THE SULPHUR ABUNDANCE BEHAVIOUR IN THE GALACTIC DISC STARS

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ABSTRACT. The sulphur abundances in the atmospheres of the F-G-K-type dwarf stars that belong to the thin and thick disc populations (in the metallicity range − 1.0 < [Fe/H] < 0.3) were determined. The observations were conducted using the 1.93 m telescope at Observatoire de Haute-Provence (OHP, France) equipped with the echelle-type spectrograph ELODIE (R = 40 000). The abundances were derived under the LTE approximation; the synthetic spectrum for the sulphur lines in the region of 6743-6762 ÅÅ was computed accounting for the hyperfine structure. The correlation between the abundances of some elements and metallicity [Fe/H] in the Galactic thin and thick disc stars was analyzed. To discuss the sources of sulphur production, the comparison between the sulphur abundance trend and current theoretical computations of the Galactic chemical evolution was made.

Key words: Stars: abundance – Stars: late-type

1. Introduction

The sulphur abundance in the Galactic disc can be a good diagnostic tool to determine the sources and conditions of the production of α-elements (e.g. Limongi & Chieffi, 2003).

The early studies of the sulphur abundance (Wallerstein & Conti 1964; Clegg et al. 1981; Francois 1988) reported a noticeable scatter of values with a potential trend on metallicity which is typical for α-elements. The further research in the sulphur abundance determination proved the presence of such a trend and drew attention to a series of issues, primarily to the presence of deviations from the LTE (e.g. Takada-Hidai et al., 2002) and complexity of the sulphur line measurements in the visible spectrum (Caffau et al., 2005a). In recent decades, an evident attention has been given to the sulphur abundance investigation in various space objects. For instance, the sulphur abundance was determined in metal-poor stars (Takada-Hidai et al., 2001; Israelian & Rebolo, 2001; Takeda et al., 2005; Ryde & Lambert, 2004; etc.); in metal-rich stars (Chen et al., 2002); in stars with planets (Ecuvillon et al. 2004); in the stars in globular and open clusters (Caffau et al., 2005b; Sbordone et al., 2009; Caffau et al., 2014; etc.), and in the disc's giants (Matrozis et al., 2013). The last study highlighted the necessity of applying of a uniform method for determination of atmospheric parameters, which the sulphur abundance is sensitive to.

The elements resulted from the α-particle capture – the so-called α-elements – are produced in massive core-collapse supernovae (CCSN) both at the pre-supernova stage and in the processes of explosive nucleosynthesis. According to Limongi & Chieffi (2003), Mg is produced by the carbon-burning process in the convective regions while the oxygen-burning process yields Si, S and Ca. In the explosive nucleosynthesis Mg is produced in the explosive neon and carbon burning processes (Thielemann & Arnett, 1985) while Si, S and Ca are produced in the explosive oxygen burning (Thielemann & Arnett, 1985; Woosley & Weaver, 1995) with the yield of elements depending on different factors from the relevant reaction cross-sections to the treatment of semi-convection. Therefore, due to the distinction in the production of Mg and Si, S and Ca, the difference in behaviour of the Mg abundance and those of Si, S and Ca can be expected. Iron and iron-peak elements result from the equilibrium process with at least two sources of production, such as CCSN and less massive supernovae SNe Ia (Timmes, Woosley & Weaver, 1995).

To determine the sulphur production sources, Chen et al. (2002) made a comparison between the sulphur and silicon abundances in the disc stars. They found a correlation between [S/H] and [Si/H], as well as reported the absence of any dependence of the S and Si abundances on the metallicity at [Fe/H] > −1.0. The obtained results are indicative of the same nucleosynthetic origin for the two elements and sustain existing models of the chemical evolution of the Galactic disc (Goswami & Prantzos (2000), Timmes et al. (1995).In these models, sulphur is synthesised predominantly by the oxygen burning in massive stars, and is ejected into the interstellar medium in the Type II supernovae explosions).

