Stellar laboratories

II. New Zn IV and Zn V oscillator strengths and their validation in the hot white dwarfs G191–B2B and RE 0503–289*,**,***

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ABSTRACT

Context. For the spectral analysis of high-resolution and high-signal-to-noise (S/N) spectra of hot stars, state-of-the-art non-local thermodynamic equilibrium (NLTE) model atmospheres are mandatory. These are strongly dependent on the reliability of the atomic data that is used for their calculation. In a recent analysis of the ultraviolet (UV) spectrum of the DA-type white dwarf G191–B2B, 21 Zn IV lines were newly identified. Because of the lack of Zn IV data, transition probabilities of the isoelectronic Ge VI were adapted for a first, coarse determination of the photospheric Zn abundance.

Aims. Reliable Zn IV and Zn V oscillator strengths are used to improve the Zn abundance determination and to identify more Zn lines in the spectra of G191–B2B and the DO-type white dwarf RE 0503–289.

Methods. We performed new calculations of Zn IV and Zn V oscillator strengths to consider their radiative and collisional bound-bound transitions in detail in our NLTE stellar-atmosphere models for the analysis of the Zn IV – V spectrum exhibited in high-resolution and high-S/N UV observations of G191–B2B and RE 0503–289.

Results. In the UV spectrum of G191–B2B, we identify 31 Zn IV and 16 Zn V lines. Most of these are identified for the first time in any star. We can reproduce well almost all of them at log Zn = −5.52 ± 0.2 (mass fraction, about 1.7 times solar). In particular, the Zn IV / Zn V ionization equilibrium, which is a very sensitive T eff indicator, is well reproduced with the previously determined T eff = 60 000 ± 2000 K and log g = 7.60 ± 0.05. In the spectrum of RE 0503–289, we identified 128 Zn V lines for the first time and determined log Zn = −3.57 ± 0.2 (155 times solar).

Conclusions. Reliable measurements and calculations of atomic data are a pre-requisite for stellar-atmosphere modeling. Observed Zn IV and Zn V line profiles in two white dwarf (G191–B2B and RE 0503–289) ultraviolet spectra were well reproduced with our newly calculated oscillator strengths. This allowed us to determine the photospheric Zn abundance of these two stars precisely.

Key words. atomic data – line: identification – stars: abundances – stars: individual: G191-B2B – virtual observatory tools – stars: individual: RE 0503-289

1. Introduction

In a recent spectral analysis of the hydrogen-rich DA-type white dwarf G191–B2B, Rauch et al. (2013) identified and reproduced stellar lines of C, N, O, Al, Si, O, P, S, Fe, Ni, Ge, and Sn. In addition, they identified 21 Zn IV lines. The determined Zn abundance (logarithmic mass fraction of −4.89, 7.5 × solar) was uncertain because the unknown Zn IV oscillator strengths were approximated by values of the isoelectronic Ge VI taken from Rauch et al. (2012).

In this paper, we introduce new oscillator strengths for Zn IV and Zn V (Sect. 2). Then, we describe briefly our observations (Sect. 3), our analysis strategy (Sect. 4), and revisit G191–B2B to perform a precise determination of its Zn abundance (Sect. 5). The white dwarf RE 0503–289 is hotter than G191–B2B and its trans-infrared element abundances are strongly oversolar (Werner et al. 2012; Rauch et al. 2013) and, thus, it appears promising to identify Zn lines. In Sect. 6, we describe our search for these and the determination of its Zn abundance. We summarize our results and conclude in Sect. 7.

