Thorium-rich halo star HD221170: further evidence against the universality of the r-process

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Abstract. We report the abundance determination in the atmosphere of the bright halo star HD221170. The spectra were taken with the Terskol Observatory’s 2.0-m telescope with a resolution R=45000 and signal-to-noise ratio up to 250 in the wavelength region 3638-10275 Å. The adopted atmospheric parameters correspond to an effective temperature $T_{\text{eff}}=4475$ K, a surface gravity $\log g=1.0$, a microturbulent velocity $v_{\text{micro}}=1.7 \text{ km s}^{-1}$, and a macroturbulent velocity $v_{\text{macro}}=4 \text{ km s}^{-1}$. The abundances of 43 chemical elements were determined with the method of spectrum synthesis. The large overabundances (by 1 dex relative to iron) of elements with $Z>38$ are shown to follow the same pattern as the solar r-abundances. The present HD221170 analysis confirms the non-universality of the r-process, or more exactly the observation that the astrophysical sites hosting the r-process do not always lead to a unique relative abundance distribution for the bulk Ba to Hg elements, the Pb-peak elements, and the actinides.

Key words. Line: identification – Stars: abundances – Stars: atmospheres – Stars: evolution – Stars: metal-poor – Stars: individual: HD221170 – r-process nucleosynthesis

1. Introduction

The chemical composition of different objects, particularly halo stars, is one of the most important clues for understanding the structure and evolution of the Universe. Typical investigations of the chemical compositions of stars usually show 15-40 chemical elements, depending the type of the star. The most detailed stellar abundance patterns consist of 50-58 elements (see Yushchenko et al. 2004 for examples). The best example is the abundance pattern of the halo star CS22892-52 with the determination of 58 elements (Sneden et al. 2003). This star and another three r-process-rich stars CS31082-001 (Cayrel et al. 2001, Hill et al. 2002), HD115444 (Westin et al. 2000) and BD+17°3248 (Cowan et al. 2002) are halo stars with known enhanced abundances of thorium with respect to iron. In the specific case of CS31082-001, the determination of the uranium abundance also enabled investigators to derive from the thorium to uranium abundance ratio a stellar age of $13\pm4$ billion years. Such an estimate directly provides an independent lower limit for the age of our Galaxy and the Universe.
The investigation of the thorium abundance in the atmosphere of different stars of our Galaxy has a long history. Bucher (1987), Morel et al. (1992) and Francois et al. (1993) studied a set of disk and halo stars using the strongest Th line at 4019.129 Å. Yushchenko & Gopka (1994) determined the thorium abundance in Procyon using 4 faint lines in the 3200-3500 Å spectral range, while Gopka et al. (1999) determined Th at the surface of Arcturus using other lines.

A special effort was later dedicated to the observation of an increasing number of Th-rich halo stars (see for example Johnson & Bolte, 2001). But the number of lines considered for the abundance determination did not necessarily increase; for example the latest investigation of Honda et al. (2004) is based on the single 4019 Å line. Numerous thorium lines were detected only in the four above-mentioned Th-rich stars.

Many authors have used the Th/Eu and other ratios to estimate the age of the observed stars, although Goriely & Clerbaux (1999) and Goriely & Arnould argued that the Th-to-Eu abundance ratio is not a reliable chronometer to derive the stellar age. New observations by Honda et al. (2004), as well as the present analysis confirm this result.

HD221170 is one of the bright template halo stars. This seven-magnitude star has been investigated regularly as new methods and new observational facilities became available. The first paper in this series was Wallerstein et al. (1963), followed by Gilroy (1988) and many others. The last detailed abundance pattern of heavy elements in this star was provided by Burris et al. (2000), Yushchenko et al. (2002) published preliminary results for the abundances of elements heavier than Dy. However, for such elements the majority of the spectral lines are located at wavelengths shorter than 4500 Å, and the low signal-to-noise ratio obtained in this spectral region at that time required further investigations. Gopka et al. (2004; hereafter Paper I) used the spectral data from the above-mentioned work and the spectrum from the archive of the Haute-Provence Observatory 1.88 m telescope to derive the abundance of elements with \( Z \leq 68 \). Previous investigations concerning the surface abundances of HD221170 and the determination of atmospheric parameters are reviewed in Paper I. According to Burris et al. (2000), Gopka et al. (2001) and Paper I, the iron abundance in HD221170 is deficient by about 2 dex with respect to the sun while the abundance of elements heavier than barium are overabundant with respect to iron. Nevertheless, since the spectrum used in Paper I from the Haute-Provence Observatory covers the limited wavelength range of 4480–6820 Å, we were unable to determine the abundance of elements heavier than Dy.

