First detection of bromine and antimony in hot stars**

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ABSTRACT

Bromine (Z = 35) and antimony (Z = 51) are extremely difficult to detect in stars. In very few instances, weak and mostly uncertain identifications of Br I, Br II, and Sb II in relatively cool, chemically peculiar stars were successful. Adopted solar abundance values rely on meteoritic determinations. Here, we announce the first identification of these species in far-ultraviolet spectra of hot stars (with effective temperatures of 49 500–70 000 K), namely in helium-rich (spectral type DO) white dwarfs. We identify the Br VI resonance line at 945.96 Å. A previous claim of Br detection based on this line is incorrect because its wavelength position is inaccurate by about 7 Å in atomic databases. Taking advantage of precise laboratory measurements, we identify this line as well as two other, subordinate Br VI lines. Antimony is detected by the Sb V resonance doublet at 1104.23/1225.98 Å as well as two subordinate Sb VI lines. A model-atmosphere analysis reveals strongly oversolar Br and Sb abundances that are caused by radiative-levitation dominated atomic diffusion.

Key words. diffusion – stars: abundances – stars: atmospheres – stars: AGB and post-AGB – white dwarfs

1. Introduction

Bromine (atomic number Z = 35) and antimony (Z = 51) are rather rare elements in the Universe and hard to detect in stars. Even the adopted solar abundance values (number ratios Br/H = 3.5 × 10⁻¹⁰, Sb/H = 1.0 × 10⁻¹¹; Asplund et al. 2009) were established indirectly from meteoritic measurements. Using improved analysis methods, it has been shown recently that the heavy halogen abundances in chondritic meteorites are significantly lower than previously thought and, for bromine in particular, this amounts to a factor of nine (Clay et al. 2017).

The detection of bromine in stars succeeded only recently. Castelli & Hubrig (2004) and Cowley & Wahlgren (2006) have identified Br II lines in the optical spectra of the mercury–manganese (HgMn) star HR 7143 and the He-weak chemically peculiar (CP) star 3 Cen A, respectively, and bromine excesses of 2.3 and 2.6 dex were measured. Br I lines were reported in the spectrum of the very peculiar star HD 101065 (alias Przybylski’s star) by Bidelman (2005). There is hardly any detection of antimony in stars, and respective claims are considered uncertain. Weak Sb II lines were reported in ultraviolet (UV) spectra of the HgMn star χ Lupi (Leckrone et al. 1999, concluding an Sb excess of 1.6 dex) and in the hot-Am star HR 3383 (Wahlgren & Leckrone 2008). In hotter stars, at higher ionization stages, bromine and antimony were not detected up to now. Here, we announce the identification of Br VI, Sb V, and Sb VI lines in three hot white dwarf stars.

2. Line identification and atomic data

We investigated UV spectra of three hot helium-rich white dwarfs (spectral type DO). In all of them, heavy elements beyond the iron group (Z > 29) were detected previously. In HD 149499 B (effective temperature T_eff = 49 000 K, surface gravity log (g/cm s^-2) = 7.97; Napiwotzki et al. 1995), Chayer et al. (2005) have identified six such species (Ge, As, Se, Sn, Te, and I). Eight trans-iron elements (Zn, Ga, Ge, Se, Sr, Sn, Te, I) were found in PG 0109+111 (T_eff = 70 000 K, log g = 8.0; Hoyer et al. 2018). The third DO discussed here (RE 0503−289, T_eff = 70 000 K, log g = 7.5; Dreizler & Werner 1996) is a truly outstanding object with respect to its heavy-element variety. Fourteen trans-iron elements (see below) were identified and abundances determined (Rauch et al. 2017, and references therein). Generally, large or extreme overabundances up to five dex oversolar were found, most probably caused by radiative levitation (Rauch et al. 2016).

For our assessment of RE 0503−289 and PG 0109+111, we used spectra taken with the Far Ultraviolet Spectroscopic Explorer (FUSE) and the Hubble Space Telescope (HST). For details of the observations, we refer the reader to our earlier work (Rauch et al. 2017; Hoyer et al. 2018). In addition, we used co-added archival FUSE spectra of HD 149499 B. In total, three Br and four Sb lines were identified (Table 1; Figs. 1 and 2).

