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Research note

Sodium enrichment of stellar atmospheres

I. Non-variable supergiants and bright giants

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Abstract. 48 supergiants and bright giants have been observed in order to investigate the sodium enrichment of their atmospheres and its connection with stellar gravity.

We present the equivalent widths of the 6154 Å and 6160 Å Na I lines measured from the program spectra, the results of effective temperature determinations, the NLTE sodium abundances, and the derived relation between the sodium overabundance and surface gravity.

Key words. stars: abundances – stars: supergiants

1. Introduction

One of the long-standing problems in observational stellar astrophysics is the sodium enrichment of supergiant atmospheres. First systematic attempt to find a relationship between the sodium overabundance and stellar mass was undertaken by Sasselov (1986), who used rather non-homogeneous literature data on sodium abundance [Na/H] for 34 stars. He found that the sodium abundance has a tendency to increase with increasing mass, but quantitative characteristics of that relation were probably significantly affected by the non-homogeneity of the [Na/H] values and somewhat unreliable mass determination.

From theoretical point of view, this problem was investigated by Denissenkov (1990), Prantzos et al. (1991) and El Eid & Prantzos (1993). These authors, using the sodium abundances in F supergiants, overestimated by Boyarchuk et al. (1988), concluded that there is a necessity either to increase the initial abundance of ^{22}Ne (that, in principle, cannot be observationally checked for the supergiants), or to increase the rate of the ^{20}Ne(p,γ)^{21}Na reaction in order to achieve match between the observations and theory predictions.

Later, El Eid & Champagne (1995) criticized those first attempts, and re-investigated the sodiun enrichment in A–F type supergiants using the data on Na excess provided by Takeda & Takada-Hidai (1994). Those authors considered the nucleosynthesis of ^{23}Na in the stars with masses 5–19 $M_\odot$. A positive correlation between [Na/H] and mass was found. Nevertheless, inspecting Fig. 3 from that work, one can conclude that the correlation between observed and calculated sodium overabundance is not well established (mainly due to the uncertainties in the observed sodium abundances).

Fragmentary observational data on [Na/H] in galactic supergiants can be found in numerous publications, but usually they are obtained using different methods, oscillator strengths and atmosphere models, spectral material of different quality and different sodium lines (in some cases using only strong lines with $W_\lambda \geq 200$ mÅ, that are not appropriate for LTE analysis).

In this work we present the results of a homogeneous spectroscopic investigation of a sample of F–G supergiant and bright giant stars based on LTE and NLTE calculations.

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2. Observations

The observations of 48 program supergiants and bright giants of the F–G spectral classes were done at the 1.52-m telescope of the Observatoire de Haute Provence (23 July to 30 July 1998). Thompson TH 7832 LA detector consisting of 2048 photodiodes with the AURELLIE spectrograph (1200 lines mm^{-1} grating in the second order) was used. The spectral domain was centered on the wavelength 6150 Å and covered the region from 6050 Å to 6250 Å. This spectral region has been selected in order to observe two sodium lines, 6154 Å and 6160 Å, that are usually not very strong in the supergiant spectra and can be used for the LTE analysis. The resolving power was 25 000. For the great majority of the program spectra the S/N ratio varied from 200 to 400.

A preliminary reduction of the spectroscopic data (an extraction from the images and wavelength calibration) was made using the MIDAS package. Further steps of the analysis (continuum level placement and equivalent width determinations) were performed with the help of DECH20 code (Galazutdinov 1992). The equivalent widths of selected sodium lines were measured in the gaussian approximation (see Table 2, the equivalent widths are given in mÅ).

3. Atmospheric parameters

3.1. The temperature estimation

We used photometric data for program stars to estimate their effective temperatures T_{eff}. All the necessary information about colour indices was selected from the SIMBAD database. From the individual estimates of colour indices that are available for each star, we derived the mean values. When it was possible, the reddenings were taken from the literature. To transform $E(B-V)$ or $E(b-y)$ values into $E(B2-V1)$, $E(R-I)$ and $E(V-R)$, we used the following expressions:

$$E(b-y) = 0.73 \times E(B-V)$$
$$E(B2-V1) = 0.83 \times E(B-V)$$
$$E(R-I) = 0.62 \times E(B-V)$$
$$E(V-R) = 0.92 \times E(B-V).$$

In some cases, when the reddenings were not available, we calculated $E(B-V)$ values using the colour indices and formula given by Arellano Ferro & Parrao (1990).

