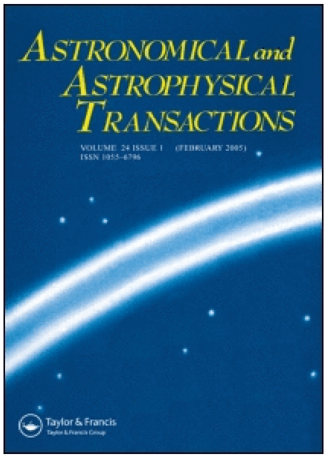

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Abundances of neutron-capture elements in red giant stars

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Abundances of neutron-capture elements in red giant stars

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The neutron-capture element abundances in the 52 red giants with metallicities spanning the range $-0.6 < [\mathrm{Fe}]/[\mathrm{H}] < 0.25$ are found. High-resolution spectra ($R = 42000$; $S/N > 100$) for the investigated stars were obtained with the ELODIE spectrograph of the 1.93 m telescope at the Observatoire de Haute Provence (France). The determination of elemental abundances was carried out with the local thermodynamic equilibrium assumption by the model atmosphere method; for Ba and Eu the hyperfine structure was taken into account. The dependences of the neutron-capture element abundances on metallicity are presented.

Keywords: Red giant stars; Abundances; Neutron-capture elements

1. Introduction

The heavy elements ($Z > 30$) in the Solar System are formed in neutron-capture processes, by either the slow or the rapid process [1].

At relatively low neutron densities, if the time between neutron captures is longer than the β-decay time, these captures are referred to as slow processes. The rapid process has traditionally been related to an astrophysical process taking place in a highly neutron-rich environment, in which the mean time between neutron captures is very short compared with the β-decay time.

The theory proposes the existence of different astrophysical sites for the operation of the two neutron-capture nucleosynthesis mechanisms. For the case of the slow process, the two astrophysical sources are, firstly, the He-burning cores of massive stars ($M > 10M_{\odot}$) [2–4] and, secondly, the thermally pulsing He shells of asymptotic giant branch stars [5, 6]. However, the specific site or sites of the rapid process is an unsolved problem, although there have been some suggestions considering the type II supernovae explosions [4, 7], the mergers of neutron stars [8, 9], accretion-induced collapse [10] and type 1.5 supernovae [11] as the possible sources.

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In this paper, we continue our discussion of elemental abundance ratios for low-mass stars in the Galactic disc. The effective temperatures $T_{\rm eff}$, the elemental abundances of C, N and O, the α elements, the elements of the Fe peak and the neutron-capture elements Y, Ba and Eu were determined earlier [12–14]. In this review we present a new determination of the Zr and Sm abundances.

2. Observations and parameters

The spectra of the studied stars were obtained on 1.93 m telescope of the Observatoire de Haute Provence (France) equipped with the echelle spectrograph ELODIE [15]. The resolving power was 42 000 in the wavelength range $\lambda = 3850$–6800 Å. Spectrum extraction, wavelength calibration and radial velocity measurement have been performed at the telescope with the online data reduction software, while straightening of the orders and removal of cosmic-ray hits, bad pixels and telluric lines were performed as described in [16]. We carried out continuum level drawing and equivalent width measurements using the DECH20 code [17]. The equivalent widths of lines were measured by Gaussian function fitting. The temperatures were determined with a very high level of accuracy using the line depth ratios [12]. The logarithm of the surface gravity g was determined using the Fe ionization equilibrium assumption, where the average Fe abundances determined from the Fe I lines and Fe II lines must be identical. The microturbulent velocities $V_{\rm t}$ were determined by forcing the abundances determined from individual Fe I lines to be independent of the equivalent width. The parameters for the stars studied are presented in table 1.