2. Transition probabilities in Zn IV and Zn V

Radiative decay rates (oscillator strengths and transition probabilities) have been computed using the pseudo-relativistic Hartree-Fock (HFR) method as described by Cowan (1981).
For Zn IV, configuration interaction has been considered among the configurations \(3d^9, 3d^84s, 3d^84d, 3d^75s, 3d^74s5s, 3d^74s4d, \) and \(3d^74s5d\) for the even parity and \(3d^84p, 3d^85p, 3d^85f, 3d^74s4p, 3d^74s5p, 3d^74s4f, 3d^74s5f, \) and \(3d^74p4d\) for the odd parity. Using experimental energy levels published by Sugar & Musgrove (1995), the Slater integrals \((F^k, G^k)\), the spin-orbit parameters \(\zeta\), and the effective interaction parameters \((\alpha, \beta)\) corresponding to \(3d^8, 3d^84s, 3d^74p\) configurations were optimized using a well-established least-squares fitting process minimizing the differences between calculated and experimental energy levels within both configurations. In the case of Zn V, the configurations included in the HFR model were \(3d^8, 3d^75s, 3d^74d, 3d^75d, 3d^64s^2, 3d^64s4d, 3d^64s5s, 3d^64s4d, \) and \(3d^64s5d\) for the even parity and \(3d^74p, 3d^74d2, 3d^74f2, 3d^74s4p, 3d^74s5p, 3d^74s4f, 3d^74s5f, \) and \(3d^74p4d\) for the odd parity. Using experimental energy levels published by Sugar & Musgrove (1995), the average energies \((E_{\text{av}})\), the effective interaction parameter \(\zeta\), and the semi-empirical fitting process were performed to optimize the radial integrals corresponding to \(3d^8, 3d^74s, 3d^74p\) configurations using the experimental energy levels compiled by Sugar & Musgrove (1995). The HFR oscillator strengths \((\log g_f)\) and transition probabilities \((g_A)\) were calculated for lower and upper energy levels and the corresponding wavelength lengths (in Å). In the last column of each table, we also give the cancellation factor CF as defined by Cowan (1981). We note that very small values of this factor (typically <0.05) indicate strong cancellation effects in the calculation of line strengths. In these cases, the corresponding \(g_f\) and \(g_A\) values could be very inaccurate and so need to be considered with some care. However, very few transitions appearing in Tables 1 and 2 are affected by these effects. Figure 1 shows Grotrian diagrams of Zn IV and Zn V including all levels and transitions from Tables 1 and 2.

### 3. Observations

In this analysis, we use the FUSE spectrum of RE 0503–289 and the FUSE and HST/STIS spectra G191–B2B that are described in detail by Werner et al. (2012) and Rauch et al. (2013), respectively.

Both FUSE spectra are co-added from all available observations of RE 0503–289 and G191–B2B. They cover the wavelength range 910 Å < \(\lambda<1188 \) Å. Their resolving power is \(R = \lambda/\Delta \lambda \approx 20,000\). The HST/STIS spectrum of G191–B2B is co-added from 105 observation with the highest resolution (grating E140H, \(R \approx 118,000, 1145 \) Å < \(\lambda<1700 \) Å) available via MAST.

### 4. Model atmospheres and atomic data

To determine the Zn abundance of G191–B2B, it would be straightforward to use the final model of Rauch et al. (2013) as well as their model atoms with the only exception that the Zn IV and Zn V model ions were replaced by the extended versions that consider the newly calculated transition probabilities.
Fig. 3. Zn iv lines (left panel, marked with their wavelengths in Å, blue in the online version) and Zn v lines (right panel, marked in green) in the FUSE (for lines at $\lambda < 1150$ Å) and HST/STIS ($\lambda > 1150$ Å) observations of G191–B2B compared with our theoretical line profiles. For the identification of other lines, see Rauch et al. (2013). The vertical bar shows 10% of the continuum flux.
Table 4. Identified Zn lines in the UV spectrum of G191–B2B.

