21). The abundances are between 3 and 1000 times solar. As described in detail below, Werner et al. (2012) discovered no less than ten trans-iron elements in the hot DO RE 0503–289. From them, Ga, Kr, Mo, and Xe are newly discovered species in WDs. The abundances of Ge (Rauch et al. 2012), Kr, and Xe range between several 100 and several 1000 solar. In essence, extreme overabundances of trans-iron elements are only seen in DO white dwarfs, in a temperature range of 49,500–70,000 K.

It might be worthwhile to recapitulate that large overabundances (up to 4 dex oversolar) of Ga, Ge, Sr, Y, Zr, Sn, and Pb where found in hot subdwarfs \( T_{\text{eff}} = 22,000–40,000 \text{ K} \); O’Toole 2004; Chayer et al. 2006; O’Toole & Heber 2007; Naslim et al. 2011), although the relevance of this fact in the context of WDs is not immediately obvious.

2. RE 0503–289

RE 0503–289 is a hot DO with \( T_{\text{eff}} = 75,000 \text{ K}, \log g = 7.5 \) (Fig. II Barstow et al. 1994; Dreizler & Werner 1996). It has a rather high C abundance (e.g., Rauch et al. 2012), namely \( \approx 3–5\% \) (mass fraction). This amount is significantly larger than that found in other DOs (<1%) but, on the other hand, much lower than the C abundance seen in PG 1159 stars (13–60%). The ISM column density towards RE 0503–289 is
Figure 1. PG 1159 stars (black small dots) and hot DO white dwarfs (red big dots) in the $g-T_{\text{eff}}$-plane. The positions and error ellipses of RE 0503-289 and KPD 0005+5106 are highlighted. Evolutionary tracks for H-deficient WDs (Althaus et al. 2009) are labeled with the respective stellar mass in solar units. Also shown is one of the theoretical wind limits (Unglaub & Bues 2000) near which PG 1159 stars transform into DOs because gravitational settling overcomes radiation-driven mass loss.

extremely low ($\log n_{\text{H}} = 17.1$; Barstow et al. 1994). This uniquely allows access to the EUV spectrum of a DO white dwarf. A remarkable spectrum was recorded with the EUVE satellite (Vennes et al. 1998). Up to now, it was not possible to fit that spectrum with a model atmosphere flux. It was realized that there are unknown absorbers in the atmosphere which were not included in the models (Werner et al. 2001).

In the years 2000 and 2001, far-UV spectra of RE 0503-289 were observed with FUSE, aiming at the ISM D/H determination along the line of sight. Since then not a single attempt was made to analyze the photospheric spectrum. What prevented us from analysing the FUSE data was the fact that the spectrum is dominated by absorption lines that are not seen in any other WDs and which remained entirely unidentified. Eventually, we realized that they stem from highly-ionized trans-iron group elements as mentioned above (examples are shown in Figs. 2–4).

The most serious problem for the determination of trans-iron element abundances is the lack of atomic data. NLTE modeling is necessary and therefore oscillator strengths
are required not only for the observed line transitions but for the entire set of lines that need to be considered in the model atoms. While for Kr and Xe we could compile atomic data from literature [Werner et al. 2012], new efforts are necessary for the other species. A first step was taken by new quantum mechanical calculations for Ge V and VI that were immediately applied to derive the Ge abundance in RE 0503–289 (Rauch et al. 2012). A further complication for future work is the lack of experimentally derived energy levels so that the line positions are uncertain.

3. KPD 0005+5106

Spectroscopically, KPD 0005+5106 is classified as a hot DO [McCook & Sion 1999]. However, it was shown recently that the temperature of this star ($T_{\text{eff}} = 200,000$ K) is much higher than previously assumed [Werner et al. 2007; Wassermann et al. 2010]. Its location in the $g$–$T_{\text{eff}}$–plane is well before the maximum-temperature “knee”, thus, it is strictly speaking no WD but a He-shell burning post-AGB star. The metal abundances in the He-dominated atmosphere (mass fractions of C, N, O, Ne, Si, S, Ca, Fe) display moderate deviations from solar abundances. They range between 0.7 and 4.3 times solar.
4. Evolutionary Status of the Hottest DO White Dwarfs

