Trans-iron elements in the hot DO-type white dwarf RE0503−289 and the prospective search for technetium

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Abstract. To date, a surprisingly large number of twelve trans-Fe elements were detected in the hot helium-rich WD RE0503−289, a phenomenon that is not observed in any other WD. Abundance analyses for most of these elements are hampered by the lack of atomic data for the relevant ionisation stages (IV–VII). To solve this problem, we perform experimental and theoretical work.

1. Introduction

RE0503−289 is a peculiar hot DO-type WD with respect to its rich diversity of trans-iron elements. At the preceding European WD Workshop in Krakow, Poland, in 2012, we announced the detection of Kr and Xe in FUSE spectra, marking the first discovery of these species in a WD, and we found extremely high overabundances relative to the solar values (Werner et al. 2012). At the same time, other trans-Fe elements were identified but abundance analyses were still lacking. In the past two years even more trans-Fe species were discovered so that the total number of these elements is now twelve (Zn, Ga, Ge, As, Se, Kr, Mo, Sn, Te, I, Xe, Ba). This is remarkable, because only in five other WDs six trans-Fe elements were found in total (Chayer et al. 2005; Vennes et al. 2005). Other achievements in the past two years are the abundance analysis for Zn, Ga, Ge, and Ba. Together with Kr and Xe, the mass fractions of these species are in the range $(0.25 - 3.5) \times 10^{-4}$; see Fig. 1 and Rauch et al. (2012, 2014a,b,c).

Temperature and gravity of RE0503−289 ($T_{\rm eff}$ = 75 000 K, $\log g$ = 7.5) suggest that the cooling WD is about to cross the wind-limit (Unglaub & Bues 2000); radiation-driven mass-loss has decreased so far that gravitational settling of heavy elements commences. The star could therefore be a PG1159–DO transition object, which is supported by the intermediate C mass fraction of about 4 %. The large overabundances of trans-Fe elements could be due to radiative acceleration or enhancement by s-process in the preceding AGB phase, or both. To clarify the situation it is desirable to derive abundances of the entire suite of the detected trans-Fe elements and to search for even more of these species. In particular, the detection of technetium would be a clear hint that

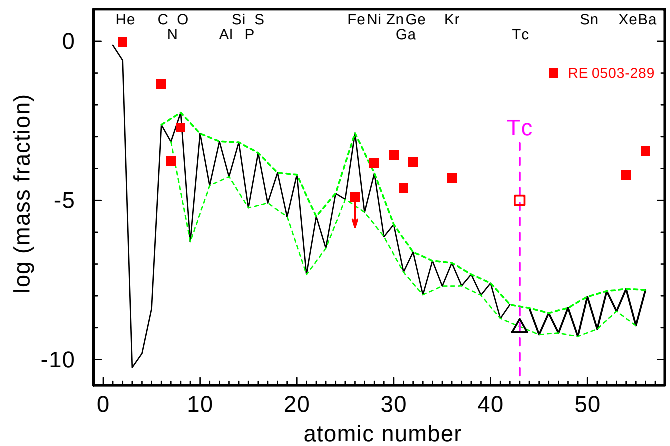

Figure 1. Element abundances in RE0503−289 (squares) compared to solar values. For Tc, the open square marks the detection threshold for RE0503−289 and the triangle is the typical abundance in red giants.

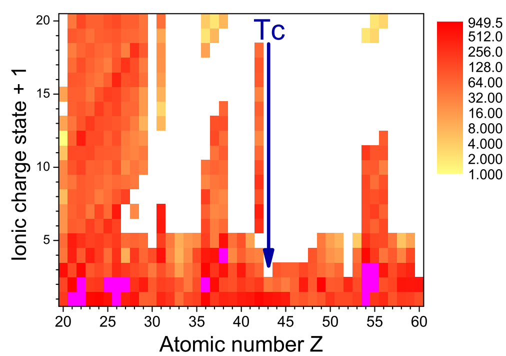

Figure 2. Number of lines known for ions with atomic number Z (abscissa) and charge state indicated in the ordinate. Magenta rectangles mark species having more than 950 known lines. The white areas show ions with no reported experimental data whatsoever (Source: NIST). For Tc, no data beyond Tc II exists.

s-processing is at least partly responsible for the presence of heavy metals. To achieve these aims, a main obstacle must be overcome, namely, the lack of atomic data.

2. Atomic data for trans-iron elements

For the computation of synthetic line spectra, we require both energy levels and f-values for line transitions. For the necessary non-LTE modeling, not only the f-values of the lines in the studied wavelength region are required, but also from all other radiative transitions within that ionisation stage because the radiative rates have to be computed to set up and solve the rate equations for the occupation numbers of the atomic energy levels. Depending on the particular ionisation stage, these requirements are not always fulfilled due to the lack of atomic data. To illustrate the problem we face in the case of heavy elements, we show in Fig. 2 the number of spectral transitions known per ion. It can be seen that beyond the iron group almost no data exist for high ionisation stages.