2.1. Bromine

The first laboratory investigation of the Br VI spectrum in the far-UV wavelength region was performed by Rao & Rao (1934). In particular, the wavelength of the 4s² 1S₂ − 4s4p 3P₀ resonence (intercombination) line was determined to 939.57 Å. The energy levels derived from these early measurements are currently still listed in the NIST database (but classified as “not

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Table 1. Spectral lines of Br and Sb detected in three He-rich white dwarfs.

| Ion   | Transition         | J→J | \( \lambda_{lab}/\text{Å} \) | \( \log g/f_{lab} \) | \( E_i/\text{cm}^{-1} \) | RE 0503–289 | PG 0109+111 | HD 149499 B |
|-------|---------------------|-----|-------------------------------|-----------------------|---------------------------|-------------|-------------|-------------|
| Br VI | 4s\(^2\)1S→4s4p\(^3\)P\(^o\) | 0→1 | 945.96                       | -2.193                | 0.0                       | ×           | ×           | ×           |
|       | 4s4p\(^1\)P\(^o\)→4p\(^3\)P\(^o\) | 1→2 | 981.42                       | -0.600                | 151 285.0                 | ×           | ×           | ×           |
|       |                    | 1→1 | 1050.55                      | -0.275                | 151 285.0                 | ×           | ×           | ×           |
| Sb V  | 5s\(^2\)S→5p\(^2\)P\(^o\) | 1/2–3/2 | 1104.20                    | 0.052                 | 0.0                       | ×           | ×           | ×           |
|       |                    | 1/2–1/2 | 1225.98                    | -0.232                | 0.0                       | ×           | ×           | ×           |
| Sb VI | 5s\(^3\)D→5p\(^1\)F\(^o\) | 3–4 | 999.40                       | 0.440                 | 242 916.8                 | ×           | ×           | ×           |
|       |                    | 1–0 | 1043.07                      | 0.520                 | 242 916.8                 | ×           | ×           | ×           |

Notes. Excitation energies \( E_i \) for Br VI from Riyaz et al. (2012), for Sb V from Chan (1966), and for Sb VI from Churilov et al. (2000). Oscillator strengths \( f_{lab} \) for Br VI from Riyaz et al. (2012), for Sb V from Morton (2000). For Br VI, we used the \( f_{lab} \) values of the respective lines in the isoelectronic Ge V ion from Rauch et al. (2012), \( g_i \) is the statistical weight of lower level \( i \). An entry "×" in the last three columns indicates which line was detected in which star.

Fig. 1. Lines of Br VI in the DO white dwarfs RE 0503–289 (top panel) and HD 149499 B (bottom panel).
3. Spectral analysis

We performed a quantitative spectral analysis to derive the abundances of Br and Sb from detailed line-profile fits. To this end, we used the Tübinger Model-Atmosphere Package (TMAP\(^1\)) to compute non-local thermodynamic equilibrium (NLTE), plane-parallel, line-blanketed atmosphere models in radiative and hydrostatic equilibrium (Werner & Dreizler 1999; Werner et al. 2003, 2012a). For HD 149499 B, which are from Churilov et al. (2000), it is the 5s\(^1\)D\(^3\)–5p\(^3\)P\(^o\) transition. This corresponds to the isoelectronic Sn\(\nu\) line at 1160.74 Å, which is of similar strength in RE 0503–289 (Werner et al. 2012b). The other components of this Sb\(\nu\) multiplet are expected to be weaker and, occasionally, they are blended with other photospheric lines. Instead, we identify the \(J = 1–0\) component of the 5s\(^3\)D\(^3\)–5p\(^3\)P\(^o\) multiplet at 1043.07 Å (Fig. 2).

![Fig. 2. Lines of Sb\(\nu\) in the DO white dwarf RE 0503–289 (top panel) and PG 0109+111 (middle), as well as two Sb\(\nu\) lines in RE 0503–289 (bottom panel).](image)

which are from Churilov et al. (2000).