| Ion | Wavelength/Å | Theoretical | Observed | Comments |
|-----|--------------|-------------|----------|---------|
| Zn IV | 1272.202 | 1272.975 | prev. unid. |
|      | 1272.990 | 1272.975 | prev. unid. |
|      | 1277.130 | 1277.130 | Δλ > 0.02 Å |
|      | 1277.080 | 1277.130 | Δλ > 0.02 Å, prev. unid. |
|      | 1283.525 | 1284.740 | |
|      | 1284.721 | 1284.740 | |
|      | 1291.810 | 1291.810 | |
|      | 1296.620 | 1296.620 | |
|      | 1320.725 | 1320.725 | |
|      | 1321.215 | 1321.215 | |
|      | 1322.320 | 1322.320 | |
|      | 1326.735 | 1326.735 | Δλ > 0.02 Å |
|      | 1326.774 | 1326.735 | Δλ > 0.02 Å |
|      | 1329.110 | 1329.110 | |
|      | 1330.325 | 1330.325 | |
|      | 1333.180 | 1333.180 | |
|      | 1336.652 | 1336.652 | |
|      | 1337.195 | 1337.195 | |
|      | 1339.302 | 1339.302 | |
|      | 1340.156 | 1340.156 | |
|      | 1341.215 | 1341.215 | |
|      | 1347.954 | 1347.954 | |
|      | 1349.876 | 1349.876 | |
|      | 1352.883 | 1352.883 | |
|      | 1356.171 | 1356.171 | |
|      | 1357.801 | 1357.801 | |
|      | 1359.477 | 1359.477 | |
|      | 1363.422 | 1363.422 | |
|      | 1363.940 | 1363.940 | |
|      | 1365.260 | 1365.260 | |
|      | 1365.704 | 1365.704 | |
|      | 1366.057 | 1366.057 | |
|      | 1369.895 | 1369.895 | |
|      | 1372.635 | 1372.635 | |
|      | 1377.720 | 1377.720 | |
| Zn V | 1116.842 | 1116.842 | |
|      | 1120.325 | 1120.325 | |
|      | 1133.031 | 1133.031 | |
|      | 1133.060 | 1133.060 | Δλ > 0.02 Å, prev. unid. |
|      | 1134.020 | 1134.020 | |
|      | 1135.985 | 1135.985 | |
|      | 1136.342 | 1136.342 | |
|      | 1136.940 | 1136.940 | |
|      | 1136.951 | 1136.951 | |
|      | 1137.325 | 1137.325 | |
|      | 1137.615 | 1137.615 | |
|      | 1138.694 | 1138.694 | |
|      | 1138.720 | 1138.720 | |
|      | 1147.040 | 1147.040 | |
|      | 1152.980 | 1152.980 | |
|      | 1155.045 | 1155.045 | |
|      | 1158.750 | 1158.750 | prev. unid. |
|      | 1158.780 | 1158.780 | |
|      | 1174.325 | 1174.325 | prev. unid. |
|      | 1174.346 | 1174.346 | |
|      | 1176.122 | 1176.122 | weak, prev. unid. |
|      | 1179.969 | 1179.969 | Δλ > 0.02 Å |
|      | 1185.905 | 1185.905 | |
|      | 1185.955 | 1185.955 | |
|      | 1186.057 | 1186.057 | |
|      | 1186.078 | 1186.078 | |

Notes. Observed wavelengths are given only in case that they deviate from the theoretical wavelengths (cf. Tables 1 and 2). “prev. unid.” denotes lines that were previously listed as unidentified by Rauch et al. (2013).

(Sect. 2). Unfortunately, the employed Tübingen non-local thermodynamic equilibrium (NLTE) model-atmosphere package (Werner et al. 2003; Rauch & Deetjen 2003, TMAP3), which is used to calculate plane-parallel, chemically homogeneous, metal-line blanketed NLTE model atmospheres, overcharged our FORTRAN compilers. The program would not compile if the array sizes were increased further according to the much higher number of atomic levels treated in NLTE and the respective higher number of radiative and collisional transitions.