In Sect. 2, new observations of higher quality and broader wavelength coverage are detailed and the adopted atmospheric parameters described. In Sect. 3 the result of the abundance analysis is presented. In Sect. 4, the surface abundances of HD221170 are compared with those of the other r-process-enriched halo stars already observed, and their implication concerning the non-universality of the r-process is discussed.

## 2. Observations and atmospheric parameters

The observations were conducted with the Coude-echelle spectrometer (Musaev et al. 1999) mounted at the 2-m "Zeiss" telescope at the Peak Terskol observatory located near Mt. Elbrus (Northern Caucasus, Russia) 3,124 m above sea level. The spectrometer is used in the mode with a spectral resolution of 45,000. The best signal-to-noise ratio is over 250 in the red spectral region and the wavelength coverage includes the 3638-10275 Å range. Galazutdinov (1992) DECH20 and Yushchenko (1998) URAN codes are used for the data processing.

In Paper I, based on previous investigations of the star and new spectral data, the following model atmosphere parameters of HD221170 were found to be optimum: \( T_{\text{eff}}=4475 \pm 50 \, \text{K} \) for the effective temperature, \( \log g=1.0 \pm 0.1 \) for the gravity, \( v_{\text{micro}}=1.7 \pm 0.1 \, \text{km s}^{-1} \) for the microturbulence and \( v_{\text{macro}}=4.0 \pm 0.5 \, \text{km s}^{-1} \) for the macroturbulence.

These parameters and the abundances from Paper I are used to construct individual atmosphere models using the standard Kurucz’s ATLAS12 code. We find for the final model that the correlation(s) of iron abundances with excitation potentials and equivalent widths of iron lines are close to zero.

We also calculated the models corresponding to the parameter sets \( (T_{\text{eff}}=4475 \, \text{K}; \log g=1.2) \) and \( (T_{\text{eff}}=4575 \, \text{K}; \log g=1.0) \). These models are used to estimate the abundance errors due to possible uncertainties in the adopted value of the temperature and gravity.

## 3. Abundance analysis

The equivalent widths of the iron lines are estimated by fitting their profiles with a Gaussian function. The iron abundance is calculated using the model atmosphere method on the basis of the Kurucz (1995) WIDTH9 program. In contrast, differential spectrum synthesis methods are used for all the other elements. For each line, we tried to find its counterpart in the solar spectrum atlas of Delbouille et al. (1973). This procedure frees us from uncertainties connected with oscillator strengths of spectral lines. The URAN code (Yushchenko 1998) and SYNTHE spectrum synthesis program (Kurucz 1995) are used to approximate the observed spectrum with the synthetic one. The solar abundances of Grevesse & Sauval (1999) are considered. A synthetic spectrum of HD221170 for the whole wavelength range helps us to identify spectral lines. SYNTHE program (Kurucz 1995) was used to produce the synthetic spectrum. Atomic and molecular lines are included from Kurucz (1995) as well as Morton (2000), Biemont et al. (2002) and partially from the VALD database (Piskunov et al. 1995).

Holweger’s partition function for thorium is used (Morell et al. 1992). Hyperfine structure and isotopic splitting are taken into account for Li, Sc, V, Mn, Co, Cu, Ba, and Eu. The splitting data for Li are taken from Shavrina et al. (2003), for Ba – from Francois (1996) and for other
elements from Kurucz (1995). We found counterparts in the solar spectrum for all elements except Li, S, K, Ir, Th, and U, so that the differential abundances are not strongly influenced by splitting effects.

This is true if the lines have approximately the same strength in both stars. However, HD221170 and the Sun are different stars and it is quite difficult to find lines of similar intensity. For example, for Hf the equivalent widths of two of lines used are of the order of 2 and 3.5 mÅ in the Sun and near 45 and 15 mÅ in HD221170. The first line, $\lambda$ 3918.094 Å, with an equivalent width of 2 and 45 mÅ in the spectra of the Sun and HD221170, respectively, shows a relative abundance difference of hafnium -0.97 dex in the atmosphere of HD221170 with respect to the solar atmosphere. In the case of the second line, $\lambda$ 4093.155 Å, the difference in the equivalent width is smaller (3.5 and 15 mÅ) and the relative abundance is -1.49 dex. We can expect that taking into account the splitting of the lines will decrease the overabundance of Hf with respect to iron in the atmosphere of HD221170. The value obtained using the second line is therefore expected to be more reliable. But even this value shows a non-negligible deviation with respect to the solar r-process pattern, as will be shown in the next section of this paper.