Table 2. Bromine and antimony abundances measured in He-rich white dwarfs.

| Star          | \(T_{eff}/K\) | \(\log g\) | Br   | Sb   |
|---------------|---------------|-------------|------|------|
| RE 0503–289   | 70000         | 7.50        | −4.5 | −4.3 |
| PG 0109+111   | 70000         | 8.00        | −5.3 |      |
| HD 149499 B   | 49500         | 7.97        | −4.3 |      |

Notes. Abundances given as logarithm of mass fraction. Solar mass fractions are \(\log Br = −7.7\) and \(\log Sb = −9.0\). Surface gravity \(g\) in cm/s².

we computed models including H, He, and Br. In a final formal solution of the radiation transfer equation, line profiles were calculated accounting for fine-structure splitting. The same procedure was performed for RE 0503–289 and PG 0109+111, but in these cases we used our detailed metal-line blanketed model atmospheres from previous work. The RE 0503–289 model includes 26 species (Rauch et al. 2017) plus Br and Sb, and the PG 0109+111 model four species (He, C, N, and O; Hoyer et al. 2018) plus Sb.

Our model atoms for Br and Sb consist of ionization stages IV–VII. The numbers of NLTE lines/lines per ion are 15/1, 5/4, 20/42, and 1/0 for Br IV–VII, respectively. Level energies and oscillator strengths \(f_{\alpha}\) for Br \(\nu\) and Sb \(\nu\) were taken from Morton (2000). Level energies for Br IV \(\nu\) were adopted from NIST and the \(f_{\alpha}\) value for the considered resonance line is from Warner & Kirkpatrick (1969).

For Sb, the numbers of NLTE lines/lines per ion are 3/1, 5/1, 8/1, and 1/0 for Sb IV–VII, respectively. Level energies for Sb IV \(\nu\) were taken from Churilov et al. (2000), and for Sb \(\nu\) from Chan (1966), and for Sb \(\nu\) from Churilov et al. (2000). The \(f_{\alpha}\) values of the considered Sb IV \(\nu\) and Sb \(\nu\) resonance lines are from Morton (2000). That of the considered Sb \(\nu\) resonance line at 285 Å is from Churilov et al. (2000). The two observed UV lines are subordinate and they were considered in the final spectrum synthesis calculation, only. For their \(f_{\alpha}\) values see Table 1.

For both species, Br and Sb, bound-free cross sections were assumed to be hydrogen-like. Line profiles for quadratic Stark broadening and electron collisional rates were computed with usual approximate formulae (see, e.g., Werner et al. 2012b).

For each star, several model atmospheres with different Br and Sb abundances were computed. Our best fits to the observed line profiles are displayed in Figs. 1 and 2. The resulting element abundances are summarized in Table 2. Analysis errors are estimated to ±0.3 dex, but a similar systematic error for Sb must be accounted for because of the atomic data approximations in our model atom. For RE 0503–289, the results are displayed in Fig. 3 together with all element abundances hitherto measured in this star.

4. Summary and conclusions

We reported the first detection of the bromine and antimony in hot stars. We identified spectral lines from Br \(\nu\) and Sb \(\nu\) in helium-rich white dwarfs. As a result of our NLTE model-atmosphere analysis, we found that the Br abundance in RE 0503–289 and HD 149499 B is 1600 and 2500 times solar and the Sb abundance in RE 0503–289 and PG 0109+111 is even 50 000 and 5000 times solar.

In the case of RE 0503–289, Br and Sb are two more trans-iron species in addition to the fourteen already found. Among all white dwarfs, this rich diversity of detected heavy
elements is outstanding. The Br and Sb abundances fit into the general trend that all trans-iron elements are extremely overabundant (Fig. 3). As we have discussed earlier, the origin for this phenomenon is most likely rather efficient radiative levitation (Rauch et al. 2017, and references therein).

As we have demonstrated, our ongoing work on the detection of trans-iron elements in hot white dwarfs and respective model-atmosphere analyses repeatedly faces the problem of inaccurate or lacking atomic data, primarily level energies of moderately ionized atoms (ionization stages IV to VIII) and oscillator strengths. For many species, laboratory spectra and their extended analysis are badly needed. A large number of spectral lines remain unidentified in hot white dwarfs and it is a reason for suspicion that many of these stem from hitherto undetected elements. Good candidates are species with atomic numbers in the range $Z = 43 - 49$ (Tc–In; as indicated by Fig. 3), or even species beyond the most heavy element discovered so far in any white dwarf ($Z = 56$, barium).