Thus, we decided to reduce the number of N and O levels treated in NLTE (Table 3) to create a TMAP executable. Test calculations have shown that the deviations in temperature and density structure between the final model of Rauch et al. (2013) and a model with reduced N and O model atoms are negligible. Then, the Zn occupation numbers are determined in a line-formation calculation, i.e., at fixed temperature and density structure. Since Zn opacities were already considered in our start model, the atmospheric structure and the background opacities are well modeled.
5. The photospheric Zn abundance in G191−B2B

Zn IV and Zn V are the dominant ionization stages of Zn in the atmosphere of G191−B2B (Fig. 2). Therefore, we closely inspected the available spectra for lines of these ions.

In the FUSE and HST/STIS observations of G191−B2B (cf. Rauch et al. 2013) we identified 31 Zn IV (10 new identifications) and 16 Zn V (all new) lines. The observed wavelength positions (a radial velocity of $v_{\text{rad}} = 22.1 \text{ km s}^{-1}$ was applied according to Holberg et al. 1994; Rauch et al. 2013) deviate partly from

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All model atoms (including Zn) are provided via the Tübingen Model-Atom Database (TMAD⁴, Rauch & Deetjen 2003), that has been set up within a project of the German Astrophysical Virtual Observatory (GAVO⁵). All SEDs that were calculated for this analysis are available via the registered Theoretical Stellar Spectra Access (TheoSSA⁶) VO service.

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⁴ http://astro.uni-tuebingen.de/~TMAD  
⁵ http://www.g-vo.org  
⁶ http://dc.g-vo.org/theossa
Table 5. Like Table 4, for RE 0503−289.

| Wavelength/Å | Ion     | Comments |
|-------------|---------|---------|
| 1029.992    | Zn v    |         |
| 1035.859    |         |         |
| 1035.887    |         |         |
| 1043.353    |         |         |
| 1055.878    |         |         |
| 1063.979    |         |         |
| 1068.284    |         |         |
| 1069.674    | blend with O v, Ga v, Ge v | |
| 1069.764    |         |         |
| 1071.501    |         |         |
| 1072.992    | 1072.950 | Δλ > 0.02 Å |
| 1074.241    | 1074.265 | Δλ > 0.02 Å |
| 1075.171    | 1075.050 | Δλ > 0.02 Å |
| 1076.239    |         |         |
| 1076.878    | 1076.895 |         |
| 1090.831    | 1090.800 | Δλ > 0.02 Å |
| 1094.088    | 1094.110 | blend with N iv |
| 1095.774    |         | blend with Ge v |
| 1095.797    |         |         |
| 1095.961    | 1095.945 |         |
| 1109.078    | 1109.110 | Δλ > 0.02 Å |
| 1109.166    |         | blend with C iv |
| 1110.821    | 1110.810 | weak |
| 1111.530    |         | blend with C III, O iv |
| 1111.603    |         |         |
| 1112.829    |         |         |
| 1114.482    |         |         |
| 1115.266    | 1115.295 | Δλ > 0.02 Å |
| 1115.668    | 1115.695 | Δλ > 0.02 Å |
| 1116.630    |         | too strong in model |
| 1116.842    | 1116.860 |         |
| 1119.950    | 1119.940 |         |
| 1120.101    | 1120.080 | Δλ > 0.02 Å |
| 1120.325    |         |         |
| 1121.109    | 1121.095 |         |
| 1121.524    |         | weak |
| 1122.502    |         | blend with Si iv |
| 1123.127    |         | blend with Ga v |
| 1125.019    | 1125.050 | Δλ > 0.02 Å |
| 1125.048    | 1125.060 |         |
| 1129.898    |         | blend with Ga v |
| 1130.051    |         |         |
| 1130.242    |         |         |
| 1131.242    | 1131.250 | prev. unid. |
| 1131.788    |         |         |
| 1131.863    |         |         |
| 1132.271    | 1132.290 |         |
| 1132.659    |         | blend with N iv |
| 1133.031    | 1133.060 | Δλ > 0.02 Å |
| 1133.128    |         |         |
| 1133.278    | 1133.300 | Δλ > 0.02 Å |
| 1133.498    |         |         |
| 1135.324    |         |         |
| 1135.588    |         |         |
| 1136.603    |         |         |
| 1136.986    | 1137.000 |         |
| 1137.625    |         |         |