To estimate the temperatures we used several calibrating relations: $T(b-y)$ – Kurucz (1991) calibration; $T(B-V)$ – Kurucz (1991); $T(R-I)$ – Buser & Kurucz (1992); $T(V1-B2)$ – Kunzli et al. (1997); $T(V-R)$ – Castelli et al. (1997) calibration.

When photometric data were not available, the effective temperature was estimated by avoiding any visible dependence between the iron abundance from Fe I lines and the excitation potentials of their lower level. Obtained results are given in Table 1. As one can see, the different calibrations give close estimates of the effective temperatures.

3.2. Gravity and microturbulent velocity

To estimate the microturbulent velocities and gravities we used the usual method based on avoiding any dependence of iron abundance derived from the Fe I lines and their equivalent widths, and subsequent adjustment of iron abundance from Fe I and Fe II lines. It should be noted that such an approach has been criticized by Kovtyukh & Andrievsky (1999) as producing somewhat incorrect gravities, but in our case there was no possibility of using the Fe II lines for the determination of atmospheric parameters (as proposed by Kovtyukh & Andrievsky), because of the restricted observed spectral region and small number of available Fe II lines. We estimate an error in the gravity $\approx\pm0.2$ dex. By varying the adopted log g value within the range ±0.2 dex, we obtained the iron abundance uncertainty of about 0.15 dex which is comparable with the typical error of abundance determination. The small gravity variations produce a similar uncertainty in the derived sodium abundance. The results of log g and V_{t} determinations are presented in Table 1.

4. Elemental abundances

4.1. LTE calculations

The LTE abundances of iron and sodium were derived from the equivalent widths (Table 2), using the Kurucz standard atmosphere models and the WIDTH9 code. The results on $\log\epsilon(\text{Fe})$ and $\log\epsilon(\text{Na})$ are given in Table 2.

4.2. NLTE results

The NLTE abundances of Na in program stars were derived with the help of the modified version of the MULTI code (Carlsson 1986) described in Korotin et al. (1999) and Korotin et al. (1999).

The model of the sodium atom (proposed by Sakhibullin 1987) has been modified (see Korotin & Mishenina 1999). The model consists of 27 levels of Na I and the ground level of Na II. The radiative transitions between the first 20 levels of Na I and the ground level of Na II were considered. Transitions between the rest levels were used only in the equations of particle number conservation. Finally, 46 $b-b$ and 20 $b-f$ transitions were included in the linearization procedure. For 34 transitions the radiative rates were fixed.

The NLTE calculations give abundance results (see Table 2) that differ from the LTE abundances in Δ value ($\Delta = \log\epsilon(\text{Na})_{\text{NLTE}} - \log\epsilon(\text{Na})_{\text{LTE}}$). In the last two columns we give the sodium abundances in program stars that are referred to the corresponding solar value and also normalized to the iron content. These results were used to investigate the dependence between the sodium overabundance and stellar gravity.

Table 1. $T_{\rm eff}$ determination for program stars.

