Behavior of $[S/Fe]$ in Very Metal-Poor Stars from the S I 1.046 µm Lines Revisited *

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Abstract

With the aim of establishing how the $[S/Fe]$ ratios behave at the very low metallicity regime down to $[Fe/H] \sim -3$, we conducted a non-LTE analysis of near-IR S I triplet lines (multiplet 3) at 10455–10459 Å for a dozen of very metal-poor stars ($-3.2 \lesssim [Fe/H] \lesssim -1.9$) based on the new observational data obtained with IRCS+AO188 of the Subaru Telescope. It turned out that the resulting $[S/Fe]$ values are only moderately supersolar at $[S/Fe] \sim +0.2$–0.5 irrespective of the metallicity. While this “flat” tendency is consistent with the trend recently corroborated by Spite et al. (2011, A&A, 528, A9) based on the S I 9212/9228/9237 lines (multiplet 1), it disaffirms the possibility of conspicuously large $[S/Fe]$ (up to $\sim +0.8$) at $[Fe/H] \sim -3$ that we once suggested in our first report on the S abundances of disk/halo stars using S I 10455–10459 lines (Takeda & Takada-Hidai 2011, PASJ, 63, S537). Given these new observational facts, we withdraw our previous argument, since we consider that $[S/Fe]$’s of some most metal-poor objects were overestimated in that paper; the likely cause for this failure is also discussed.

Key words: stars: abundances — stars: atmospheres — stars: late-type
— stars: Population II

1. Introduction

The galactic evolution of sulfur (one of the $\alpha$-group elements) has been a matter of controversy, since different $[S/Fe]$ behaviors with a decrease of $[Fe/H]$ were suggested in the regime of metal-poor halo stars depending on the lines used; i.e., ever-increasing $[S/Fe]$ even up to $\sim +0.8$ (S I 8693–4 lines of multiplet 6) or nearly constant $[S/Fe]$ at a mildly supersolar value around $\sim +0.3$ (S I 9212/9228/9237 lines of multiplet 1). See, e.g., Takeda et al. (2005) and the references therein for more details.

Given this situation, we recently carried out a systematic study on the $[S/Fe]$ ratios of 33 disk/halo stars over a wide range of metallicity ($-3.7 \lesssim [Fe/H] \lesssim 0.3$) while newly exploiting the S I triplet lines at 10455–10459 Å (multiplet 3) based on the near-IR spectra obtained with Subaru IRCS+AO188, which had barely been used before (Takeda & Takada-Hidai 2011; hereinafter referred to as Paper I). Rather unexpectedly, while the the local plateau of $[S/Fe] \sim +0.2$–0.4 (flat trend) was confirmed at $-2.5 \lesssim [Fe/H] \lesssim -1.5$ in consistent with the tendency already established from the S I 9212/9228/9237 lines (e.g., Nissen et al. 2007), we found a considerably large $[S/Fe]$ ratio amounting to $\sim +0.7$–0.8 dex at very low metallicity ($[Fe/H] \sim -3$), which apparently makes a puzzling discontinuity in the narrow interval of $-3 \lesssim [Fe/H] \lesssim -2.5$. If this trend is real, the chemical evolution of sulfur would have to be considered differently from other $\alpha$ elements generally showing a plateau at a mildly supersolar $[\alpha/Fe]$ over the halo metallicity range.

Soon after we published Paper I, however, Spite et al. (2011) reported new results of their extensive study on the $[S/Fe]$ of extremely metal-poor stars, which are markedly against our conclusion (i.e., considerably high $[S/Fe]$ at $[Fe/H] \sim -3$). That is, using the S I 9212/9228/9237 lines based on the VLT/UVES data, they showed that $[S/Fe]$ ratio is almost constant at mildly supersolar values of $\sim 0.2$–0.5 over the very metal-poor regime of $-3.5 \lesssim [Fe/H] \lesssim -2.5$. How should we interpret this discordance? Do multiplet 1 lines ($\sim 0.92$ µm) and multiplet 3 lines ($\sim 1.05$ µm) yield different $S$ abundances at the extremely low-metallicity regime?