Table 5. continued.

| Wavelength/Å | Ion     | Comments |
|-------------|---------|---------|
| 1138.248    |         |         |
| 1138.497    |         |         |
| 1139.278    | 1139.220 | Δλ > 0.02 Å |
| blend with Ge v |         |         |
| 1140.703    |         |         |
| 1141.003    | 1141.015 |         |
| 1141.095    |         |         |
| 1141.344    |         |         |
| 1142.792    |         |         |
| 1142.925    |         |         |
| 1142.938    |         | prev. unid. |
| 1143.196    |         |         |
| 1143.403    |         |         |
| 1144.136    | 1144.160 | Δλ > 0.02 Å |
| 1145.151    |         |         |
| 1146.057    |         |         |
| 1146.149    |         | too strong in model |
| 1147.020    | 1147.040 |         |
| 1147.371    | 1147.425 | Δλ > 0.02 Å |
| 1148.922    | 1148.915 |         |
| 1149.398    | 1149.370 | Δλ > 0.02 Å |
| 1149.486    |         |         |
| 1149.608    |         |         |
| 1149.873    | 1149.855 |         |
| 1150.743    |         |         |
| 1151.368    |         |         |
| 1152.985    | 1152.980 |         |
| 1153.160    |         |         |
| 1155.027    | 1155.045 |         |
| 1155.725    | 1158.750 |         |
| 1156.520    |         |         |
| 1156.885    |         |         |
| 1158.122    |         |         |
| 1158.475    |         |         |
| 1158.759    | 1158.750 |         |
| 1160.091    |         | weak |
| 1160.221    |         |         |
| 1161.971    |         |         |
| 1162.281    |         |         |
| 1162.401    |         |         |
| 1164.090    |         | blend of |
| Zn v λλ 1165.082, 1164.101 Å |         |         |
| 1164.632    |         | blend with O iv |
| 1165.189    |         |         |
| 1165.706    |         | blend with C III |
| 1165.716    |         | blend with C III |
| 1165.880    |         | blend with Xe VI |
| 1170.105    |         |         |
| 1171.106    | 1171.130 |         |
| 1173.366    |         |         |
| 1174.346    | 1174.325 |         |
| 1174.945    |         | blend with C III |
| 1176.122    |         | blend with C III |
| 1178.759    |         |         |
| 1179.145    |         |         |
| 1179.179    |         |         |
| 1179.969    | 1180.005 | Δλ > 0.02 Å |
Table 5. continued.

| Ion           | Wavelength/Å | Theoretical | Observed | Comments                      |
|---------------|--------------|-------------|----------|-------------------------------|
| 1180.018      |              | blend of    |          | Zn IV λ1180.018, 1180.025 Å   |
| 1182.019      |              |             |          |                               |
| 1182.567      |              |             |          |                               |
| 1183.041      |              |             |          |                               |
| 1183.100      |              |             |          |                               |
| 1183.158      |              |             |          |                               |
| 1183.314      |              |             |          |                               |
| 1185.619      |              |             |          |                               |
| 1185.645      |              |             |          |                               |
| 1185.676      |              |             |          |                               |
| 1185.898      | 1185.905    | blend of    |          | Zn V λ1185.948, 1185.961 Å   |
| 1185.948      |              |             |          |                               |
| 1186.057      |              |             |          |                               |
| 1186.447      | 1186.420 Δλ > 0.02 Å | too strong in model | |
| 1187.664      |              |             |          |                               |
| 1187.706      |              |             |          |                               |

those given in Tables 1 and 2 by some hundreds of an Å. The good agreement of the strongest, unshifted lines in our model\(^7\) (Fig. 3) with the observations permits to shift the lines to observed absorption features in their closest vicinity. The reason for this uncertainty is most likely the limited accuracy of the Zn IV and Zn V energy levels from which the wavelengths of the line transitions were calculated. The identified lines are summarized in Table 4.