Star	$T(b-y)$	$T(B-V)$	$T(B2-V1)$	$T(R-I)$	$T(V-R)$	σ	$T_{\rm eff}$	log g	$V_{\rm t}$	Sp
HD 371	5250	5220				15	5235	1.6	2.2	G3 II
HD 725	6375	6550				88	6500	0.5	2.5	F5 Ib-II
HD 4362	5400	5440				20	5420	1.5	3.7	G0 Ib
HD 5747	5120	5020				50	5100	3.0	1.5	G8 II
HD 9900		4430					4430	0.6	2.5	G5 II
HD 10806							5300	2.9	2.3	G9 Ib
HD 11544	5140	5130				5	5135	0.7	2.9	G2 Ib
HD 15784	6500	6500				0	6500	2.5	3.0	F4 II
HD 16901	5550	5530				10	5540	1.1	3.5	G0 Ib
HD 20902	6175	6240	6160			25	6200	0.6	2.9	F5 Ib
HD 25291	6600	6690				45	6750	1.0	3.0	F0 II
HD 134852*	6860	6690				85	6750	2.4	3.4	F2 II
HD 139862*	5050	5040	4880	5080	4860	46	5000	2.0	1.7	G8 II
HD 159181	5250	5290	5140	5370	5460	54	5400	2.0	3.0	G2 II
HD 171635*	6000	5910	5820	5940	5720	49	6000	1.0	3.3	F7 Ib
HD 176155*	6400	6260	6000			117	6350	1.2	3.0	F8 Ib
HD 179784		4915	4560	5150	4860	121	5100	1.8	2.8	G5 Ib
HD 180028	6000	6100				50	6050	1.3	3.0	F6 Ib
HD 180583*	6360	6090	5940	6140	6140	67	6200	2.0	3.1	F6 Ib-II
HD 182296		4930	4640	5060	4820	89	5000	1.0	2.8	G3 Ib
HD 182835	6550	6100	6480	6070		125	6500	0.5	2.2	F2 Ib
HD 185018	5750	5690	5530			66	5700	2.3	2.5	G0 Ib
HD 185758	5625	5640	5480	5660	5680	36	5500	3.6	2.6	G0 II
HD 185958	5100	4860	4730	5000	4850	64	5250	1.5	1.8	G8 II
HD 189671							4850	1.8	2.3	G8 II
HD 190323	5900	5760				70	5900	0.1	4.2	G0 Ia
HD 190403		4730					4850	1.5	2.5	G5 Ib-II
HD 193370*	6400	6410	6300	6220		45	6350	1.5	3.2	F5 Ib
HD 194069		5210	5030			90	5100	1.8	2.8	G5 II
HD 194093	6065	5920	5840	5960	6100	48	6000	0.6	3.5	F8 Ib
HD 194951*	6150	6290				70	6350	1.0	2.8	F1 II
HD 195295	6500	6430	6360	6380		31	6500	1.6	3.0	F5 II
HD 195593	6130	6260	6080	5640		135	6100	0.5	2.6	F5 Iab
HD 199394*	5030	4950				40	5000	2.2	1.4	G5 II
HD 200102	5350	5380	5110			85	5250	0.8	2.4	G1 Ib
HD 202109	5130	5070	4900	5120	5100	42	5100	2.5	1.5	G8 II
HD 202314	4750	4750	4640		5070	93	4900	1.5	3.2	G2 Ib
HD 205603*	5200						5200	3.1	1.2	G8 II
HD 206731*	5000	4990				5	5000	2.0	1.8	G8 II
HD 206859	4670	4650	4540		4550	34	4750	0.8	2.7	G5 Ib
HD 211153*	5125						5125	2.5	1.4	G8 Ib-II
HD 216206	4950	5010	4780			69	5100	1.1	2.5	G4 Ib
HD 220102	6450	6580	6790			99	6600	1.0	2.7	F5 II
HD 220819							7000	0.5	1.3	F0 II
HD 221661*	4950	5060	4840			64	5000	2.3	1.5	G8 II
HD 223047	5180	5050	4840	5060	5120	58	5000	1.5	3.0	G5 Ib
HD 224165	4500	4660	4420			71	4600	0.5	2.3	G8 Ib
HD 225292*	5100	5070				15	5100	2.7	1.3	G8 II

* For stars denoted by asterisks, the reddenings were calculated.

Table 2. Sodium line equivalent widths and abundance results.

