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High-resolution spectroscopy of giant stars in the open clusters IC 4651 and IC 4725

Orlando J. Katime Santrich and Silvia Rossi

Abstract: Open clusters are important astrophysical laboratories to study the stellar formation and evolution and to verify the disk structure of the Milky Way. We present calculations of stellar atmospheric parameters and s-process abundances for 9 giant stars in the galactic open clusters IC 4651 & IC 4725. These objects have their memberships confirmed from dynamic studies and chemical analysis. The high resolution spectra are available in the FEROS ESO archive. We have applied an line by line analysis relative to Juno solar spectrum to determine the stellar atmospheric parameters and chemical abundances of Y II, Zr I, La II, Ce II and Nd II under LTE-hypothesis. The obtained results were compared to the literature values. The derived s-process abundance pattern agrees with the most recent behaviors reported for giant stars in galactic open clusters.

Resume français:

1. Introduction

Open clusters (OC) can be seen as important astrophysical objects to study stellar formation and evolution, and galactic structure and evolution. These objects help us to understand how conceivable is the simultaneous formation and evolution of stars from the same molecular cloud. They can also be thought as laboratories to study the stellar interiors because chemical abundance studies allow to probe usual assumptions made about mixing phenomena at RGB (Red Giant Branch) and AGB (Asymptotic Giant Branch) stellar evolutionary phases. One of the most promising ways to analyze the structure of the Milky Way (MW), specifically its disk, is studying OCs since their radial metallicity gradients outline the disk structure and reveal the distinction between thin and thick disk. To unveil the formation of the Galaxy is crucial to analyze the galactic thin disk as it is the component with higher stellar formation rate and the easiest to be observed.

Calculations of heavy element abundances have become more and more important in recent years. There are only a few stars in OC with such measured abundances since high signal-to-noise (S/N) spectra are necessary to identify the absorption lines of those elements. Besides that, the existence of strong molecular opacity make hard tangle these calculations such as it happens in the spectra of AGB stars. Furthermore, abundances of s-process elements in RGB cluster stars are interesting to find changes in the stellar evolution, as found in Barium Stars due to mass transfer events [1].

In this work we present abundances of heavy elements for two galactic OC, IC 4651 and IC 4725. These clusters are the first analyzed within our project on the behavior of the heavy elements in the galactic disk. IC 4651 was studied by many different authors [2], [3], [4], [5] & [6], but no s-process element abundances were determined. In addition, there are three stars in common with the work of [7] which present abundances of many chemical elements. IC 4725 has two stars in common with [8]. Whenever possible, we compare our results with those obtained in the literature.

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2. Methodology

Data for IC 4651 and IC 4725 appear in many different sources. Information on distance, reddening, distance modulus and age were gathered from WEBDA¹ website and are presented in Table 1.

The high resolution spectra ($R = 48\,000$) were obtained from FEROS ESO archive. Stars have their memberships confirmed from dynamic studies [9]. The stars analyzed in this work are shown in Table 2. For all stars in OC IC 4651 the exposure times were 1800 s, while for IC 4725–150 and IC 4725–251 exposure times were 90 s and 60 s, respectively. For all stars, the spectra have the (S/N) around 200 and for the Juno solar spectrum is 800.

Radial velocities for stars considered in this work were obtained from Doppler shift and are shown in Table 2. Note that exists a difference of almost 5 km s^{-1} between our V_r^a and V_r^b for the star IC 4651–14527. However, our adopted value ($V_r^a = -27.16 \pm 0.96$) is very similar to the value found by [10] of -27.88 km s^{-1} . The spectrum from [10] was observed in 04/29/2000 while our was obtained in 06/29/2010, according to the ESO/archive. In the Mermilliod's survey, IC 4651–14527 was observed between 03/08/1983 and 07/10/1996 and is not reported as binary. Therefore, this star has a very low probability to be binary and, if so, its orbit would be very eccentric.

Stellar atmospheric parameters and s-process abundances were calculated based on LTE-hypothesis: effective temperatures were obtained from excitation equilibrium, microturbulence velocities from zero slope between Fe I abundances and reduced equivalent width, surface gravities from ionization equilibrium between Fe I and Fe II lines, and the metallicity [Fe/H] is established from the final value fixed by the ionization equilibrium. Because of our sample has stellar parameters published in the literature, these values were used as initial guesses in the process. For the stars IC 4651–6333 and –9025 with no previous spectroscopic analysis, the mean values for T_{eff} , $\log g$, ξ and [Fe/H] of the cluster IC 4651 were used as initial values in the calculations.