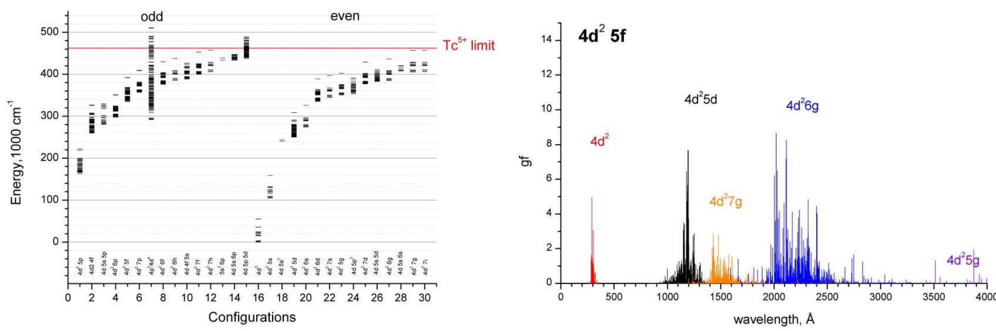

Figure 3. Predicted energy levels (left) and lines (right) for Tc v.

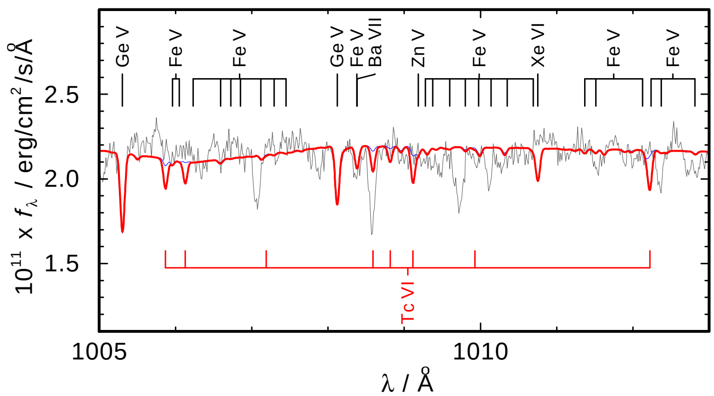

Figure 4. Section of the FUSE observation (gray) of RE0503−289 compared with synthetic spectra (blue, thin: Tc mass fraction 1.0×10^{-7}, red, thick: 1.0×10^{-4}).

In principle, this problem can be overcome by quantum mechanical computations of f-values, provided the energy levels are known accurately enough to predict the line positions in the UV wavelength range to within about 0.1 Å. This procedure was applied in our analyses of Zn, Ge, Ga, and Ba. However, the situation is decidedly worse in the many cases where even energy levels are unknown. One example is Tc, for which they are only known for the two lowest ionisation stages. Eventually, the only way to proceed in these cases are laboratory measurements of line spectra to derive the energy levels and the f-values (at least for the observed lines; quantum mechanical calculations are necessary for the other lines).

We decided to set up a laboratory experiment to study the line spectra of these unexplored ions. Our immediate interest is focused on Tc, but once the equipment is available, other trans-Fe elements shall be studied, too.

3. Search for technetium

Why is Tc so interesting? It is a key element to decide whether s-process played a role to shape the abundance pattern in RE0503−289. It has only unstable isotopes, hence, any Tc must have been produced during the preceding AGB phase. The discovery of Tc in red giants by Merrill (1952) was, thus, a historical milestone for our understanding of

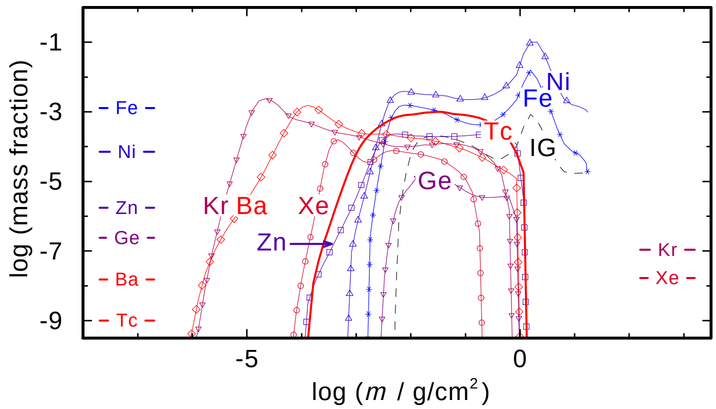

Figure 5. Stratification of the most-heavy elements in our model for RE0503−289. IG denotes a generic atom (including Ca, Sc, Ti, V, Cr, Mn, and Co). Solar abundances are indicated on the left and right sides of the panel. The value for Tc is a typical abundance measured in red giants.