3. Elemental abundance determination

Using the derived stellar parameters and the atmosphere models given by Kurucz [18] we determined the elemental abundances of Y, Zr and Sm from a local thermodynamic equilibrium analysis of equivalent widths using the WIDTH9 code. The solar abundances of Y, Zr and Sm ($\log\{[\epsilon({\rm Y})]_\odot\} = 2.24$, $\log\{[\epsilon({\rm Zr})]_\odot\} = 2.6$ and $\log\{[\epsilon({\rm Sm})]_\odot\} = 1.01$) were calculated with the solar model given by Kurucz [18] from the spectra of the Moon and asteroids that were obtained with the echelle spectrograph ELODIE. The oscillator strengths for the Zr II and Sm II lines have been adjusted as described in [19]. The lines included in our analysis and atomic data are listed in table 2.

The mean Y, Zr and Sm abundances are $[{\rm Y}]/[{\rm Fe}] = -0.09 \pm 0.09$, $[{\rm Zr}]/[{\rm Fe}] = -0.04 \pm 0.06$ and $[{\rm Sm}]/[{\rm Fe}] = 0.04 \pm 0.07$, respectively.

The Ba and Eu abundances are determined from line profile fitting of the stellar spectra using the STARSP code developed by Tsymbal [20].

The elemental abundances are derived from the Ba II resonance line ($\lambda = 4555$ Å) and from the Eu II subordinate line ($\lambda = 6645$ Å). The Ba II and Eu II ions considered here have lines that show appreciable hyperfine structure. The atomic data for these lines were taken from [21]. Recent non-local thermodynamic equilibrium (NLTE) calculations for Ba II and Eu II have been carried out and were reported in [21, 22]. It was shown that, for the Ba II line ($\lambda = 4555$ Å) that we used in our calculations, the NLTE effects are small for $[{\rm Fe}]/[{\rm H}] > -1.9$. For the Eu II line ($\lambda = 6645$ Å) the NLTE correction ranges from 0.04 dex to 0.06 dex. Therefore, we did not take into account the NLTE effects in our calculations. The solar Ba and Eu abundances, $\log\{[\epsilon({\rm Ba})]_\odot\} = 2.21$ and $\log\{[\epsilon({\rm Eu})]_\odot\} = 0.53$, and the van der Waals damping constants C_6 for the Ba II and Eu II lines were determined in [21] from solar line profile fitting. The

Table 1. Atmospheric parameters and neutron-capture abundances.