Yet, we need to ascertain in the first place that the trend of high $[S/Fe]$ at $[Fe/H] \sim -3$ we obtained in Paper 1.

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* Based on data collected at Subaru Telescope, which is operated by the National Astronomical Observatory of Japan.
I from the S i 10455–10459 lines universally exists for extremely metal-poor stars in general, since that conclusion was extracted from only a few objects based on the spectra of not-so-sufficient quality. We thus decided to reinvestigate the [S/Fe] behavior for a larger sample (ca. a dozen objects) specifically confined to very metal poor stars (−3.2 ≤ [Fe/H] ≤ −1.9) based on our new observations lately conducted again with Subaru IRCS+AO188. The purpose of this article is to report the outcome of this new analysis.

2. Observational Data

The near-IR spectroscopic observations were conducted on 2011 August 17 and 18 (UT) by using IRCS+AO188 of the Subaru Telescope for the selected 13 very metal-poor stars, among which 4 are turn-off dwarfs and 9 are evolved giants. In addition, we also observed Vesta in order to get the sun-light reference spectrum with the same equipment. The list of the targets is given in table 1. Note that G 64-37 (which was studied in Paper I) was again included in the present sample. The details of the instrument and its setting along with the data reduction procedures (the same as in our previous observations in 2009 July) are described in section 2 of Paper I.

In this observing run, a special attention was paid to achieve a sufficiently high signal-to-noise ratio so as to detect very weak S i 10455–10459 lines of extremely metal-poor stars. For this purpose, especially long integrated exposure times (≈1–4 hours) were expended to the comparatively faint $(J \sim 9–11$ mag) lowest metallicity stars ([Fe/H] $\sim −3$), such as CS 30323-048, HD 126587, G 206-34, G 64-37, HE 1523-0901, and BD−16 251. For the other brighter objects of $J \sim 5–8$ mag, we set the exposure times from a few minutes to ≈20 min depending on the brightness. The S/N ratios, eventually accomplished in the neighborhood of the S i lines in our finally resulting $zJ$-band spectra (with the resolving power of $R \sim 20000$), are typically $≈ 300–500$ (cf. table 1).

3. Analysis and Results

The atmospheric parameters ($T_{\text{eff}}$, log $g$, $v_t$, and [Fe/H]) necessary for constructing the model atmosphere for each star were taken from various published studies (cf. table 1). Then, as in Paper I, the S abundance was evaluated by way of the non-LTE spectrum-synthesis analysis while applying Takeda’s (1995) automatic fitting procedure to the region of S i 10455–10459 lines.

Since we modeled the observed stellar line profile ($D_{\text{obs}}$) by the convolution of (i) the intrinsic spectrum ($D_0$; where only the elemental abundance $A$ is allowed to vary since the model atmosphere and the microturbulence are given)

Actually, we noticed that some ripple patterns appeared in several restricted portion of the spectrum, which may be attributed to an imperfect flat-fielding. While this pattern was found to fall on the region of the S i lines in several cases depending on the stellar radial velocity, we could successfully remove them by dividing the spectrum by that of a rapid rotator.

and (ii) the Gaussian macro-broadening function $f_M (v) \propto \exp(-v^2 / v_M^2)$) parametrized by $v_M$ (including the combined effects of the instrumental broadening, the macro-turbulence, and the projected rotational velocity), such as $D_{\text{obs}} = D_0 \cdot f_M$, adjustable free parameters in accomplishing the best fit are $A$ and $v_M$, both of which were actually varied in the previous analysis of Paper I. However, for the reason mentioned in the next section, we intentionally fixed the $v_M$ parameter in this S i 10455–10459 fitting for five extremely metal-poor stars (CS 30323-048, HD 126587, G 206-34, G 64-37, HE 1523-0901, and BD−16 251) at the pre-determined values which had been established in advance from the analysis applied to the strong C+Si feature at $\sim 1.069$ μm [where $A(C)$, $A(Si)$, and $v_M$ were varied to search for the best fit]. The final $v_M$ values resulting from (or assumed as fixed in) the profile-fitting analysis are given in table 1.