For the lines of several heavy elements (U, Th, Os, Ir), no counterparts in the solar spectrum exist, and therefore the latest values of the oscillator strength (Nilsson et al. 2002a,b, Ivarsson 2003) are adopted. Several lines of hafnium, lead, thorium and uranium can be found in Fig. 1–6. The line data of iron and other chemical elements observed in the photosphere of HD221170 can be obtained in table format at the websites: “users.odessa.net/~yua” and

Fig. 1. The observed spectrum of HD221170 (squares) and the synthetic spectra (solid lines) calculated with our final abundances. The axes are the wavelength in angstroms and relative fluxes. The positions of the spectral lines taken into account in the calculations are marked in the bottom part of the figure by short and long dashes. For some of the strong lines, the identification and isotopic composition for molecular lines are given. The position of the Hf II 4093.155 Å line is marked by a vertical dotted line. The different synthetic spectra correspond to a Hf abundance lower or higher by 0.5 dex with respect to the abundance obtained from the optimum value.

Fig. 2. Same as Fig. 1 in the vicinity of the Pb I 4057.806 Å line. The three different synthetic spectra correspond to the optimum lead abundance and a deviation by ±0.5 dex from this value. Note that the unmarked strong line on the blueside of the Pb line corresponds to the $^{12}$CH line. The separation of the $^{12}$CH and Pb lines is smaller than the instrumental profile, so that the uncertainties in the determination of the wavelength and oscillator strength can strongly affect the Pb abundance determination.

Fig. 3. Same as Fig. 1 in the vicinity of the Th II 4019.129 Å line. The different synthetic spectra correspond to the mean thorium abundance of -1.18 (in the scale log N(H)=12) and a deviation by ±0.5 dex from this value.
Table 3. The mean abundances of chemical elements in the atmosphere of HD221170 with respect to their abundances in the solar atmosphere.