Star, HD	6154 Å	6160 Å	$\log\epsilon$(Fe)	σ	$\log\epsilon$(Na)	σ	Δ	[Na/H]	[Na/Fe]
371	68	99	7.41	0.10	6.35	0.03	−0.09	0.10	0.19
725	24	39	7.26	0.10	6.37	0.02	−0.06	0.12	0.36
4362	57	98	7.42	0.12	6.27	0.03	−0.08	0.02	0.10
5747	81	107	7.70	0.20	6.44	0.01	−0.14	0.19	−0.01
9900	154	177	7.33	0.25	6.55	0.03	−0.18	0.30	0.47
10806	92	111	7.64	0.18	6.53	0.05	−0.11	0.28	0.14
11544	85	129	7.52	0.12	6.44	0.06	−0.13	0.19	0.17
15784	25	46	7.50	0.09	6.34	0.02	−0.07	0.09	0.09
16901	64	100	7.47	0.10	6.41	0.02	−0.10	0.16	0.19
20902	38	66	7.28	0.13	6.43	0.02	−0.08	0.18	0.40
25291	16	31	7.15	0.15	6.28	0.03	−0.05	0.03	0.38
134852	30	48	7.48	0.17	6.41	0.02	−0.05	0.16	0.18
139862	82	107	7.42	0.15	6.38	0.01	−0.13	0.13	0.21
159181	62	95	7.61	0.12	6.31	0.01	−0.08	0.06	−0.05
171635	43	86	7.26	0.10	6.42	0.07	−0.08	0.17	0.41
176155	48	87	7.45	0.10	6.63	0.03	−0.09	0.38	0.43
179784	107	149	7.58	0.12	6.58	0.04	−0.17	0.33	0.25
180028	45	99	7.53	0.22	6.56	0.16	−0.11	0.31	0.28
180583	37	69	7.56	0.10	6.45	0.04	−0.08	0.20	0.14
182296	118	150	7.60	0.12	6.59	0.01	−0.18	0.34	0.24
182835	24	50	7.31	0.22	6.45	0.06	−0.08	0.20	0.39
185018	62	93	7.66	0.10	6.49	0.01	−0.12	0.24	0.08
185758	115	141	7.88	0.19	6.82	0.04	−0.17	0.57	0.19
185958	65	93	7.30	0.15	6.34	0.02	−0.13	0.09	0.29
189671	116	145	7.47	0.15	6.54	0.01	−0.18	0.29	0.32
190323	71	119	7.40	0.10	6.65	0.04	−0.12	0.40	0.50
190403	108	140	7.48	0.20	6.42	0.01	−0.16	0.17	0.19
193370	46	73	7.44	0.12	6.53	0.01	−0.07	0.28	0.34
194069	94	121	7.52	0.20	6.40	0.03	−0.11	0.15	0.13
194093	63	102	7.38	0.10	6.60	0.02	−0.11	0.35	0.47
194951	19	61	7.20	0.22	6.29	0.18	−0.06	0.04	0.34
195295	33	56	7.36	0.12	6.42	0.01	−0.06	0.17	0.31
195593	38	70	7.31	0.18	6.43	0.05	−0.09	0.18	0.37
199394	73	100	7.42	0.20	6.31	0.04	−0.15	0.06	0.14
200102	72	107	7.30	0.10	6.39	0.03	−0.14	0.14	0.34
202109	94	118	7.65	0.20	6.59	0.01	−0.21	0.34	0.19
202314	98	-	7.28	0.15	6.32	–	−0.06	0.07	0.29
205603	73	103	7.65	0.14	6.46	0.04	−0.17	0.21	0.06
206731	88	121	7.55	0.30	6.47	0.04	−0.17	0.22	0.17
206859	109	145	7.31	0.15	6.34	0.01	−0.17	0.09	0.28
211153	85	105	7.62	0.16	6.51	0.02	−0.17	0.26	0.14
216206	91	124	7.38	0.16	6.37	0.01	−0.16	0.12	0.24
220102	20	37	7.23	0.12	6.24	0.01	−0.11	0.00	0.26
220819	10	22	7.32	0.25	6.40	0.05	−0.11	0.15	0.33
221661	85	114	7.55	0.25	6.46	0.03	−0.11	0.21	0.16
223047	117	163	7.52	0.15	6.60	0.05	−0.16	0.35	0.33
224165	111	133	7.21	0.15	6.30	0.03	−0.14	0.05	0.34
225292	68	96	7.45	0.15	6.32	0.03	−0.14	0.07	0.12

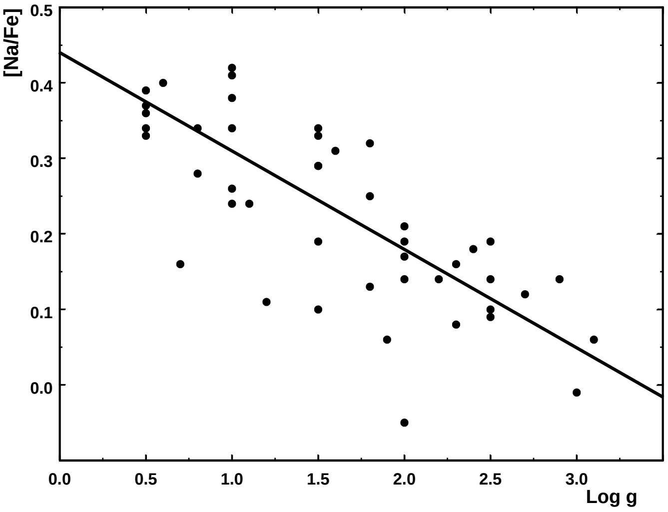

Fig. 1. Sodium abundance versus surface gravity.