How the theoretical spectrum for the converged solutions fits well with the observed spectrum is displayed in figure 1, and the resulting non-LTE S abundances ($A^N$) along with the [S/Fe] values are presented in table 1.

In figure 2a are plotted the resulting [S/Fe] ratios against [Fe/H], where the abundance uncertainties ($\delta_{\text{TP}}$; cf. subsection 4.2 in Paper I) caused by ambiguities in $T_{\text{eff}}$ (±100 K), log $g$ (±0.2 dex), and $v_t$ (±0.3 km s$^{-1}$) are shown by thin error bars (though they are typically on the order of ±0.1 dex and not very significant). We also derived $EW_{10455}$ (equivalent width in $\frac{\text{m}}{\text{A}}$)

and (we denote $[\text{S}/\text{Fe}]$ = $[\text{S}/\text{H}]$ − [Fe/H], where $[\text{S}/\text{H}] = A^N − 7.20$. We used $A^N = 7.20$ (the value derived in Paper I based on the solar flux spectrum atlas of Kurucz et al. 1984) as the reference solar abundance in order to keep consistency with our previous study, which anyhow matches the present result (7.21; cf. table 1) derived from the spectrum of Vesta very well.

We should remark that largely different atmospheric parameters from those adopted here are reported in the literature, especially for high-gravity turn-off stars. For example, Ishigaki, Chiba, and Aoki (2010) derived ($T_{\text{eff}}$, log $g$, [Fe/H]) of (5821,
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ure 2c are the S/N-dependent uncertainties ($\delta EW$) estimated by Cayrel's (1988) formula, $\sim 1.6 (w \times d_\epsilon)^{1/2}$, where $w$ is the typical line FWHM ($\sim 0.5-1$ Å; assumed to be 0.75 Å), $d_\epsilon$ is the pixel size (0.25 Å), and $\epsilon$ is the photon-statistics accuracy ($\sim (S/N)^{-1}$). The abundance errors ($\Delta EW_{\text{err}}$) in response to these uncertainties in $EW_{10455}$ are further displayed in figure 2d, where we can see that these errors become considerable (e.g., a few tenths dex) for extremely metal-deficient stars ($[\text{Fe/H}] \lesssim -3$) showing very weak lines ($EW_{10455} \lesssim 5-6$ mA).

4. Discussion

We are now ready to answer the question which motivated this study: "How do the [S/Fe] ratios of very metal-poor stars behave around $[\text{Fe/H}] \sim -3$; a sudden jump to a considerably high value of $\sim +0.8$ (as suggested in Paper I) or only a mildly supersolar value at $\sim +0.4$ maintaining a flat trend (as derived by Spite et al. 2011)"? We can recognize in figure 2a that the [S/Fe] ratios do not show any appreciable increase with a decrease in the metallicity, which are almost constant over $-3.2 \lesssim [\text{Fe/H}] \lesssim -1.9$ with the mean of $<[\text{S/Fe}]> = +0.34$ ($\sigma = 0.16$) irrespective of dwarfs and giants. These [S/Fe] values of very metal-deficient stars resulting from this study are combined with those of halo/disk stars derived in Paper I on the [S/Fe] vs. [Fe/H] plot displayed in figure 3, from which we can state that [S/Fe] ratios are almost "flat" around $\sim +0.3$ over the wide metallicity range between [Fe/H] $\sim -1$ and $\sim -3$. Thus, we have to admit that Spite et al.'s (2011) argument actually represented the truth, which (in turn) means that our previous conclusion of Paper I was not correct, as far as the run of [S/Fe] around the regime of [Fe/H] $\sim -3$ is concerned. From an impartial point of view, however, this is a gratifying consequence in a sense, because the different abundance indicators (S I 9212/9228/9237 and S I 10455–10459) eventually turned out to yield consistent results with each other.