In this type of spectroscopic analysis is always necessary to use the Sun as the reference star, for both dwarf and giant stars. In some cases, giants are compared to the Arcturus giant but it is very frequent to transform the Arcturus abundances in solar. **In this work, to obtain stellar parameters and s-process abundances with the best possible precision, we have decided to use a line-by-line analysis (lbl analysis) relative to Juno² solar spectrum. This method allows to get abundances by means of the relationship: $\delta A_i = A_i^* - A_i^\odot$, where A_i^* is the stellar logarithmic abundance of a chemical species i for a given wavelength λ , and $A_i^\odot$ is the same related to the Sun. Accordingly δA_i represents the differential abundance of the species i for the same λ .**

This method has been used for several purposes in the literature as to study stellar evolution effects [11] and [12], to find planetary signatures in host-stars [13], [14] and [15], to calculate chemical abundances in the solar neighborhood [16] and [17], to find abundance anomalies in stellar clusters [18] and to distinct populations in the stellar halo [19] and [20]. [21]³ show a comparison between the classical and differential abundance estimates.

To carry out the analysis we have used the python-code q²(qoyllur-quipu⁴). This code uses the Kurucz atmospheric grids⁵ and spectral code MOOG⁶. The absorption lines of the Iron I & II were taken from [23] and [24] and are shown in Table 7. The lines of the s-process elements were taken from several sources and are shown in Table 8.

¹ database available on <https://www.univie.ac.at/webda/>

² Juno is a solar reflection spectrum used as reference to carry out the analysis.

³ paper presented at ASOS 12

⁴ this code was developed by [22] and is available on <https://github.com/astroChasqui/q2>

⁵ grids available on <http://kurucz.harvard.edu/grids.html>

⁶ available in its last version on <http://www.as.utexas.edu/chris/moog.html>

3. Results and analysis

The open cluster IC 4651 was previously studied in the literature using high-resolution spectroscopy. The stellar atmospheric parameters for the stars IC 4651–7646 and –9122 were calculated by [5] while [7] calculated the chemical abundances for the stars IC 4651–8540, –9791 and –14527 using the stellar parameters calculated by [10]. The stars IC 4651–6333 & –9025 have no previous determination of chemical abundances, and therefore, it is the first time they are spectroscopically studied. In the case of IC 4725, [8] has also analyzed the stars IC 4725–150 & –251. This OC has no other stars chemically studied.

Such as can be observed in Table 3, the results indicate that the studied sample has effective temperatures and surface gravities typically of cool giant stars. The metallicities are slightly enhanced in IC 4651–7646, IC 4651–9025, IC 4651–14527 and IC 4725–150 while for IC 4651–8540, IC 4651–9791 and IC 4725–251 are slightly lower than the solar value. IC 4651–6333 and IC 4651–9122 have solar metallicities.

Chemical abundances for the s-process elements are shown in Table 4. From these results we have noted that there is a small enhancement of La II and Nd II in some stars when compared with the field giants, showed in Figure 1 left. Those elements have a tendency to be lightly increased in the two OC. However, this enhancement is not large enough to consider these cluster giants as stars with s-process overabundances such as it happens with the Barium stars discovered in the OC NGC 5822 [1]. Furthermore, this figure also shows that $[s/Fe]$ ratios found in these cluster giants are similar to the ones in the field. The Figure 1 right presents a comparison between our results and other cluster giants reported in the literature. These OC were divided by age using the criteria of [25]: old (age > 1.0 Gyr) and young (age < 1.0 Gyr) OC. This separation is important to unveil the differences between the thin and thick galactic disks because the old OC can offer a view of what could be happening on the thick disk. Old and young OC can also be important to ascertain the differences in abundances, because if there are, they could be due to nuclear processes in intermediate-mass stars, such like that in globular clusters [26]. The literature data were taken from [26]; [27]; [28]; [29]; [30]; [31]; [32]; [33]; [34]; [35]; [36]; [37]; [38]; [39] and [40]. It has to be mentioned that IC 4651 and IC 4725 have average s-process element abundances in agreement with other cluster giants in literature.

Fig. 1. Left: s-process abundances star by star. Black crosses: field giants of [41]; blue crosses: field giants [42]; green squares: barium stars of [1]; green triangles: giants in IC 4725; red triangles: giants in IC 4651. Right: s-process abundances by cluster. Black squares: old OC from literature; blue squares: young OC from literature; green square: IC 4725; red square: IC 4651.

In Table 5 are shown the stellar parameters calculated by [10] and s-process abundances calculated by [7] for the stars IC 4651–9791, –8540 and –14527. We can see that there are more differences than similarities between our results and theirs. This may be due to differences in the way of analysis. [10], for instance, did automatic measurements of equivalent widths using the spectrum analysis package developed in Padova [43] and [44], while [7] used Carretta's ([10]) stellar parameters to calculate their chemical abundances. In the case of IC 4725, the differences should be on the log gf values used by [8]. The authors [8], [10] and [7] used different line lists and none of them performed the lbl analysis as done in this work.