H_d	T_{eff}	log g	[Fe]/[H]	[Y]	[Zr]	[Ba]	[Eu]	[Sm]
2 910	4756	2.7	0.12	−0.03	−0.04	−0.18	0.07	0.04
4 188	4809	2.7	0.04	0	0	−0.05	0.13	−0.06
4 482	4917	2.65	0.02	−0.11	0.02	0.07	0.02	−0.05
5 395	4849	2.15	−0.32	−0.24	−0.06	−0.09	−0.01	−0.06
6 319	4650	2.3	0.06	−0.14	−0.06	−0.17	0.06	0
6 482	4738	2.4	−0.11	−0.29	−0.07	0.05	0.23	0.01
7 106	4684	2.55	0.05	−0.19	−0.18	−0.16	−0.43	−0.02
7 578	4680	2.5	0.12	−0.09	−0.01	−0.13	0.03	0.2
8 207	4750	2.75	0.27	−0.26	−0.01	−0.18	0.05	−0.09
8 599	4781	2.5	−0.22	−0.06	−0.11	0.11	0.09	0.21
8 733	4932	2.7	0.02	−0.13	−0.08	0.07	−0.05	−0.02
9 408	4804	2.3	−0.21	−0.04	−0.13	0.05	0.18	−0.03
10 975	4881	2.4	−0.19	−0.07	−0.01	0.08	0.34	0.12
11 559	4977	3	0.05	−0.13	0.03	−0.06	−0.23	0.02
11 749	4679	2.4	−0.1	−0.22	−0.03	−0.01	0.17	0.01
11 949	4708	2.3	−0.16	−0.11	−0.08	0.1	0.13	0.04
15 453	4696	2.4	−0.07	−0.1	0.06	0.01	0.04	−0.06
15 755	4611	2.3	−0.01	−0.2	−0.07	−0.1	−0.02	−0.03
15 779	4821	2.7	0.02	−0.06	−0.02	−0.03	0.15	−0.02
16 247	4629	2.2	−0.22	−0.02	−0.06	0.06	0.09	0.15
16 400	4840	2.5	−0.01	0.06	0	0.05	0.08	0.06
17 361	4646	2.5	0.12	−0.17	−0.08	−0.18	0	0.04
18 885	4722	2.5	0.16	−0.16	−0.14	−0.17	−0.09	0.03
19 270	4723	2.4	0.15	−0.22	−0.16	−0.06	0.02	0.13
19 787	4832	2.75	0.14	−0.14	−0.02	−0.05	0.05	0.02
19 845	4933	2.8	0.11	−0.01	−0.02	−0.92	0.06	0.04
20 791	4986	2.8	0.11	−0.08	0	0.03	0.08	0.16
25 602	4693	2.4	−0.42	−0.08	−0.08	0.01	0.12	0.09
25 604	4764	2.7	0.13	0.06	−0.01	−0.14	0.04	0.06
26 546	4743	2.25	−0.01	−0.06	−0.08	0	0.03	0.03
26 659	5178	2.9	−0.13	0.02	0.03	0.22	0.05	0.01
26 755	4630	2.2	−0.06	−0.11	0	−0.05	0.08	0.09
27 348	5003	2.8	0.14	−0.09	−0.1	−0.05	−0.07	−0.02
27 371	4955	2.7	0.11	−0.11	−0.05	−0.07	0.06	0.06
27 697	4975	2.65	0.11	−0.1	−0.06	−0.02	0.01	0.05
28 292	4453	2.1	−0.18	−0.11	0.01	0.02	0.17	0.1
28 305	4925	2.55	0.11	−0.11	−0.06	−0.02	0.01	0.06
28 307	4961	2.7	0.12	−0.11	−0.03	−0.13	0	−0.08
30 557	4829	2.45	−0.07	0.03	0.04	0.16	0.14	0.09
31 444	5080	2.75	−0.17	0	0.12	0.16	0.19	0.11
33 419	4708	2.3	0	−0.11	−0.03	−0.01	0.02	0.16
33 618	4590	2.3	0.05	−0.08	−0.07	−0.06	0.02	0.14
34 200	5055	2.8	0.04	−0.09	−0.06	0.05	0.08	−0.06
34 559	5010	2.9	0.04	0.13	0.08	0.1	0.18	0.05
35 369	4931	2.4	−0.14	−0.11	−0.06	0.23	0.21	0.08
37 638	5093	2.8	−0.01	0.1	0	0.1	0.13	0.01
39 070	5047	2.8	0.03	−0.03	0	−0.04	0.09	−0.02
39 910	4618	2.6	0.27	−0.12	−0.05	−0.13	0.05	0.11
40 020	4670	2.3	0.13	−0.26	−0.13	−0.19	−0.06	0.02
40 801	4703	2.2	−0.21	−0.19	−0.15	0.2	0	−0.06
42 341	4655	2.6	0.25	−0.11	−0.11	−0.21	−0.03	0.08
43 023	4994	2.6	−0.13	0.05	−0.08	0.12	0	0.04

mean Ba and Eu abundances are $[Ba]/[Fe] = -0.02 \pm 0.11$ and $[Eu]/[Fe] = 0.09 \pm 0.12$, respectively.

The obtained abundances are presented in table 1.

The dependences of the neutron-capture element abundances on metallicity are presented in figure 1.

Table 2. Oscillator strengths for the lines used.