Then, how should we interpret the prominently high [S/Fe] results once obtained for all three most metal-poor stars around [Fe/H] $\sim -3$ among the sample in Paper I; i.e., ([S/Fe], [Fe/H]) = (+0.69, -3.08) [G 64-37], (+0.76, -3.06) [BD–18 5550], and (+0.66, -2.71) [HD 115444]? With an intention to confirm whether or not these results are really reliable, we reexamined the process of the previous analysis for these stars.

Regarding BD–18 5550 and HD 115444, we noticed that the solutions of $v_{\text{broad}}$ (macrobroadening parameter; cf. section 3) resulting as by-products of spectrum fitting are unusually high (18.6 and 19.4 km s$^{-1}$, respectively) compared to other stars where values around $\sim 10$ km s$^{-1}$ are in common. However, additional spectrum fitting

Fig. 2. Sulfur abundances and the related quantities plotted against [Fe/H]: (a) [S/Fe] corresponding to non-LTE sulfur abundance, where attached thin error bars represent the ambiguities due to uncertainties in the atmospheric parameters ($\delta g_{\text{vi}}$; cf. subsection 4.2 in Paper I), (b) $\Delta_{10455}$ (non-LTE correction for the S I 10455 line). (c) $EW_{10455}$ (equivalent width for the S I 10455 line) with the S/N-dependent intrinsic random error ($\delta EW$) estimated from Cayrel’s (1988) formula. (d) $\Delta EW_{\text{err}}$ (abundance variation in response to $EW$ changes of $\pm \delta EW$). Dwarfs ($\log g > 3$) and giants ($\log g < 3$) are indicated by filled (scarlet) and open (brown) squares, respectively.
analyzes to the C+Si feature at $\lambda \sim 1.069$ $\mu$m carried out for these stars yielded quite reasonable $v_M$ values of 9.4 km s$^{-1}$ (BD$-18$ 5550) and 10.2 km s$^{-1}$ (HD 115444) (cf. figures 4a and 4c). Since almost the same $v_M$ should (in principle) result from different lines, we can not help considering that the $v_M$ values for these two stars obtained from the S $10455$–$10459$ fitting in Paper I were inadequately overestimated, which we suspect may presumably related to the profile-fitting technique we adopted. That is, the automatic solution-search algorithm (Takeda 1995), which simultaneously varies several parameters to accomplish the best fit, is very efficient in case where the stellar line profiles are well defined. However, we should be careful when it is applied to the very weak-line case where noises are comparable to the signal of stellar lines, since it may yield physically meaningless solutions where profiles are appreciably damaged by noises. In such cases, $v_M$ had better be fixed at a (more reliable) value derived from other stronger lines (such as the C+Si feature), instead of varying both $A(S)$ and $v_M$, which is the approach we adopted for the five most metal-poor stars in this study (cf. section 3).$^6$ Accordingly, we redetermined the S abundances from the S $10455$–$10459$ lines while fixing the $v_M$ values at the values derived from the C+Si feature, and obtained $A(S)$ values (4.67 and 4.83), which are appreciably lower than the results in Paper I (4.90 and 5.15) by 0.23 dex and 0.32 dex for BD$-18$ 5550 and HD 115444, respectively (cf. figures 4b and 4d). We thus consider that the [S/Fe] values of these two stars reported in Paper I should be revised downward by these amounts, which eventually makes $+0.53$ (BD$-18$ 5550) and $+0.34$ (HD 115444); i.e., being almost within the [S/Fe] range concluded in this study.

Fig. 3. [S/Fe] vs. [Fe/H] relation based on the results in obtained this study (larger squares) combined with those derived in Paper I (smaller circles). As in figure 2, open and filled symbols are for giants ($\log g < 3$) and for dwarfs ($\log g > 3$), respectively.