In order to apply the lbl analysis is necessary that the objects and the standard star have similar spectral types (F, G or K in this case). This is observed in the Table 2 where six stars in the two OC have spectral types G & K confirmed. Another constrain is that the absorption lines are formed in different atmospheric regions in giants and dwarfs. Then, this analysis among them are limited by the number of lines, specially when the s-process lines are considered. However, if the solar spectrum has high (S/N) is possible to obtain high precision abundances, even with few lines available. To show this, we compare non-differential with differential Nd II abundances for the star IC 4651–14527, see Table 6. Then, in the non-differential we obtained the mean abundance ratios of $[\text{Nd II}/\text{H}]_1 = 0.631 \pm 0.479$ dex, $[\text{Nd II}/\text{H}]_2 = 0.795 \pm 0.458$ dex and $[\text{Nd II}/\text{H}]_1 = 0.678 \pm 0.519$ dex by using the solar abundance of $\log \text{Nd II} = 1.42$ dex [45] and the mean values of $(\log \text{Nd II})_1 = 2.051$ dex; $(\log \text{Nd II})_2 = 2.215$ dex and $(\log \text{Nd II})_3 = 2.098$ dex respectively. While for lbl analysis we obtained the mean abundance ratio of $\delta[\text{Nd II}/\text{H}] = 0.168 \pm 0.230$ dex. This last value is in better agreement with those expected to RGB stars.

4. Conclusions

Because of important differences reported in the literature, the differential method is the best option to eliminate the dependency on the log gf values that chemical abundance calculations present. In this work, the line-by-line analysis relative to Juno solar spectrum was an excellent option to avoid long and subjective comparisons between the different line lists published in literature. This situation is specially shown for the Nd II abundances in the star IC 4651–14527. From its atmospheric parameters we see that this star is not in AGB-phase and, as mentioned above, it has a very low probability of being binary. Then it is very unlikely that this star has overabundances of the s-process (Nd II in this case) as shown by the abundance ratios $[\text{Nd II}/\text{H}]_1 = 0.631 \pm 0.479$ dex, $[\text{Nd II}/\text{H}]_2 = 0.795 \pm 0.458$ dex and $[\text{Nd II}/\text{H}]_1 = 0.678 \pm 0.519$ dex. Therefore the value $\delta[\text{Nd II}/\text{H}] = 0.168 \pm 0.230$ dex obtained from the lbl analysis is the most plausible in this case.

For the first time the stars IC 4651–6333 and –9025 were studied, since no previous abundance results were found in the literature. Their stellar parameters and s-process abundances are similar to the other giants within IC 4651. We obtained abundances for the chemical elements La II and Ce II in IC 4725. The stars IC 4725–150 & –251 have no previous results for these elements.

The stars analyzed in this work show stellar parameters in accordance to RGB stars and chemical abundances similar to other cluster giants of the galactic disk also studied using high-resolution. In other words, our results are congruent with the global chemical evolution of the MW. This is an ongoing project and more stars in different OC will be analysed in the future.

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Table 1. Basic parameters for the open clusters analyzed in this paper.

Parameter	IC 4651	IC 4725
Right ascension α (2000)	17 24 49	18 31 47
Declination δ (2000)	−49 56 00	−19 07 00
Galactic longitude	340.09	13.70
Galactic latitude	−7.91	−4.43
Distance [pc]	888	620
Reddening [mag]	0.12	0.48
Distance modulus [mag]	10.10	10.44
log Age	9.06	7.97

Note. Information obtained from WEBDA database: <http://www.univie.ac.at/webda/>

Table 2. Stars analyzed in this work.

Star	α	δ	V	B−V	V_r^a Km s ^{−1}	V_r^b Km s ^{−1}	Spec. type (source)
IC 4651−6333	17 24 33	−49 54 56	10.75	0.96	−29.56±0.79	−30.87±0.10	—
IC 4651−7646	17 24 42	−49 59 06	10.36	1.04	−30.65±0.96	−31.18±0.13	K0 (WEBDA)
IC 4651−8540	17 24 47	−49 54 07	10.89	1.13	−29.93±0.84	−30.36±0.14	—
IC 4651−9025	17 24 50	−49 57 27	10.90	1.13	−29.70±0.93	−30.46±0.14	K0 (SIMBAD)
IC 4651−9122	17 24 50	−49 56 56	10.89	1.22	−29.77±1.24	−30.58±0.13	—
IC 4651−9791	17 24 14	−49 53 07	10.43	1.33	−30.75±1.80	−31.44±0.12	K2 (WEBDA)
IC 4651−14527	17 25 24	−49 55 47	10.94	1.14	−27.16±0.96	−31.85±0.26	K0 (SIMBAD)
IC 4725−150	18 32 13	−19 07 26	7.36	1.53	2.15±0.68	2.84±0.06	K0 (SIMBAD)
IC 4725−251	18 32 30	−18 58 22	6.99	1.35	3.97±1.30	2.13±0.12	G3 (SIMBAD)

Note 1. Where V_r^a and V_r^b are the radial velocities obtained in this work and Mermilliod's survey respectively.