| Z | Ident. | Paper I | Terskol | This paper | Paper I | Terskol, new spectrum |
|---|--------|---------|---------|------------|---------|----------------------|
|   |        | Haute-Provence | Terskol | This paper | Haute-Provence | Terskol, new spectrum |
|   |        | ATLAS9 | ATLAS9 | [N/H] | ATLAS9 | [N/H] |
| 1 | Li I   |        |        | 1.86   |        | 1.84(15) |
| 2 | C I    | -2.43(00) | 2      | -2.22(05) | -2.22(05) | 2   |
| 3 | N I    | -1.69(08) | 2      | -1.89(05) | -1.89(05) | 2   |
| 4 | N I    | -1.77(10) | 9      | 1.92(00) | 1.92(00) | 2   |
| 5 | Na I   | -2.00(09) | 43     | -1.97(07) | -1.97(07) | 8   |
| 6 | Mg I   | -1.77(10) | 19     | -1.64(14) | -1.64(14) | 9   |
| 7 | Si I   | -2.20(09) | 11     | -2.10    | -2.10    | 1   |
| 8 | Si I   | -1.86(07) | 21     | -1.84(15)| -1.84(15)| 10  |
| 9 | S I    | -2.26(09) | 10     | -2.20(01)| -2.20(01)| 2   |
| 10| K I    | -2.03(12) | 3      | -2.12(14)| -2.12(14)| 3   |
| 11| Ca I   | -2.04(11) | 23     | -1.99(07)| -1.99(07)| 5   |
| 12| Sc I   | -2.07(08) | 50     | -2.12(11)| -2.12(11)| 15  |
| 13| Ti I   | -1.77(10) | 19     | -1.86(14)| -1.86(14)| 9   |
| 14| V I    | -1.86(07) | 21     | -1.84(15)| -1.84(15)| 10  |
| 15| Cr I   | -2.26(09) | 10     | -2.20(01)| -2.20(01)| 2   |
| 16| Mn I   | -2.03(12) | 3      | -2.12(14)| -2.12(14)| 3   |
| 17| Fe I   | -2.04(11) | 23     | -1.99(07)| -1.99(07)| 5   |
| 18| Fe II  | -1.77(10) | 19     | -1.86(14)| -1.86(14)| 9   |
| 19| Ni I   | -2.07(08) | 50     | -2.12(11)| -2.12(11)| 15  |
| 20| Cu I   | -1.83     | 1      | -1.82(03)| -1.82(03)| 2   |
| 21| Zn I   | -2.23     | 1      | -2.02    | -2.02    | 1   |
| 22| Sr I   | -2.23     | 1      | -2.02    | -2.02    | 1   |
| 23| Y II   | -2.12(10) | 10     | -2.22(15)| -2.22(15)| 5   |
| 24| Zr II  | -2.23     | 1      | -2.12    | -2.12    | 1   |
| 25| Mo I   | -2.22     | 1      | -2.09(16)| -2.09(16)| 2   |
| 26| Ba II  | -2.03(12) | 3      | -2.12(14)| -2.12(14)| 3   |
| 27| La II  | -1.90(06) | 13     | -1.90(13)| -1.90(13)| 14  |
| 28| Ce II  | -1.56(14) | 5      | -1.56(14)| -1.56(14)| 14  |
| 29| Pr II  | -1.56(06) | 3      | -1.56(06)| -1.56(06)| 12  |
| 30| Nd II  | -1.46(18) | 2      | -1.46(18)| -1.46(18)| 6   |
| 31| Sm II  | -1.57(13) | 2      | -1.57(13)| -1.57(13)| 2   |
| 32| Eu II  | -1.57(09) | 2      | -1.57(09)| -1.57(09)| 2   |
| 33| Gd II  | -1.54(09) | 3      | -1.54(09)| -1.54(09)| 3   |
| 34| Dy II  | -1.55     | 1      | -1.25(11)| -1.25(11)| 6   |
| 35| Er II  | -1.35     | 1      | -1.38    | -1.38    | 1   |
| 36| Tm II  | -1.15     | 1      | -1.15    | -1.15    | 1   |
| 37| Hf II  | -1.23     | 1      | -1.23    | -1.23    | 1   |
| 38| W I    | -1.69     | 1      | -1.69    | -1.69    | 1    |
| 39| Os I   | -1.23     | 1      | -1.23    | -1.23    | 1    |
| 40| Ir I   | -1.18     | 1      | -1.18    | -1.18    | 1    |
| 41| Pt I   | -1.85     | 1      | -1.85    | -1.85    | 1    |
| 42| Rh II  | -1.21     | 1      | -1.21    | -1.21    | 1    |
| 43| Pd II  | -1.27     | 1      | -1.27    | -1.27    | 1    |
|   | U II   | -1.45(30) | 8      | -1.45(30)| -1.45(30)| 8   |
|   | U II   | -1.55(19) | 5      | -1.55(19)| -1.55(19)| 5   |

1 adopted from molecular lines
2 Only lines with Nilsson et al. (2002a,b) oscillator strengths
Table 1 and 2 contain data on lines for iron and other chemical elements. Table 1 provides the ionization stage, equivalent width, oscillator strength, energy of lower level and derived iron abundance for each iron wavelength considered. For the other elements, Table 2 gives in addition to the line data (identification, wavelength, oscillator strength, the energy of lower level), the abundance determination (relative abundance with respect to the solar system value, and absolute values of the abundance calculated from this line using the spectrum of HD221170 and the solar spectrum), the levels of blending of the line in the synthetic spectra of HD221170 and of the Sun, the depths of the line in the synthetic spectra of HD221170 and of the Sun, and the abundances in the atmosphere of HD221170, calculated with two different atmosphere models, namely for a surface gravity increased by 0.2 dex, and for an effective temperature increased by 100 K.

In Table 3, the mean elemental abundances in the atmosphere of HD221170 are given with respect to the solar atmosphere value. For all investigated elements, Table 3 includes information on the atomic number, designation of the ionization stage, as well as the relative abundances (the last digits in brackets correspond to the estimated errors) and the number of lines determined in Paper I and in the present study. Mean abundances are calculated with the best set of atmosphere parameters, with a surface gravity increased by 0.2 dex and with an effective temperature increased by 100 K. The absolute abundances are available in the electronic version of the table. A comparison of our abundances with previously published data can be found in Paper I. The abundances of Mo, Er, Tm, Hf, W, Os, Ir, Th, and U first determined by Yushchenko et al. (2002) are updated in the present study.