Fig. 4. Reanalysis of two stars (BD$-18$ 5550 and HD 115444 in the left and right panels, respectively) which showed particularly high [S/Fe] values in Paper I, in order to demonstrate the choice of $v_M$ (macrobroading parameter) influences the resulting sulfur abundance derived from spectrum fitting. Upper panels (a) and (c) • Derivation of best-fit $v_M$ from the C+Si feature at $\sim 1.069$ $\mu$m. Lower panels (b) and (d) • Determination of $A(S)$ with two kinds of $v_M$ treatments, where $v_M$ is varied as an adjustable parameter (upper spectrum; method adopted in Paper I) or $v_M$ is fixed at the value derived from the C+Si feature (lower spectrum).

\[v_M^2 + v_{int}^2 + v_{in}^2\] Under this approximation, $v_M$ is evaluated as $v_M = \text{FWHM}/(2\sqrt{\ln 2}) \sim 9$ km s$^{-1}$ (FWHM $\sim 15$ km s$^{-1}$ for $R \approx 20000$). Then, we may expect that $v_M$ would be as small as $\sim 2$ km s$^{-1}$ according to the relation $v_M \approx 0.4 v_{RT}$ (cf. footnote 12 of Takeda et al. 2008) since the typical $Q_{RT}$ (radial-tangential macroturbulence) is $\sim 5$ km s$^{-1}$ for early G dwarfs and early-K giants (cf. figure 17.10 in Gray 2005). Finally, we may regard that $v_M$ ($\sim 0.94 v_0 \sin i$; cf. footnote 12 of Takeda et al. 2008) is of minor importance (e.g., presumably no larger than $\sim 2$–3 km s$^{-1}$ in most cases), since the stellar rotation must have been spun down in these old halo stars. Accordingly, $v_M$ is reasonably expected to be around $\sim 10$ km s$^{-1}$, because it is primarily determined by the contribution from $v_0$.

For the other stars, both $A(S)$ and $v_M$ were varied to determine as in Paper I. However, we checked for each star that the resulting $v_M(S)$ (cf. table 1) is not in serious disagreement with $v_M$ (C+Si). Note that HD 195630 is a rather unusual star, whose $v_M$ is appreciably high ($17.0$ km s$^{-1}$) is remarkably large (an alternative C+Si fitting also yielded a similar result), which might have a comparatively high $v_0 \sin i$ for stars of this class.
This study was motivated by the recent extensive work done by Spite et al. (2011) who reported that [S/Fe] ratios of very metal-poor stars determined from the Si I 9212/9228/9237 lines show a nearly flat behavior at a mildly supersolar level of $\sim +0.2$–$0.5$ over a wide metallicity range of $-3.5 \lesssim [\text{Fe/H}] \lesssim -2$, which markedly contradict the conclusion of our previous study based on Si I 10455-10459 lines (Paper I) that such a flat tendency of [S/Fe] (persisting down to $[\text{Fe/H}] \sim -2.5$) is followed by a sudden jump up to $+0.7$–$0.8$ around $[\text{Fe/H}] \sim -3$.

With an intention to resolve the cause of this discrepancy, we rechallenged the task of clarifying the [S/Fe] ratios at the extremely low metallicity regime down to $[\text{Fe/H}] \sim -3$ by using the same triplet lines as used in Paper I, based on the new observational data for an extended sample of 13 very metal-poor stars observed with IRCS+AO188 of the Subaru Telescope.

In almost the same manner as in Paper I, we conducted a non-LTE spectrum fitting analysis of Si I 10455–10459 triplet, and found that the resulting [S/Fe] values were moderately supersolar uniformly scattering around $\sim +0.3$–$0.4$ [with the mean abundance of $[\langle \text{S/Fe} \rangle] = +0.34$ ($\sigma = 0.16$)] over $-3.2 \lesssim [\text{Fe/H}] \lesssim -1.9$ without any systematic [Fe/H]-dependence, which confirmed the consequence corroborated by Spite et al. (2011) based on the Si I 9212/9228/9237 lines.