Further studies by Nissen et al. (2004), including the halo stars, showed that for the disc stars with [Fe/H] > −1, [S/Fe] decreases with increasing [Fe/H]. Hence, sulphur behaves like other typical α-capture elements, Mg, Si and Ca. In the meantime, it is reported for zinc, which is an iron-peak element, that there is some evidence for a small systematic Zn overabundance ([Zn/Fe] ∼ +0.1) among metal-poor disc stars and halo stars with [Fe/H] < −2.0.

On the other hand, the comparison between the abundance of sulphur as a volatile element and refractory element abundance can reflect one of the hypotheses of the planets' existence around stars (e.g. Ecuvillon et al., 2004).

The investigation of planet-hosting stars revealed that those stars are on average metal richer than normal stars of the disc (e.g. Gonzalez, 1997; Santos et al., 2001). It was assumed on the one of the hypotheses (Gonzalez, 1997) that it is accreted materials (rocky planetesimals) which are responsible for the metal overabundance while volatile elements (with low condensation temperatures) should be deficient due to high temperatures of circumstellar matter. Hence, the self-enrichment scenario should result in relative overabundance of refractory materials, such as α-elements Si, Mg, Ca, Ti and iron-group elements comparing to volatile elements, such as CNO, S and Zn. In further studies, any significant difference in behaviour of the abundances of those elements for normal and planet-hosting stars was not found (e.g. Santos et al., 2000; Gonzalez et al., 2001; Ecuvillon et al., 2004). That could be due to the small number of stars, for which the determination of parameters and elemental abundances was performed by a uniform method; and that highlighted the importance of elemental abundance determination for a larger number of stars with and without known planetary systems. The alternative was the hypothesis of increased metal enrichment of protoplanetary (pre-stellar) cloud (Santos et al., 2000; 2001). That hypothesis did not state any differences in the abundances of refractory metals and volatile elements between planet-hosting and normal stars.

Thus, the sulphur abundance is a good test for 1) the nucleosynthesis of α-elements (S, Si and Ca vs. Mg); and 2) the self-enrichment hypothesis in the case of planet-hosting stars (S and Zn vs. Si, Mg and Ca).

The aim of this study is 1) to determine the sulphur abundance for a large set of the disc's stars, for which reliable atmospheric parameters and abundances of a series of elements had been obtained earlier; 2) to compare the sulphur, silicon and magnesium behaviour to study dissimilar conditions of the synthesis of α-elements; 3) to compare the behaviour of volatile elements, namely sulphur and zinc, with that one of refractory materials for normal and planet-hosting stars (or for the stars with [Fe/H]>−0.5 dex) to estimate the potential of demonstration or influence of the chemical composition on planet-hosting stars.

2. Observations, spectra processing and parameter determination

The present paper continues a series of earlier studies of the Galactic thick and thin disc and is based on the spectral material obtained at Observatoire de Haute-Provence (France). The spectra of 175 stars were obtained in the wavelength region 4400-6800 ÅÅ with S/N about 100-350 using the 1.93 m telescope at the Observatoire de Haute-Provence (OHP, France), equipped with the echelle-type spectrograph ELODIE (Barrane et al., 1996) with the resolving power R = 42000. The primary processing of images is available online immediately after the exposure. The spectra have been treated to correct the blaze efficiency, cosmic and telluric lines as per Katz et al. 1998.The next processing of the studied spectra (including the continuous spectrum level installation, the construction of the dispersion curve, the measurement of

equivalent widths EW, etc.) was performed with the DECH20 software package (Galazutdinov 1992).

The parameters of the investigated stars were taken from Mishenina et al. (2013). The effective temperatures Teff were estimated using the line-depth ratio method (Kovtyukh et al., 2004). The surface gravities lg g were computed by two methods, namely the iron ionization balance and the parallax. The results of application of these two methods are in good agreement. The microturbulent velocity Vt was derived considering that the iron abundance log A(Fe) obtained from the given Fe I line was not correlated with the equivalent width EW of that line. The iron abundance determined from the iron Fe I lines was taken as the metallicity [Fe/H].