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References

Asplund, M., Grevesse, N., Sauval, A. J., & Scott, P. 2009, ARA&A, 47, 481
Badami, J. S. 1931, Proc. Phys. Soc., 43, 538
Bidelman, W. P. 2005, in Cosmic Abundances as Records of Stellar Evolution and Nucleosynthesis, eds. T. G. Barnes, III, & F. N. Bash, ASP Conf. Ser., 336, 309
Castelli, F., & Hubrig, S. 2004, A&A, 425, 263
Chan, C. 1966, PhD thesis, The University of British Columbia, Canada
Chayer, P., Vennes, S., Dupuis, J., & Kruk, J. W. 2005, ApJ, 630, L169
Churilov, S. S., Azarov, V. I., Ryabtsev, A. N., Tchag-Brillet, W.-U. L., & Wyatt, J.-F. 2000, Phys. Scr., 61, 420
Clay, P. L., Burgess, R., Bussemann, H., et al. 2017, Nature, 551, 614
Cowley, C. R., & Wahlgren, G. M. 2006, A&A, 447, 681
Curtis, L. J., Martinson, I., Leavitt, J. A., et al. 1984, Phys. Lett. A, 105, 212
Dreizler, S., & Werner, K. 1996, A&A, 314, 217
Gibbs, R. C., Vieweg, A. M., & Gurtlein, C. W. 1929, Phys. Rev., 34, 406
Hoyer, D., Rauch, T., Werner, K., & Kruk, J. W. 2018, A&A, 612, A62
Joshi, Y. N., & van Kleef T. A. M. 1986, Phys. Scr., 34, 135
Kelly, R. L. 1987, J. Phys. Chem. Ref. Data, 16
Kramida, A., Ralchenko, Yu., Reader, J., & NIST ASD Team 2017, NIST Atomic Spectra Database (ver. 5.5.1), https://physics.nist.gov/asd
Lang, R. J. 1927, Proc. Natl. Acad. Sci., 13, 341
Leckrone, D. S., Proffitt, C. R., Wahlgren, G. M., Johansson, S. G., & Brage, T. 1999, AJ, 117, 1454
Moore, C. E. 1971, Selected Tables of Atomic Spectra – A: Atomic Energy Levels, 2nd edn.; – B: Multiplet tables; N IV, N V, N VI, N VII. Data derived from the analyses of optical spectra (Washington, DC: NSRDS-NBS)
Morton, D. C. 2000, ApJS, 130, 403
Napiwotzki, R., Hurwitz, M., Jordan, S., et al. 1995, A&A, 300, L5
Rao, A. S., & Rao, K. R. 1934, Proc. Phys. Soc., 46, 163
Rao, A. S., Werner, K., Bismont, E., Quinet, P., & Kruk, J. W. 2012, A&A, 546, A55
Rauch, T., Quinet, P., Hoyer, D., et al. 2016, A&A, 587, A39
Rauch, T., Quinet, P., Knörzer, M., et al. 2017, A&A, 606, A105
Riyaz, A., Tauheed, A., & Rahimullah, K. 2012, J. Quant. Spec. Radiat. Transf., 113, 2072
Riyaz, A., Tauheed, A., & Rahimullah, K. 2014, J. Quant. Spec. Radiat. Transf., 147, 86
Wahlgren, G. M., & Leckrone, D. S. 2008, Contr. Astron. Obs. Skalnaté Pleso, 38, 463
Warner, B., & Kirkpatrick, R. C. 1969, MNRAS, 142, 265
Werner, K., & Dreizler, S. 1999, J. Comput. Appl. Math., 109, 65
Werner, K., Deetjen, J. L., Dreizler, S., et al. 2003, in Stellar Atmosphere Modeling, eds. I. Hubeny, D. Mihalas, & K. Werner, ASP Conf. Ser., 288
Werner, K., Dreizler, S., & Rauch, T. 2012a, TMAP: Tübingen NLTE Model-Atmosphere Package, Astrophysics Source Code Library [record ascl:1212:015]
Werner, K., Rauch, T., Ringat, E., & Kruk, J. W. 2012b, ApJ, 753, L7