In Table 4 we show the differential and absolute abundances of iron and some of the key elements used to trace back the nucleosynthesis and corresponding cosmochronometry discussed below. The errors correspond to the standard deviations of abundances derived from the individual lines of the element. For uranium and thorium, only lines with new oscillator strengths are considered.

Concerning the detection of carbon and nitrogen, their atomic lines are hardly detectable, so that their abundance determinations are usually based on molecular lines. We calculated several synthetic spectra in the whole observed region using different C and O abundances and found...
Table 4. Abundance of iron and of some elements determined in the present work. The columns provide, respectively, the atomic number, the element symbol, the number of lines analyzed, the mean abundance in the atmosphere of HD221170 with respect to solar photosphere (Grevesse & Sauval 1998) and the abundance in the scale logN(H)=12.

| Z   | Ident. | N       | Δlog N  | logN     |
|-----|--------|---------|---------|----------|
| 26  | Fe I   | 221     | -2.09±0.07 | 5.41±0.07 |
| 63  | Eu II  | 6       | -1.54±0.13 | -1.03±0.13 |
| 76  | Os I   | 4       | -1.23±0.12 | 0.22±0.12  |
| 77  | Ir I   | 1       | 0.17±0.20  |          |
| 82  | Pb I   | 1       | -1.85±0.29 | 0.10±0.20  |
| 90  | Th II  | 5       | -1.18±0.11 |          |
| 92  | U II   | 5       | < -2.02±0.20 |         |

Fig. 7. The abundances of chemical elements and ions in the atmosphere of HD221170 with respect to the solar atmosphere value. Triangles correspond to upper limits for Li, Al, U.

abundances close to -2.7 and -2.13 with respect to the Sun. This result is in good agreement with Sneden et al. (1986) and Craft et al. (1992), so that it is adopted in the abundance determination of the other elements. Special attention was also paid to the determination of the isotopic carbon ratio which can strongly influence the final results. To estimate the 12C/13C ratio, several synthetic spectra were calculated and compared with observation. We finally obtained the value of 12C/13C=6 in agreement with the determination of Sneden et al. (1986).

The wavelengths of several 13CH lines were changed according to Johnson & Bolte (2001). The corresponding list of spectral lines in the vicinity of the Th II 4019.128 Å line was considered in our calculations. Note that our result concerning the thorium abundance is based on 5 lines with Nilsson et al. (2002) oscillator strengths. Similar abundances are obtained with all these lines. We therefore recommend them for future abundance determinations in other stars.

4. Discussion

About half of the stable nuclei heavier than iron in the Universe are synthesized by the rapid neutron-capture process, also known as the r-process. The r-process is believed to occur predominantly in the latest stages of evolution of massive stars (heavier than about 10 solar masses) during their supernova explosion. Fig. 8 compares HD221170 abundances with the solar content in r-process nuclei. It clearly shows that for elements heavier than Ba (Z=56), the HD221170 surface abundance pattern is very similar to the solar one. Globally, it confirms the previous observation of ultra-metal-poor stars (Westin et al. 2000; Cayrel et al. 2001; Hill et al. 2002; Cowan et al. 2002; Sneden et al. 1998, 2003) that already in the early age of the Galaxy, the r-process was operational and quite unique in its production of, at least, the Z=56 to 78 elements all along the life of the Galaxy. However, the universality of the r-process for the production of elements Z=56, including the Pb-peak elements and the actinides, still remains to be confirmed. Such a universality has deep implications in particular the invariance of the relative r-nuclidic abundances with respect to galactic chemical evolution effects and the possibility to develop a stellar chronometry based on the actinide content of the metal-poor stars and consequently to estimate a lower limit to the age of the Galaxy.

Although for most of the elements with Z=56-78 the present observations seem to confirm this conclusion, the specific cases of Eu and Hf observed in HD221170 show the first indication of a non-negligible deviation with respect to the solar pattern (Fig. 8). Such a deviation remains rather small, but, as shown by Goriely & Arnould (1997), large deviations are not expected in this mass region because of the nuclear correlations inherent to the nuclear aspects of the r-process nucleosynthesis. It was shown in the previous section that taking into account the hyperfine and isotopic structure of Hf lines could reduce the deviation but not to the extent to become compatible with the solar pattern. In the case of Eu, the abundance determination includes the splitting effects in both HD221170 and the Sun.