Note 2. SIMBAD astronomical database is available on <http://simbad.u-strasbg.fr/simbad/>

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Table 3. Stellar parameters for the stars analyzed in this work.

Star	T_{eff} Kelvins	$\log g$ dex	ξ Km s^{-1}	[Fe I/H] (#) dex	[Fe II/H] (#) dex
IC 4651–6333	4647±99	2.55±0.23	2.0±0.1	0.009±0.078 (63)	0.011±0.145 (12)
IC 4651–7646	4947±31	2.72±0.10	1.6±0.1	0.096±0.033 (65)	0.100±0.085 (13)
IC 4651–8540	4865±95	2.68±0.27	2.0±0.2	-0.085±0.086 (69)	-0.085±0.131 (14)
IC 4651–9025	4906±52	2.77±0.19	1.7±0.1	0.109±0.068 (67)	0.109±0.110 (14)
IC 4651–9122	4745±55	2.69±0.16	1.7±0.1	0.005±0.054 (60)	0.008±0.092 (13)
IC 4651–9791	4564±83	2.20±0.25	1.9±0.1	-0.082±0.082 (65)	-0.084±0.082 (12)
IC 4651–14527	5015±70	3.09±0.14	1.8±0.1	0.139±0.058 (64)	0.139±0.113 (13)
Mean values	4813±68	2.70±0.11	1.8±0.1	0.027±0.037	0.028±0.037
IC 4725–150	4582±57	1.79±0.23	2.5±0.2	0.089±0.070 (31)	0.088±0.033 (7)
IC 4725–251	5217±51	1.89±0.17	4.5±0.4	-0.086±0.060 (48)	-0.086±0.134 (6)
Mean Values	4900	2.74	3.5	0.002	0.001

Table 4. s-process abundance ratios for IC 4651 and IC 4725.

Star	[YII/Fe]	[ZrI/Fe]	[LaII/Fe]	[CeII/Fe]	[NdII/Fe]	[s/Fe]
IC 4651–6333	0.176±0.138 (4)	0.036±0.112 (3)	0.395±0.068 (3)	0.192±0.143 (3)	0.216±0.072 (4)	0.203±0.128
IC 4651–7646	0.079±0.053 (5)	-0.071±0.078 (3)	0.175±0.089 (3)	-0.187±0.151 (3)	0.127±0.123 (5)	0.025±0.150
IC 4651–8540	-0.055±0.081 (5)	0.080±0.118 (3)	0.209±0.076 (3)	0.019 (1)	0.250 (2)	0.101±0.128
IC 4651–9025	0.030±0.037 (3)	-0.089±0.096 (3)	0.204±0.047 (3)	0.005±0.058 (3)	0.007 (2)	0.031±0.107
IC 4651–9122	0.092±0.106 (5)	-0.031±0.107 (3)	0.238±0.059 (3)	-0.033±0.080 (3)	0.083±0.105 (4)	0.108±0.115
IC 4651–9791	0.232 (2)	-0.077±0.115 (3)	0.197±0.047 (3)	0.137 (2)	0.119±0.058 (4)	0.122±0.120
IC 4651–14527	0.309±0.078 (5)	0.170±0.089 (3)	0.381±0.057 (3)	0.165±0.133 (3)	0.029±0.230 (5)	0.211±0.137
Mean value	0.123±0.152	0.003±0.119	0.257±0.112	0.052±0.158	0.137±0.115	0.114±0.073
IC 4725–150	-0.017±0.159 (4)	-0.199±0.084 (3)	0.243 (2)	0.199 (2)	0.362±0.238 (4)	0.118±0.224
IC 4725–251	0.195 (2)	-0.095 (1)	0.195 (1)	0.213±0.198 (3)	0.202±0.172 (6)	0.142±0.133
Mean value	0.089	-0.147	0.219	0.206	0.282	0.130

Table 5. Stellar parameters and s-process abundance ratios found in literature in common with our sample.

OC	T_{eff}	$\log g$	[Fe/H]	[YII/Fe]	[ZrI/Fe]	[LaII/Fe]	[CeII/Fe]	[NdII/Fe]
IC 4651–9791/72	4500	2.23	0.13	-0.03±0.04 (6)	-0.13 (2)	-0.03 (2)	0.07 (2)	0.15±0.06 (3)
IC 4651–8540/76	4620	2.26	0.11	-0.07±0.01 (6)	-0.07 (2)	0.04 (2)	0.13 (2)	0.04±0.05 (3)
IC 4651–14527/146	4730	2.14	0.10	0.04±0.04 (6)	-0.10 (2)	0.05 (2)	0.10 (2)	0.08±0.03 (3)
IC 4725–150/HD 170820	4700	1.63	0.22	—	-0.06±0.05 (3)	—	—	-0.03 (1)
IC 4725–251/HD 170885	5100	1.00	0.08	0.13	0.05±0.16 (3)	—	—	0.49 (2)

Table 6: Nd II abundance comparisons for the star IC 4651 – 14527.