Figure 4 displays the location of DO and PG 1159 stars in the $g$–$T_{\text{eff}}$–plane. Also shown is a theoretical PG 1159 wind limit which means that any PG 1159 star that approaches this line during its evolution transforms into a DO WD. This is because gravitational settling of heavy elements overcomes radiation-driven mass-loss in the fading stars. The location of the wind-limit line depends on the assumed mass-loss law and is therefore somewhat uncertain. It is probably intrinsically “fuzzy” because of the metallicity dependence of the mass-loss rate. In any case, no PG 1159 stars is expected below that limiting line, and indeed this is supported by the observations. On the other hand, DO WDs above this line cannot have evolved from PG 1159 stars. This was also concluded by Quirion et al. (2012), who investigated theoretically the red edge of the GW Vir instability strip. GW Vir stars are pulsating PG 1159 stars and it was originally proposed by Quirion et al. (2006) that the red edge is a consequence of gravitational settling the removes the driving agents, mainly C and O, from the stellar envelope. Quirion et al. (2012) emphasize that at any time during the evolution there is no significantly different composition in the driving region and the photosphere, so that the location in the $g$–$T_{\text{eff}}$–plane where PG 1159 stars transform into DOs coincides with the red edge of the GW Vir strip. The wind limits derived by Quirion et al. (2012) are qualitatively similar to those derived by Unglaub & Bues (2000) but, quantitatively different because of diverse assumptions.

RE 0503−289 is located close to the wind limit that is displayed in Fig. 4. This fact, as well as the intermediate carbon abundance, suggests that the star is about to trans-
form from a PG 1159 star into a DO WD (Vennes et al. 1998; Unglaub & Bues 2000). While C is already depleted because of gravitational settling, the trans-iron elements are strongly enhanced by radiative levitation. The reservoir from which the heavy metals are drawn is the former He-rich intershell region, which dominates the envelope composition in PG 1159 stars as the result of a late He-shell flash (e.g. Werner & Herwig 2006) and which can be enriched with s-process elements by 2–3 dex (Gallino, priv. comm; Karakas et al. 2007). This circumstance could explain that hot DAs do not show the extreme overabundances of trans-iron elements. The only disturbing fact is that iron is not detected, suggesting that the abundance must be less than 2.5 dex subsolar (Barstow et al. 2000). This is surprising because we would expect that Fe is also kept in the photosphere with higher abundances due to radiative levitation. The iron abundance in PG 1159 stars is solar (Werner et al. 2011) and diffusion calculations predict roughly solar abundances in a DO like RE 0503–289 (Chayer et al. 1995). Nickel could also pose a problem for the interpretation of the metal abundances. The presence of Ni (0.3 dex oversolar) in HST spectra of RE 0503–289 was claimed (Barstow et al. 2000), however, from today’s view this seems doubtful to us and a reassessment of this question, including FUSE spectra, would be useful.

DOs that have not quite reached the wind limit indicated in Fig. 1 could stem from “milder” PG 1159 stars in a sense, that their C abundance was relatively low. This could result in lower mass-loss rates and hence a shift of the wind limit towards lower gravities. One example could be the DO PG 0108+101 (Teff = 95,000 K, log g = 7.5) which has a C abundance similar to RE 0503–289 (3%, Dreizler 1999). It would be interesting to know whether this WD also exhibits large amounts of trans-iron elements. Unfortunately, there are no FUSE observations, but HST could be used to record a FUV spectrum.

KPD 0005+5106 is located well before the wind limit and, thus, cannot have been a PG 1159 star (Wassermann et al. 2010). Its metal abundance pattern suggests a possible relation to the RCrB stars which in turn are probably the result of a WD merger. This evolutionary context was discussed in detail in other papers of this conference, presented in the talks by Clayton, Reindl, and Staff.