Given these new observational facts, we reexamined the process of our previous analysis for the three extremely metal-poor stars (G 64-37, BD–18 5550, and HD 115444), for which we derived prominently high [S/Fe] values ($\sim +0.7$–$0.8$) that eventually lead to the conclusion of Paper I. Regarding G64-37, our reanalysis using a new spectrum of higher quality yielded a result lower than the previous value by $\sim 0.3$ dex. For BD–18 5550 and HD 115444, we noticed that our automatic profile-fitting method (which varies both the abundance and the broadening parameter to find the best fit) resulted in unreasonably large solutions of the broadening width, because of the considerable weakness of the line profile severely damaged by noises. When the broadening parameter was fixed at the more reasonable values determined from stronger lines, we found that the revised solution of the S abundance is lowered by $\sim 0.3$–$0.4$ dex for both of these stars. Consequently, it is likely that we had overestimated the [S/Fe] values of these three stars in Paper I by $\sim 0.3$–$0.4$ dex.

Accordingly, we now consider that the flat trend of [S/Fe] (without any systematic rise with a decrease of metallicity) represents the truth, at least with regard to the overall [S/Fe] behavior of very metal-poor stars in general, which means the withdrawal of our previous argument that [S/Fe] experiences a sudden jump up to conspicuously large [S/Fe] of $\sim +0.8$ as the metallicity is lowered down to the [Fe/H] $\sim -3$ regime.

We finally remark, however, that the existence of some stars deviating from the main trend with appreciably higher/lower [S/Fe] amounting to [S/Fe] $\sim +0.7$/$0.0$ as a result of the natural diversity is not necessarily be excluded (e.g., we derived [S/Fe] $\sim +0.66$ for HD 126587 and [S/Fe] $\sim -0.01$ for HD 13979). Actually, since our 13 stars ($[\text{Fe/H}] \lesssim -2$) yielded $[\langle \text{S/Fe} \rangle] = +0.34$ with $\sigma$ (standard deviation) of 0.16, we may expect the probability of finding $\geq 1\sigma$ deviation ($[\text{S/Fe}] \lesssim +0.2$ or $[\text{S/Fe}] \gtrsim +0.5$) and $\geq 2\sigma$ deviation ($[\text{S/Fe}] \lesssim 0.0$ or $[\text{S/Fe}] \gtrsim +0.7$) to be

![Fig. 5.](image)

Comparison of the spectra and the A(S) determination procedures for G 64-37, for which two independent analyses were performed in Paper I (based on the 2009 data) as well as in this study (based on the 2011 data).
∼ 30% and ∼ 5%, respectively. Form this point of view, the recent Koch and Caffau’s (2011) result of [S/Fe] as somewhat high as ∼ +0.5 for a red giant in the very metal-poor globular cluster NGC 6397 ([Fe/H] ∼ −2.1) may be understandable without invoking a bimodal [S/Fe] trend such as they discussed.

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This estimation naturally depends on the extent of σ. We note that the σ([S/Fe]) of [Fe/H] ≤ −2 stars derived by other investigators are somewhat smaller than our result; e.g., σ = 0.07 (Nissen et al. 2007), σ = 0.12 (Spite et al. 2011), σ = 0.11 (Jönsson et al. 2011). It should thus be important to quantitatively establish not only the trend of [S/Fe] on the average but also the extent of its dispersion based on a large sample of very metal-poor stars.
Table 1. Parameters of the program stars and the results of abundance analyses.