stellar nucleosynthesis. The half-life of ^{99}Tc, which is the Tc isotope that is produced by s-process, is 210 000 years. In comparison, the post-AGB age of RE0503−289 is about 650 000 years, i.e., three half-lives so that we expect that a significant fraction of the produced ^{99}Tc nuclei did not yet suffer radioactive decay and could be present in the photosphere.

To justify the experimental effort to measure the Tc line spectra, we performed estimates as to the probability that Tc can be detected in RE0503−289. To that aim, energy levels and f-values of Tc IV-VI were computed (Fig. 3). This allows us to estimate what minimum Tc abundance is necessary in the stellar atmosphere to detect spectral lines but, of course, individual line identifications are prevented by the inaccurate theoretical line positions because the energy levels cannot be computed with sufficient accuracy. We found that detectable UV lines can be expected provided the Tc abundance is of the same order as the abundances of the hitherto detected trans-Fe elements (Fig. 4). We also used these computed atomic data to predict the vertical Tc abundance profile in the atmosphere of RE0503−289 assuming equilibrium of gravitational settling and radiative acceleration. Interestingly, the Tc abundance even exceeds the abundance of other trans-Fe elements in the line-forming regions (Fig. 5).

All these considerations encouraged us to produce a Tc plasma in the laboratory to study the line spectra of its highly charged ions. We will utilize the Electron Beam Ion Traps (EBIT) facility at the Max Planck Institute for Nuclear Physics in Heidelberg (Fig. 6). One of its big advantages is that we need only minute quantities of Tc (some 10^{-12} grams), an important aspect given the radioactivity of the material. We have attached a 3m UV spectrograph, on loan from the electron synchrotron institute in Berlin (BESSY), to the EBIT. We are currently integrating an MCP detector which is the flight spare of the ORFEUS far-UV space telescope that was flown twice on Space Shuttles in the 1990s. Once thought to record the spectra of stars, we now use this detector in the laboratory to prepare the analysis of stellar spectra! We anticipate that measurements will commence at the end of 2014. We are therefore optimistic to gather atomic data such that we can compute synthetic stellar Tc line spectra for comparison with the FUSE and HST observations within 2015.

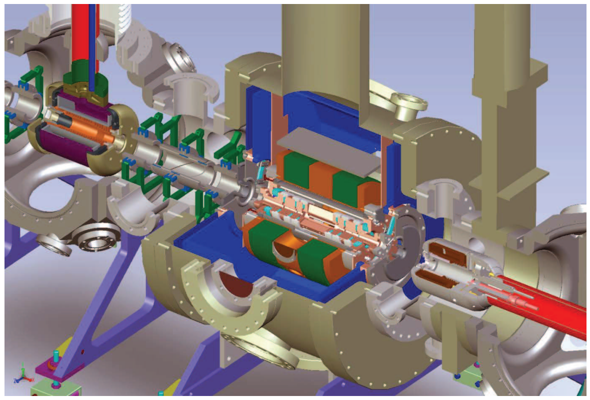

Figure 6. Section across an electron beam ion trap showing the electron gun (inside the right chamber), trap region (in the cold bore of the superconducting magnet at the center), and the electron collector (in the left chamber). The central magnetic field of 6 T focuses the axially injected electron beam to a diameter of less than 50 μm. This beam ionizes neutrals injected into the apparatus stepwise to selectable high charge states, and traps the generated ions by its negative space charge potential.

4. Outlook

Our spectral analyses are aiming at the abundance determination of trans-Fe elements in RE0503−289. By doing so, we are using the WD as a stellar laboratory to study the spectra of high ionisation stages of these species, to derive energy levels and validate computed oscillator strengths. In this sense, we are exploring blank areas of atomic spectroscopy. It is therefore rewarding to look for even more elements in RE0503−289. To this end, we have obtained high-resolution HST/STIS spectra in the hitherto unrecorded wavelength range of 1190–3070 Å. The observations were performed during the week of this workshop in Montréal and the spectra are now being scrutinized.

Is RE0503−289 a unique object? Are there other hot DOs alike, which also show a plethora of trans-Fe elements? Two years ago in the previous workshop, we already posed this question and suggested to perform UV spectroscopy of related objects (with similar temperature and gravity). Accordingly, we will observe two other hot DOs and one PG1159 star with HST/COS during 2015.

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