3. The sulphur abundance determination

The sulphur abundances were obtained under the LTE approximations by the synthetic spectrum method accounting for the hyperfine structure (HFS) and the oscillator strengths of lines from Korotin (2009). The Kurucz atmospheric models (Kurucz, 1993) and a new version of the STARSP code by Tsymbal (1996) were applied. We used the sulphur lines in the region of 6743-6762 ÅÅ available in our spectra. The adopted sulphur solar abundance is log $A(S)_\odot$ = 4.84 in the scale where log A(H) = 12.00. The NLTE corrections for those lines are small and do not exceed 0.1 dex (Korotin, 2009). An example of the fitting of the computed synthetic and observed spectrum in the sulphur line region is shown in Fig. 1.
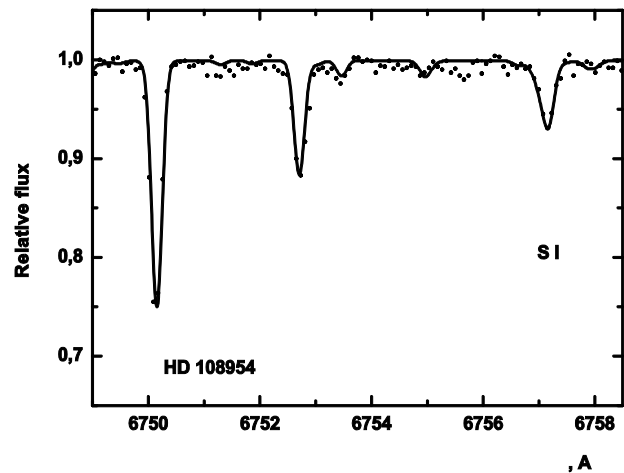

Figure 1: An example of the fitting of the observed and synthetic spectrum in the sulphur line region

4. The comparison with the results of other authors

The comparison of the data obtained by us with those from the studies by Chen et al. (2002) for one common star HD 9826 and Ecuvillon et al. (2004) for 12 common stars, including HD 9826, was made.

Table 1: The comparison of parameters and S abundance in star HD 9826

Teff	log g	[Fe/H]	[S/Fe]	References
6119	4.12	0.12	0.04	Chen et al. (2002)
6212	4.26	0.13	−0.33	Ecuvillon et al. (2004)
6074	4.00	0.10	−0.12	Our study

For star HD 9826 (50 And), we can see (in Table 1) that our determined parameters and sulphur abundances are in good agreement with the results by Chen et al. (2004) within the determination errors while the comparison with the data obtained by Ecuvillon et al. (2004) shows the difference in temperature and sulphur abundance. At that, the data for 12 common stars received in the same study (Ecuvillon et al. 2004, Ec04) are in good agreement with our data:

$\Delta Teff_{(our - Ec04)} = -4 \pm 73$ K, $\Delta \log g_{(our - Ec04)} = 0.11 \pm 0.12$, $\Delta [Fe/H]_{(our-Ec04)} = 0.05 \pm 0.04$, $\Delta [S/Fe]_{(our-Ec04)} = -0.03 \pm 0.11$.

Therefore, we can conclude that our determinations are in good agreement with those in the literature within the determination errors.

To calculate errors in the sulphur abundance determinations, we supposed the accuracy of effective temperature determination is $\delta Teff = \pm 100$ K, the surface gravity log g – $\delta \log g = \pm 0.2$ dex, $\delta Vt = \pm 0.2$ km/s ; and also the uncertainty of 0.03 dex in the computed spectrum fitting (Table 2). These estimations of the accuracy in the parameter determination and spectral fitting are in good correspondence with those from Mishenina et al. (2013), as well as with our estimations given above.

For sulphur the variation in parameters by $\delta Teff = -100$ K, $\delta \log g = +0.2$, $\delta Vt = +0.2$ km/s is given in columns 1, 2 and 3, respectively. The total error is given in column 4 supposing that the uncertainty in the spectrum fitting is 0.03 dex.

Table 2: Influence of stellar parameters on S abundance determination

El	1	2	3	4
[S/H]	−0.11	−0.03	0.02	0.12

As can be seen from Table 2, the total error is about 0.12 dex.

5. Results and discussion

Sulphur is an important element which can serve as a good test of the nucleosynthesis theory and various conditions of the synthesis of α-elements, on the one hand, and potentially different enrichment of chemical elements in stars with and without planets, on the other hand.