λ	(log gf) ₁ /ref	(log gf) ₂ /ref	(log gf) ₃ /ref	(log Nd II) ₁	(log Nd II) ₂	(log Nd II) ₃	[Nd II/H] ₁	[Nd II/H] ₂	[Nd II/H] ₃	δ [Nd II/H]
4811.34	-1.015/[46]	-1.140/VALD3	—	1.924	2.049	—	0.504	0.629	—	0.216
4959.12	-0.916/[46]	-0.980/VALD3	-0.740/VALD3	2.476	2.540	2.300	1.056	1.120	0.880	-0.023
5130.59	0.450/[47]	0.100/[49]	0.570/VALD3	1.399	1.748	1.279	-0.021	0.328	-0.141	-0.127
5212.36	-0.700/[48]	-0.960/VALD3	-0.870/VALD3	2.707	2.968	2.877	1.287	1.548	1.457	—
5234.19	-0.460/[49]	-0.510/VALD3	-0.330/VALD3	2.066	2.116	1.936	0.646	0.696	0.516	0.536
5740.88	-0.530/[47]	-0.680/VALD3	—	1.736	1.866	—	0.316	0.446	—	0.236
Mean values	—	—	—	2.051	2.215	2.098	0.631±0.479	0.795±0.458	0.678±0.519	0.168±0.230

Note 1. Where (log Nd II)₁, (log Nd II)₂ and (log Nd II)₃ are the Nd II abundances obtained using (log gf)₁, (log gf)₂ and (log gf)₃ respectively. [Nd II/H]₁, [Nd II/H]₂ and [Nd II/H]₃ were obtained using the solar value 1.42 dex from [45]. δ [Nd II/H] are the abundance ratios obtained from lb1 analysis.

Note 2. Some log gf values were obtained from the Vienna Atomic Line Database 3 (VALD 3). This database is available on <http://vald.astro.uu.se>

Table 7: List of the Iron I & II absorption lines.