In this comparison with the solar r-abundance distribution, another interesting feature of HD221170 is its high Pb surface abundance. Such an unusually high abundance has been already observed in the previous ultra-metal-poor r-process-enriched stars except CS31082-001. Lead can be efficiently produced by the r-process, but also by the slow neutron-capture process, known as the s-process, during the AGB phase of low-metallicity stars with masses in the range 0.8-8 solar masses (Van Eck et al. 2001). Such a Pb s-enrichment is however systematically accompanied by a simultaneous carbon enrichment. For this reason, the significant Pb enrichment of a star like CS22892-052 characterized by a large C/O>1 ratio could be explained by...
Table 5. Comparison of abundance ratios (in log scale) in Th-rich stars. The second column gives the metallicity in terms of [Fe/H].

| Star             | [Fe/H] | Th/Eu | Th/Pb   | Th/U   |
|------------------|--------|-------|---------|--------|
| HD221170         | -2.1   | -0.15 | -1.28   | >0.84  |
| CS31082-001a     | -2.9   | -0.22 | >-0.78  | 0.94   |
| CS22892-052b     | -3.1   | -0.62 | -1.62   | >0.73  |
| HD115444c        | -3.0   | -0.60 | -1.8d   | >0.40  |
| BD+17°3248c      | -2.1   | -0.51 | >1.48   | >0.82  |

*a* Hill et al. (2002).  
*b* Sneden et al. (2003).  
*c* Westin et al. (2000) for all ratios except Th/Pb.  
*d* Th: Westin et al. (2000), Pb: Sneden et al. (1998).  
*e* Cowan et al. (2002).

Finally, the present observation provides an accurate determination of the surface Th as well as an upper limit of U abundances in HD221170. These actinides have been used extensively in recent years to estimate the age of the oldest metal-poor stars of the Galaxy and in so doing, a lower limit to the age of our Galaxy. The Th/Eu, Th/Pb and Th/U abundance ratios in HD221170 are compared in Table 5 to the corresponding ratios determined in the other four r-process-rich metal-poor stars. These ratios are of particular interest since they compare the Th abundance to light species (represented here by Eu), Pb (believed to be produced in the same “environment” as Th, see e.g. Goriely & Clerbaux, 1999) and U, a neighboring element. Based on the universality of the r-process, a relatively reliable Th/U chronometry can be built. An absolute determination of the Th and U abundances has been achieved for CS31082-001 only, leading to an age estimate of 13±4 Gyr (Hill et al. 2002; Goriely & Arnould 2001). From Table 5, it can be deduced from the Th/U ratio that, within the universality assumption, HD221170 is older or at most 2 Gyr younger than CS31082-001.

The HD221170 Th/Eu ratio is seen to be the highest among the different stars, which is compatible with its relatively higher metallicity [Fe/H]. However, assuming the universality of the r-process, i.e. the same original actinide production in all these stars (relative to the Z = 56 – 78 r-elements), this would imply that HD221170 is younger than CS22892-052 by about 22±4 Gyr, but also younger by 17±4 Gyr than BD+17°3248, a star of similar metallicity. This would imply that BD+17°3248 would be at least 28 Gyr old, an observation that is difficult to reconcile with the traditional Big-Bang cosmology or the WMAP observation. It is also seen that as far as the Th/Eu ratio is concerned, HD221170 is compatible with CS31082-001, clearly confirming that the Th-rich star CS31082-001 is not a rare exceptional case. This conclusion was also drawn by Honda et al. (2004) who determined at the surface of CS30306-132 a ratio of [Th/Eu]=−0.10 even higher than for CS31082-001 or HD221170. The Th/Pb ratios shown in Table 5 again confirms the previous conclusion that there is a large scatter in the r-abundances for the heaviest elements. The Th/Pb chronometry assuming the universality of the r-process would lead to the conclusion that HD115444 is older than CS31082-001 (of similar metallicity) by about 48±14 Gyr.

5. Conclusion

We determined the abundances of 43 chemical elements (including Th and U) in the atmosphere of the bright halo star HD221170. The present spectroscopic observation indicates that the r-process is not universal or more exactly the astrophysical site(s) hosting the r-process do(es) not always lead to a unique relative abundance distribution for the bulk Ba to Hg elements, the Pb-peak elements, and the actinides. Although the previous observations of CS22892-052, HD115444 and BD+17°3248 suggested the universal feature of the r-process, the present HD221170 analysis confirms the non-universal trend originally suggested by the CS31082-001 observation. This new finding rules out the use of thorium chronometry to estimate the age of the oldest stars in the Galaxy.

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