5. Summary and Conclusions

Some hot DOs above the PG 1159 wind limit are not descendants from PG 1159 stars but belong to a distinct helium-rich post-AGB sequence (whatever its origin is). The most prominent example is KPD 0005+5106. RE 0503–289 is a unique white dwarf. It could be in the transition phase from the PG 1159 into the DO class. The high trans-iron element abundances result from s-process enhancement, possibly amplified by radiative levitation. The two other, cooler DOs with abundant trans-iron species mentioned in the Introduction are cooled-down versions of RE 0503–289 and, thus, PG 1159 descendants. Note that both of these WDs exhibit H as a trace element (i.e., they are DOAs) which might be an indication that they went through a particular subclass of the various final-thermal pulse (FTP) scenarios, the so-called AGB- (AFTP) and late-thermal pulse (LTP) events (for details on these events see, e.g., Werner & Herwig 2006). The lack of DAs with extreme trans-iron enrichments supports the idea that a LTP is a necessary condition for the trans-iron overabundances in the DO white dwarfs.

Future work should aim at the determination of all other trans-Fe elements discovered in RE 0503–289. Are they related to the s-process abundance pattern or dominated
by radiative levitation? For this, we need theoretical predictions from diffusion calculations, in a manner pioneered by Chayer et al. (2006) who performed such modeling for Ge, Zr, and Pb in sdB stars. Such calculations should account for the effects of (selective) stellar winds. Another ingredient for the diffusion calculations as well as for the abundance analyses are oscillator strengths that must be obtained by quantum-mechanical calculations.

6. Closing Remark

In 1904, the Scottish chemist Sir William Ramsay received the chemistry Nobel prize for the discovery of the noble gases He, Ne, Ar, Kr, and Xe in the air and for their isolation. He earned his doctorate in 1873 – at the University of Tübingen.

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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
Barstow, M. A., Dreizler, S., Holberg, J. B., Finley, D. S., Werner, K., Hubeny, I., & Sion, E. M. 2000, MNRAS, 314, 109
Barstow, M. A., Holberg, J. B., Werner, K., Buckley, D. A. H., & Stobie, R. S. 1994, MNRAS, 267, 653
Chayer, P., Fontaine, G., & Wesemael, F. 1995, ApJS, 99, 189
Chayer, P., Fontaine, M., Fontaine, G., Wesemael, F., & Dupuis, J. 2006, Baltic Astronomy, 15, 131
Chayer, P., Vennes, S., Dupuis, J., & Kruk, J. W. 2005, ApJ, 630, L169
Dreizler, S. 1999, A&A, 352, 632
Dreizler, S., & Werner, K. 1996, A&A, 314, 217
Karakas, A. I., Lugaro, M., & Gallino, R. 2007, ApJ, 656, L73
McCook, G. P., & Sion, E. M. 1999, ApJS, 121, 1
Naslim, N., Jeffery, C. S., Behara, N. T., & Hibbert, A. 2011, MNRAS, 412, 363
O’Toole, S. J. 2004, A&A, 423, L25
O’Toole, S. J., & Heber, U. 2007, in 15th European Workshop on White Dwarfs, edited by R. Napiwotzki, & M. R. Burleigh, vol. 372 of Astronomical Society of the Pacific Conference Series, 209
Quirion, P.-O., Fontaine, G., & Brassard, P. 2006, Mem. Soc. Astron. Ital., 77, 53
— 2012, ApJ, 755, 128
Rauch, T., Werner, K., Biemont, E., Quinet, P., & Kruk, J. W. 2012, A&A, in press
Unglaub, K., & Bues, I. 2000, A&A, 359, 1042
Vennes, S., Chayer, P., & Dupuis, J. 2005, ApJ, 622, L121
Vennes, S., Dupuis, J., Chayer, P., Polomski, E. P., Dixon, W. V. D., & Hurwitz, M. 1998, ApJ, 500, L41
Wassermann, D., Werner, K., Rauch, T., & Kruk, J. W. 2010, A&A, 524, A9
Werner, K., Deetjen, J. L., Rauch, T., & Wolff, B. 2001, in 12th European Workshop on White Dwarfs, edited by J. L. Provencal, H. L. Shipman, J. MacDonald, & S. Goodchild, vol. 226 of Astronomical Society of the Pacific Conference Series, 55
Werner, K., & Herwig, F. 2006, PASP, 118, 183
Werner, K., Rauch, T., & Kruk, J. W. 2007, A&A, 474, 591
Werner, K., Rauch, T., Kruk, J. W., & Kurucz, R. L. 2011, A&A, 531, A146
Werner, K., Rauch, T., Ringat, E., & Kruk, J. W. 2012, ApJ, 753, L7