λ	species	$\chi(eV)$	$\log gf$	E 6333	E 7646	E 8540	E 9025	E 9122	E 9791	E 14527	E 150	E 251	Jun0
5159.05	26.0	4.28	-0.650	—	—	—	85.7	—	—	—	—	—	68.6
5242.49	26.0	3.63	-0.970	129.6	120.9	129.3	126.9	122.0	128.4	128.6	—	—	85.9
5253.03	26.0	2.28	-3.790	68.8	60.1	64.2	70.6	72.4	95.5	72.7	—	—	17.1
5288.52	26.0	3.69	-1.510	129.2	93.8	113.3	117.6	106.3	118.7	105.9	—	142.1	58.6
5315.05	26.0	4.37	-1.400	—	—	—	—	—	—	—	111.5	76.5	34.3
5321.10	26.0	4.43	-1.190	86.8	69.3	73.4	76.2	69.5	—	76.2	109.9	111.2	42.1
5322.04	26.0	2.28	-2.840	137.5	114.7	118.5	114.4	121.6	130.8	117.6	—	—	62.1
5364.87	26.0	4.45	0.230	—	141.1	150.2	143.6	—	—	—	—	—	132.9
5367.46	26.0	4.42	0.439	—	148.8	160.4	163.2	—	—	—	—	—	145.1
5373.70	26.0	4.47	-0.710	97.3	89.6	93.4	86.0	87.2	96.7	90.7	133.3	132.2	62.6
5389.47	26.0	4.42	-0.250	119.5	103.0	116.2	110.7	103.5	113.2	111.0	—	—	81.9
5410.91	26.0	4.47	0.400	—	133.3	141.0	139.8	142.0	—	139.0	—	—	130.9
5417.03	26.0	4.42	-1.530	73.5	62.0	68.7	69.7	66.1	71.4	68.8	88.3	65.9	35.2
5441.33	26.0	4.31	-1.580	77.4	60.9	67.1	66.0	68.9	71.2	66.9	93.8	70.5	31.5
5445.04	26.0	4.39	0.041	—	134.2	142.4	144.1	140.3	—	147.2	—	—	122.2
5522.44	26.0	4.21	-1.400	81.0	72.0	72.1	74.0	—	76.0	—	113.5	85.3	45.1
5554.89	26.0	4.55	-0.380	—	134.4	141.9	149.8	142.3	—	143.4	—	—	100.1
5560.21	26.0	4.43	-1.040	80.9	73.9	81.6	79.0	75.7	82.9	78.0	—	105.2	51.1
5584.76	26.0	3.57	-2.170	96.8	71.8	83.8	81.3	—	91.4	—	109.6	100.3	39.2
5624.02	26.0	4.39	-1.330	97.9	85.6	86.0	88.4	85.4	91.4	84.9	109.6	99.4	52.3
5633.94	26.0	4.99	-0.120	98.6	87.7	92.9	89.0	88.5	94.4	92.8	—	124.5	65.2
5635.82	26.0	4.26	-1.740	71.9	62.7	60.3	68.6	61.9	67.5	61.5	88.2	58.6	34.0
5638.26	26.0	4.22	-0.720	122.8	111.1	115.4	111.7	114.9	120.9	110.9	—	148.9	77.4
5691.49	26.0	4.30	-1.370	98.2	70.0	86.0	89.8	—	79.1	83.3	121.4	95.1	40.7
5705.46	26.0	4.30	-1.360	78.9	69.8	74.7	74.3	70.2	61.0	71.3	—	86.6	38.8
5717.83	26.0	4.28	-0.979	125.2	102.2	105.2	120.8	—	107.7	—	—	—	63.1
5731.76	26.0	4.26	-1.150	103.7	91.3	92.5	92.2	88.5	99.4	90.0	—	136.8	57.4
5806.72	26.0	4.61	-0.900	97.5	85.8	88.1	85.9	89.0	94.3	82.6	—	—	53.9
5814.80	26.0	4.28	-1.820	61.1	53.0	58.1	52.6	52.9	56.4	54.1	79.9	—	23.4
5852.21	26.0	4.55	-1.180	111.8	78.8	92.5	87.4	90.6	110.0	82.0	114.6	80.8	39.9
5883.81	26.0	3.96	-1.210	105.5	101.3	100.5	105.9	99.6	103.7	101.9	147.6	137.8	70.5
5916.24	26.0	2.45	-2.990	130.0	112.0	116.7	117.3	—	130.0	—	—	—	53.3
5934.65	26.0	3.93	-1.020	119.6	—	—	—	111.1	129.4	104.2	—	151.1	75.0
6024.05	26.0	4.55	-0.060	144.8	132.9	137.4	144.2	126.8	115.7	132.3	—	—	110.4
6027.05	26.0	4.08	-1.090	106.4	92.0	98.2	92.8	96.3	104.2	91.5	—	147.0	62.5
6056.00	26.0	4.73	-0.400	98.0	99.7	101.6	100.2	99.0	98.5	96.6	143.7	133.8	71.1
6079.00	26.0	4.65	-0.970	79.9	76.7	79.0	78.6	73.8	76.8	77.3	109.3	90.1	47.4
6082.71	26.0	2.22	-3.580	—	—	—	—	—	—	—	—	124.2	35.4
6093.64	26.0	4.61	-1.350	67.5	56.4	66.1	60.1	58.7	59.4	59.4	91.0	54.5	30.1

Table 7 continuation.