5. Sodium abundance vs. surface gravity

In Fig. 1 we present graphically the main result of the present study. A clear dependence between the sodium abundance and stellar gravity has been detected:

$$[\mathrm{Na/Fe}] = -0.116(\pm 0.014)\log g + 0.427(\pm 0.026). \qquad (1)$$

As one can see from Fig. 1, no sodium overabundance is expected for the stars having gravities of about 1000 cm s^{-2}. For the supergiant stars only a moderate overabundance of the sodium is seen.

A thorough discussion of the sodium overproduction in the low and intermediate mass AGB stars was recently presented by Mowlavi (1999a, 1999b), who calculated the surface sodium abundance prior to the thermally pulsing AGB phase (i.e. after 1st and 2d dredge-up). According to his result, the surface sodium overabundace ranges from $\approx$0 dex for the low mass stars to 0.25 dex for the intermediate mass stars at the evolutionary stages before the AGB phase (see Table 2 of that paper). Thus, our empirical data are in agreement with the results of those calculations, and they indicate that no extreme overabundances of the sodium are expected for the intermediate mass stars.

Of course, it would be much more astrophysically important to investigate a relation between the sodium abundance and stellar mass. Unfortunately it is quite difficult to estimate the correct masses of the stars of our sample, because we do not reliably know their luminosities. Without knowing this principal stellar parameter, we can state only qualitatively that the lower gravity stars are (on avarage) more luminous, and thus they should probably be more massive (the luminosities of supergiants are proportional to their masses, i.e. $L \sim M^{3.5}$, see e.g. Chiosi et al. 1992). This means that the detected [Na/Fe]–$\log g$ dependence implies the existence of [Na/Fe]–mass relation, but its quantitative characteristics still should be evaluated.

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References

Arellano Ferro, A., & Parrao, L. 1990, A&A, 239, 205
Boyarchuk, A., Hubeny, I., Kubat, J., Lyubimkov, L. S., & Sakhibullin, N. A. 1988, Ap, 28, 202
Buser, R., & Kurucz, R. L. 1992, A&A, 264, 557
Carlsson, M. 1986, Uppsala Obs. Rep., 33
Castelli, F., Gratton, R. G., & Kurucz, R. L. 1997, A&A, 318, 841
Chiosi, C., Wood, P. R., Bertelli, G., Bressan, A., & Mateo, M. 1992, ApJ, 385, 205
Denissenkov, P. A. 1990, Ap, 31, 588
El Eid, M. F., & Champagne, A. E. 1995, ApJ, 451, 298
El Eid, M. F., & Prantzos, N. 1993, Origin and Evolution of the Elements, ed. N. Prantzos, E. Vangioni-Flam, & M. Casse (Cambridge Univ. Press), 279
Galazutdinov, G. A. 1992, Prepr. SAO RAS, No. 92
Korotin, S. A., Andrievsky, S. M., & Luck, R. E. 1999, A&A, 351, 168
Korotin, S. A., Andrievsky, S. M., & Kostynchuk, L. Yu. 1999, Ap&SS, 260, 531
Korotin, S. A., & Mishenina, T. V. 1999, ARep, 43, 533
Kovtyukh, V. V., & Andrievsky, S. M. 1999, A&A, 351, 597
Kunzli, M., North, P., Kurucz, R. L., & Nicolet, B. 1997, A&A, 122, 51
Kurucz, R. L. 1991, Precision photometry: Astrophysics of the Galaxy, ed. A. G. D. Philip, A. R. Upgren, & K. A. Janes (L. Davis Press), 1
Mowlavi, N. 1999, A&A, 344, 617
Mowlavi, N. 1999, A&A, 350, 73
Prantzos, N., Coc, A., & Thibaud, J. P. 1991, ApJ, 379, 729
Sakhibullin, N. A. 1987, SvA, 31, 666
Sasselov, D. D. 1986, PASP, 98, 561
Takeda, Y., & Takada-Hidai, M. 1994, PASJ, 46, 395