| Name         | \( T_{	ext{eff}} \) (K) | \( \log g \) (cm s\(^{-2}\)) | \( v_t \) (km s\(^{-1}\)) | \([\text{Fe/H}]\) Ref. | \( v_M \) (km s\(^{-1}\)) | \( A^N \) (dex) | \( EW_{10455} \) (mÅ) | \( \Delta_{10455} \) (dex) | \([S/Fe]\) (dex) | \( S/N \) | Remark |
|--------------|--------------------------|-------------------------------|-----------------|------------------|-----------------|----------------|-----------------|-----------------|----------------|-------|--------|
| CS 30323-048 | 6338                     | 4.32                          | 1.5             | –3.21            | NIS07           | 4.29           | 2.8             | –0.25           | +0.30          | 350   | \( v_M \) fixed, larger uncertainty |
| HD 126587    | 4700                     | 1.05                          | 1.7             | –3.16            | HAN11           | 4.70           | 14.2            | –0.27           | +0.66          | 300   | \( v_M \) fixed |
| G 206-34     | 5825                     | 3.99                          | 1.5             | –3.12            | RIC09           | 4.55           | 3.6             | –0.19           | +0.47          | 450   | \( v_M \) fixed |
| G 64-37      | 6432                     | 4.24                          | 1.5             | –3.08            | NIS07           | 4.54           | 5.5             | –0.26           | +0.42          | 200   | \( v_M \) fixed |
| HE 1523-0901 | 4630                     | 1.00                          | 2.6             | –2.95            | FRE07           | 4.42           | 6.7             | –0.19           | +0.17          | 350   | \( v_M \) fixed |
| HD 195636    | 5370                     | 2.40                          | 1.5             | –2.77            | CAR03           | 17.0           | 19.1            | –0.35           | +0.45          | 300   | large \( v_M \) (cf. footnote 5) |
| G 186-26     | 6417                     | 4.42                          | 1.5             | –2.54            | NIS07           | 12.0           | 10.7            | –0.15           | +0.36          | 500   | \( v_M \) fixed |
| HD 186478    | 4730                     | 1.50                          | 1.8             | –2.42            | HAN11           | 13.3           | 22.8            | –0.19           | +0.41          | 350   | \( v_M \) fixed |
| HD 6268      | 4735                     | 1.61                          | 2.1             | –2.30            | SAI09           | 9.5            | 21.4            | –0.17           | +0.30          | 450   | \( v_M \) fixed |
| HD 13979     | 5075                     | 1.90                          | 1.3             | –2.26            | BUR00           | 11.8           | 16.6            | –0.21           | –0.01          | 450   | \( v_M \) fixed |
| HD 221170    | 4560                     | 1.37                          | 1.6             | –2.00            | SAI09           | 9.4            | 28.7            | –0.16           | +0.29          | 200   | \( v_M \) fixed |
| HD 216143    | 4525                     | 1.77                          | 1.9             | –1.92            | SAI09           | 9.4            | 19.9            | –0.10           | +0.22          | 550   | \( v_M \) fixed |
| Vesta (Sun)  | 5780                     | 4.44                          | 1.0             | 0.00             | \( \cdots \)    | 10.7           | 7.21            | 123.5           | –0.09          | 600   | \( v_M \) fixed |

In columns 1 through 6 are given the star designation, effective temperature, logarithmic surface gravity, microturbulent velocity dispersion, Fe abundance relative to the Sun, and key for the reference of atmospheric parameters: BUR00 \( \cdots \) Burris et al. (2000), CAR03 \( \cdots \) Carney et al. (2003), FRE07 \( \cdots \) Frebel et al. (2007), HAN11 \( \cdots \) Hansen and Primas (2011), NIS07 \( \cdots \) Nissen et al. (2007), RIC09 \( \cdots \) Rich and Boesgaard (2009), SAI09 \( \cdots \) Saito et al. (2009). Columns 7–11 present the results of the abundance analysis based on the S\(^{10455\text{–}10459}\) profile-fit: \( v_M \) is the best-fit macrobroadening parameter (while those in parentheses are the assumed or fixed values, which were separately derived from the C+Si 1.069 µm feature fitting), \( A^N \) is the non-LTE logarithmic abundance of S (in the usual normalization of H = 12.00) derived from spectrum-synthesis fitting, \( EW_{10455} \) is the equivalent width (in mÅ) for the S\(^{10455}\) line inversely computed from \( A^N \), \( \Delta_{10455} \) is the non-LTE correction \( \equiv A^N - A^L_{10455} \) for the S\(^{10455}\) line, and \([S/Fe]\) \( \equiv A^N - 7.20 - [\text{Fe/H}] \) is the S-to-Fe logarithmic abundance ratio relative to the Sun. The \( S/N \) ratio of the spectrum estimated at the position of the S\(^{10455}\) lines is given in column 12. The objects are arranged in the ascending order of \([\text{Fe/H}]\).