λ	species	$\chi(eV)$	log gf	E 6333	E 7646	E 8540	E 9025	E 9122	E 9791	E 14527	E 150	E 251	Juno
6096.66	26.0	3.98	-1.780	80.2	73.0	72.1	75.5	77.7	76.9	74.3	111.3	71.9	37.2
6120.24	26.0	0.91	-5.950	76.2	45.5	57.0	50.8	62.6	74.3	46.5	108.3	—	5.1
6151.61	26.0	2.18	-3.290	119.1	102.7	107.0	107.1	—	117.2	104.6	—	125.7	49.2
6157.72	26.0	4.08	-1.110	126.0	106.2	118.2	111.8	112.2	123.6	117.3	—	148.7	63.5
6165.36	26.0	4.14	-1.470	87.9	78.9	80.8	83.2	80.0	84.9	75.7	125.7	98.4	44.0
6170.50	26.0	4.80	-0.380	—	—	—	—	—	—	155.2	—	—	82.9
6173.33	26.0	2.22	-2.880	139.7	123.6	129.6	112.6	128.2	144.7	126.7	—	—	67.7
6187.99	26.0	3.94	-1.570	98.7	86.7	93.8	90.3	90.4	92.6	88.3	128.2	94.2	47.7
6200.31	26.0	2.61	-2.440	144.7	126.2	135.6	131.0	131.3	140.5	126.6	—	—	71.7
6311.50	26.0	2.83	-3.230	—	—	—	—	—	—	—	—	100.1	29.4
6322.68	26.0	2.59	-2.430	—	133.6	136.9	108.1	138.3	150.4	135.7	—	—	78.6
6380.74	26.0	4.19	-1.320	109.9	90.0	102.4	99.3	—	103.3	—	—	112.5	53.8
6392.53	26.0	2.28	-4.030	83.8	—	67.5	—	71.5	81.9	62.6	—	47.1	18.2
6419.95	26.0	4.73	-0.090	—	—	126.3	—	—	122.2	—	—	—	87.0
6469.19	26.0	4.84	-0.620	120.8	—	—	—	103.2	120.7	102.1	—	122.2	58.4
6518.36	26.0	2.83	-2.300	118.8	104.7	108.3	107.7	107.4	118.2	105.6	—	—	58.1
6551.67	26.0	0.99	-5.790	—	—	—	—	—	—	—	—	25.6	6.0
6574.22	26.0	0.99	-5.020	123.4	100.8	104.2	103.7	111.8	130.9	102.4	—	97.8	29.0
6591.31	26.0	4.59	-2.070	32.4	—	—	—	—	—	—	—	—	10.5
6593.87	26.0	2.44	-2.420	—	—	—	—	151.3	—	149.4	—	—	87.5
6597.56	26.0	4.80	-0.920	73.8	71.5	70.8	75.5	67.9	69.5	66.5	109.7	78.0	42.4
6608.02	26.0	2.28	-4.030	100.6	65.4	74.7	77.3	75.7	93.5	64.3	130.3	55.3	17.1
6609.11	26.0	2.56	-2.690	—	128.9	138.8	140.3	—	154.2	—	—	—	68.2
6646.93	26.0	2.61	-3.990	86.3	50.2	66.7	67.0	61.5	81.2	66.4	90.8	34.1	8.2
6653.85	26.0	4.14	-2.520	35.2	—	—	—	33.4	38.5	31.6	—	—	10.9
6699.14	26.0	4.59	-2.190	35.6	28.1	30.6	27.4	28.3	33.5	29.3	43.5	—	7.5
6703.56	26.0	2.76	-3.160	116.1	87.5	98.3	95.6	90.3	109.1	98.3	—	102.5	37.8
6704.48	26.0	4.22	-2.660	24.9	19.1	24.8	22.9	21.5	27.0	21.1	32.7	—	6.1
6710.31	26.0	1.80	-4.880	117.6	79.4	95.4	88.3	93.4	114.2	82.2	—	66.9	15.7
6713.74	26.0	4.79	-1.600	49.2	50.4	51.6	49.7	46.8	50.9	45.0	65.3	34.6	21.4
6739.52	26.0	1.56	-4.950	91.5	62.1	75.1	73.5	74.0	81.3	57.2	118.5	40.7	11.8
6745.95	26.0	4.07	-2.770	26.7	—	22.8	—	21.8	27.9	21.8	—	—	8.3
6750.15	26.0	2.42	-2.620	—	136.2	138.3	142.5	137.5	149.3	134.6	—	—	76.2
6752.70	26.0	4.64	-1.200	—	—	61.8	—	—	—	86.7	—	—	38.2
6783.70	26.0	2.59	-3.980	—	56.7	—	—	—	98.9	—	—	—	14.3
6793.25	26.0	4.07	-2.470	45.2	38.6	—	33.4	42.8	46.0	34.3	—	—	13.2
6806.84	26.0	2.73	-3.210	107.5	88.7	92.6	94.7	94.8	102.7	92.9	147.1	101.7	34.0
6810.26	26.0	4.61	-0.990	87.9	75.5	78.8	69.9	76.8	85.2	82.8	—	91.0	50.0
6820.37	26.0	4.64	-1.170	86.6	76.6	78.7	80.5	81.5	86.1	83.2	107.8	75.1	40.9
6841.33	26.0	4.61	-0.600	—	—	—	—	—	—	—	—	146.6	67.2

Table 7 continuation.