To test the nucleosynthesis theories, let us make a comparison between the sulphur behaviour in stars of the Galactic thin and thick discs (Fig. 2) and the Si and Mg behaviour in those stars (see Fig. 5 in Mishenina et al., 2013). The probability of each star's belonging to the thin or thick discs was determined by the method of Soubiran & Girard (2005).
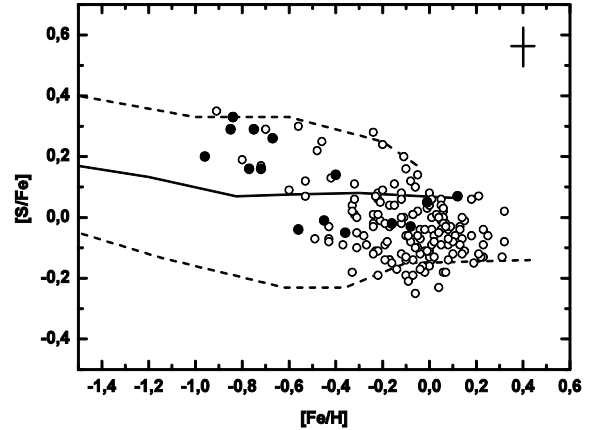

Figure 2: The correlation between the sulphur abundance and metallicity in the stars of the thin (marked with blank circles) and thick (marked with solid circles) discs. The comparison with the computations made by the chemical evolution models (Timmes et al., 1995) with twofold iron yield in supernovae SN Ia.

As is seen from these figures, there is a correlation between all those α-process elements and metallicity: the elemental abundances are higher at lower metallicities. At that, the observed correlations for sulphur and silicon are practically similar with those for magnesium. That can be a good argument in favour of modern computations of nucleosynthesis where core-collapse supernovae (CCSN) are reckoned as the main contributors of α-elements and are responsible for the production of magnesium, sulphur and silicon. The obtained trends are similar within our determination errors and do not enable to distinguish the behaviour of magnesium, sulphur and silicon. Hence, based on our data, we can not discuss the observed demonstration of different behaviour of the carbon combustion products, on the one hand, and oxygen and neon, on the other hand, in massive supernovae.

It is also interesting to compare the obtained sulphur abundances with the computations of the Galactic chemical evolution. Fig. 2 shows the comparison with the models by Timmes et al. (1995) with different iron yield in supernovae SN Ia. In general, the computations specify the observation data. Therefore, we can substantiate that the adopted characteristic parameters of the chemical evolution (the Galaxy structure, the star formation and mass functions) and yield of elements (in our case, the sulphur production in the neon and oxygen burning processes) correspond to the observed reality.