Our calculations have shown that the Zn IV/Zn V ionization equilibrium at \( T_{\text{eff}} = 60,000 \) K and \( \log g = 7.6 \) (cf. Rauch et al. 2013) is well reproduced (Figs. 3, 4). On the other hand, the Zn abundance given by Rauch et al. (2013, \( 1.3 \times 10^{-5} \pm 0.5 \) dex by mass) is too high. We reduced it to \( 3.0 \times 10^{-6} \pm 0.2 \) dex (about 1.7 times solar, following Asplund et al. 2009) to reproduce the observed Zn lines best. This agrees with the previous value within the error limits. Even a solar Zn abundance, however, is possible within the error limits.

6. The photospheric Zn abundance in RE 0503–289

Our inspection of all UV spectra that were already used by Werner et al. (2012) has shown that only RE 0503–289 exhibits prominent Zn lines (Fig. 5). We find that in its FUSE spectrum (\( \Delta v_{\text{rad}} = 26.3 \text{ km s}^{-1} \)), a rich Zn V spectrum of 128 lines (Fig. 6, Table 5) is present. The synthetic spectrum of our final model shows more, weak lines that do not have an unambiguous line identification due to the signal-to-noise ratio (S/N) of the observation. The model’s prediction of their relative line strengths facilitates to distinguish between noise and “real” lines in the observation and, hence, to identify even such weak lines. In general, all lines with oscillator strengths \( gf \geq 0.01 \) can be detected.

Dreizler & Werner (1996) determined \( T_{\text{eff}} = 70,000 \pm 4000 \) K and \( \log g = 7.50 \pm 0.25 \) for RE 0503–289. This was recently verified by well-matched ionization equilibria of Kr and Xe (Werner et al. 2012). We used a high resolution model atmosphere made with radiative transfer and atomic data from the SIMBAD database (http://www.pw.iki.edu/~Peter/atomic) for RE 0503–289.

7. Results and conclusions

The identified Zn IV and Zn V lines in the high-resolution UV spectra of G191–B2B and RE 0503–289 are well reproduced with our newly calculated oscillator strengths by our NLTE model-atmosphere calculations.

We determined photospheric abundances of \( \log Zn = -5.52 \pm 0.2 \) (mass fraction, \( 1.9–4.8 \times 10^{-6} \), 1.1–2.8 times the solar abundance) and \( \log Zn = -3.57 \pm 0.2 \) (1.7–4.3 \( \times 10^{-4} \), 98–248 times solar) for the DA-type white dwarf G191–B2B and the DO-type white dwarf RE 0503–289, respectively. The highly supersolar Zn abundance is in line with the high abundances of trans-iron elements Ge (650× solar, Rauch et al. 2012), Kr (450× solar), Xe (3800× solar, Werner et al. 2012) in RE 0503–289.

The identification of new lines due to trans-iron elements, e.g., Ga, Ge, As, Se, Kr, Mo, Sn, Te, I, and Xe (Werner et al. 2012) and Zn (Rauch et al. 2013, and in this paper) in G191–B2B and RE 0503–289 promises to help enhance the understanding of extremely metal-rich white dwarf photospheres and their relation to AGB and post-AGB stellar evolution. Their reproduction, i.e., the precise abundance determination, e.g., of Kr and Xe (Werner et al. 2012), Ge and Sn (Rauch et al. 2012), and Zn (this paper) is strongly dependent on the available atomic data. This remains a challenge for atomic and theoretical physicists.

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\(^7\) All synthetic spectra shown in this paper are convolved with Gaussians to match the spectral resolution (FUSE: \( FWHM = 0.06 \) Å, STIS: \( FWHM = 0.01 \) Å).

\(^8\) Extreme ultraviolet.

\(^9\) http://www.pa.uky.edu/~Peter/atomic
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