Ion	λ	X (eV)	log gf
Zr II	5112.28	1.66	−0.79
	5350.09	1.76	−0.89
	5350.36	1.81	−0.8
	6114.79	1.66	−1.48
Sm II	4523.92	0.43	−0.08
	4577.69	0.25	−0.61

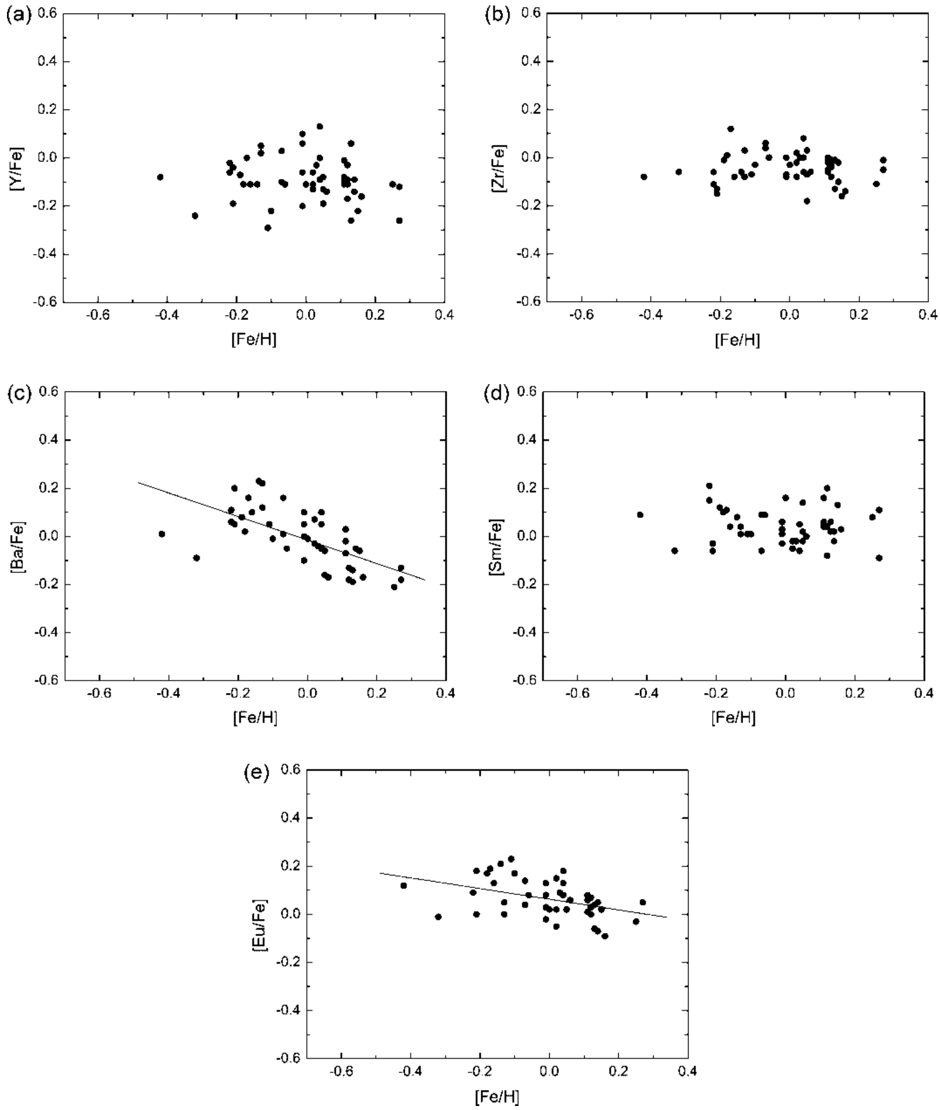

Figure 1. The abundance ratios [X]/[Fe] versus [Fe]/[H]: (a); (b); (c); (d); (e).

4. Conclusions

(1) Using spectra of high quality, we have carried out an analysis of the abundances of the 'lighter' neutron-capture elements Y and Zr and the 'heavier' elements Ba, Sm and Eu in the stars of the Galactic disc.
(2) We observe in our sample of giants the trends of [Ba]/[Fe] and [Eu]/[Fe] versus [Fe]/[H] and there is no correlation between [Y]/[Fe], [Zr]/[Fe] and [Sm]/[Fe] versus [Fe]/[H].

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