λ	species	$\chi(eV)$	log gf	E 6333	E 7646	E 8540	E 9025	E 9122	E 9791	E 14527	E 150	E 251	Juno
6851.63	26.0	1.61	-5.320	84.8	—	62.0	60.6	—	74.8	—	97.3	—	6.7
6858.15	26.0	4.61	-0.930	85.6	81.2	84.9	85.7	81.8	88.1	80.1	125.6	105.1	50.2
7132.98	26.0	4.08	-1.610	88.6	75.0	80.2	81.5	76.8	84.0	87.1	133.6	92.7	42.5
4993.34	26.1	2.81	-3.670	62.6	60.0	53.5	56.6	54.1	58.1	56.3	92.3	—	38.0
5132.65	26.1	2.81	-4.000	—	—	45.3	43.5	42.0	—	53.5	—	107.6	23.8
5197.55	26.1	3.23	-2.250	114.5	101.7	109.8	111.9	102.2	109.4	105.5	—	—	81.9
5234.61	26.1	3.22	-2.240	99.2	109.8	101.9	102.9	94.8	94.9	103.9	—	—	81.9
5284.09	26.1	2.89	-3.010	—	84.5	93.0	91.7	82.0	—	87.5	—	—	66.7
5325.55	26.1	3.22	-3.170	47.1	61.6	55.1	67.3	45.8	46.4	60.1	—	—	38.7
5414.04	26.1	3.22	-3.620	32.6	43.9	40.4	45.4	33.9	54.5	45.6	67.5	128.0	25.9
5425.24	26.1	3.20	-3.210	50.1	63.3	55.7	60.6	50.8	38.8	63.1	91.2	—	39.6
5991.36	26.1	3.15	-3.560	54.2	55.5	64.0	54.0	48.3	52.4	56.7	—	—	29.9
6084.09	26.1	3.20	-3.800	40.9	44.9	45.2	45.1	—	35.6	—	—	134.3	22.2
6149.24	26.1	3.89	-2.720	47.7	49.4	47.0	46.8	43.6	43.0	46.9	73.8	150.0	37.7
6247.54	26.1	3.89	-2.340	58.0	71.0	63.5	61.0	56.2	58.6	60.1	95.2	—	55.9
6416.92	26.1	3.89	-2.680	54.1	63.8	63.7	57.8	50.5	55.2	54.9	76.2	154.9	39.6
6432.68	26.1	2.89	-3.580	53.4	63.0	61.9	56.6	57.8	52.6	68.8	92.6	152.8	43.1

Table 8: Line list of the s-process elements.

λ	species	$\chi(\text{eV})$	$\log gf$	References	E 6333	E 7646	E 8540	E 9025	E 9122	E 9791	E 14527	E 150	E 251	Jun0
4883.68	39.1	1.08	0.070	[49]	24.6	—	103.6	—	105.8	—	115.4	—	—	60.1
5087.43	39.1	1.08	-0.170	[49]	—	—	93.6	—	84.7	—	97.6	128.5	—	48.8
5200.42	39.1	0.99	-0.570	[49]	106.4	85.6	83.3	84.6	92.1	107.2	99.4	137.2	—	38.9
5289.82	39.1	1.03	-1.850	[46]	25.9	26.0	21.4	25.2	25.2	—	35.3	53.1	71.5	5.2
5402.78	39.1	1.84	-0.440	[50]	61.3	46.2	43.4	44.5	47.5	57.7	56.2	89.6	117.2	13.0
5385.13	40.0	0.52	-0.640	[51]	50.3	20.3	28.6	26.9	36.0	47.5	27.1	46.7	—	1.9
6127.46	40.0	0.15	-1.060	[52]	70.4	29.7	35.5	33.2	46.5	61.2	40.2	78.5	—	3.8
6134.57	40.0	0.00	-1.280	[52]	62.7	23.5	32.1	32.6	41.1	55.9	35.0	71.7	—	2.2
6143.18	40.0	0.07	-1.100	[52]	73.7	31.5	36.9	38.7	46.8	66.2	44.6	85.5	19.2	3.0
5303.53	57.1	0.32	-1.350	[46]	44.3	24.3	34.1	31.8	29.9	39.8	34.3	71.9	—	3.6
5880.63	57.1	0.24	-1.830	[53]	30.2	20.4	20.8	18.0	18.2	24.9	15.6	—	—	1.4
6390.48	57.1	0.32	-1.410	[49]	56.2	31.9	33.0	32.0	38.7	47.8	41.8	81.0	65.1	3.9
5117.17	58.1	1.40	0.011	[46]	—	—	—	—	—	—	—	38.0	42.2	1.5
5187.46	58.1	1.21	0.300	[46]	51.7	12.6	33.1	34.1	33.8	45.2	29.8	64.7	80.4	7.5
5274.24	58.1	1.28	0.389	[46]	45.0	36.9	—	36.8	31.4	—	42.6	—	95.6	7.9
5472.30	58.1	1.25	-0.190	[46]	28.6	—	—	16.0	13.8	26.7	23.4	—	—	2.4
4811.34	60.1	0.06	-1.015	[46]	—	55.6	61.5	60.1	60.0	79.7	63.0	115.4	135.9	10.8
4959.12	60.1	0.06	-0.916	[46]	109.8	78.0	—	79.8	83.0	107.3	89.5	145.0	132.7	32.4
5130.59	60.1	1.30	0.100	[49]	—	36.2	—	—	—	—	—	—	141.9	12.2
5234.19	60.1	0.55	-0.460	[49]	—	62.0	—	—	—	—	—	—	—	5.6
5311.46	60.1	0.98	-0.560	[49]	32.3	—	—	—	—	—	—	—	77.2	2.4
5319.81	60.1	0.55	-0.350	[49]	79.8	—	—	—	64.4	79.2	60.4	—	—	13.0
5740.88	60.1	1.16	-0.560	[46]	25.4	19.4	25.8	—	19.6	23.9	18.4	63.8	87.4	2.4