To estimate the effects of the planet formation on the chemical composition of a star, we considered the abundances of refractory metals (Mg and Ni) and volatile elements (S and Zn). The Mg, Ni and Zn abundances were adopted from our earlier studies of the dwarfs with temperatures in the range of 5500 – 6200 K and metallicities from -0.5 dex. The metallicity range was extended to -0.5 dex as there is also a possibility of planet formation for metallicities lower than the solar one as reported by Adibekyan et al. (2012). The stars with planets were selected from the catalogue by Schneider et al. (2011).
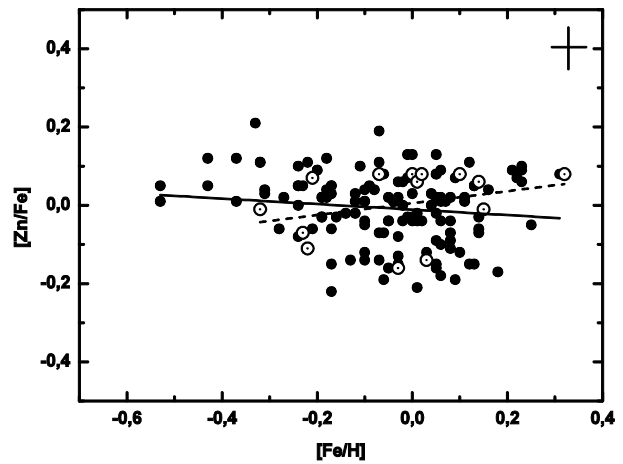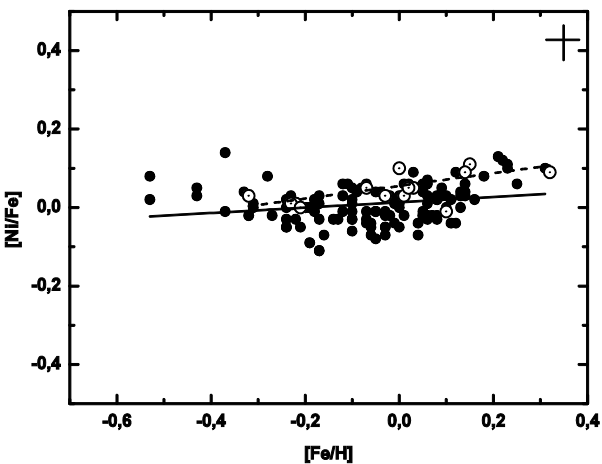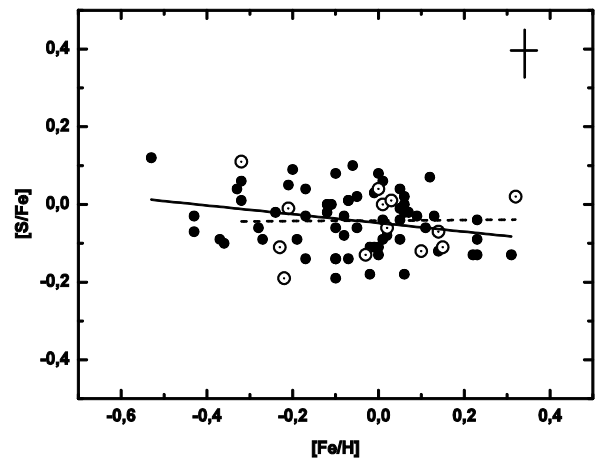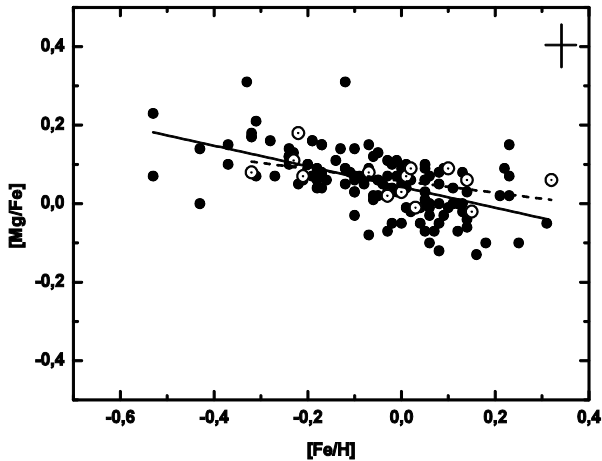
Figures 3, 4: The dependence of the magnesium and nickel (refractory elements) abundances on [Fe/H] in planet-hosting stars (marked with circled dots) and stars without planets around them (marked with solid circles).

Figures 5, 6: The dependence of the sulphur and zinc (volatile elements) abundances on the metallicity in planet-hosting stars (marked with circled dots) and stars without planets around them (marked with solid circles).

As is seen from the presented figures (Figs. 3-6), there are neither differences in the abundances nor trends exceeding the determination errors for either stars with or without planets.

6. Conclusions

Based on the high-resolution spectra and computed synthetic spectra accounting for the hyperfine structure, we determined the sulphur abundance for 175 dwarfs of the thin and thick discs. We found the following:
1) Sulphur behaves as a typical alpha-element showing no difference comparing to the behaviour of other α-elements. The comparison with the theories of nucleosynthesis and chemical evolution of the Galaxy counts in favour of the hypothesis that the primary source of the sulphur production is the oxygen and neon burning both at the pre-supernova stage and in the explosive burning processes in massive core-collapse supernovae.
2) As a volatile element sulphur does not exhibit any difference in behaviour for either stars with or without planets discovered around.

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