Photospheric silicon abundances of upper main-sequence stars derived from Si II 6347/6371 doublet lines

Y. Takeda
11-2 Enomachi, Naka-ku, Hiroshima-shi, 730-0851, Japan
(E-mail: ytakeda@js2.so-net.ne.jp)

Received: September 26, 2021; Accepted: October 22, 2021

Abstract. Silicon abundances were determined by applying the spectrum-fitting technic to the Si II doublet lines at 6347 and 6371 Å for a sample of 120 main-sequence stars in the $T_{\text{eff}}$ range of $\sim$ 7000–14000 K (comprising not only normal stars but also non-magnetic chemically peculiar stars) with an aim of investigating their behaviors (e.g., correlation with stellar parameters and abundances of other elements such as Fe or C) and the background physical mechanisms involved therein, where attention was paid to taking into account of the non-LTE effect and to assigning a reasonable value of microturbulence. The following trends were revealed from the analysis: (i) The resulting [Si/H] values, mostly ranging from $\sim -0.5$ to $\sim +0.3$, show a positive correlation with [Fe/H]. (ii) A kind of anti-correlation exists between Si and C as seen from the tendency of $[C/Si]$ steeply decreasing with [Si/H]. (iii) Si abundances do not show any clear dependence upon $T_{\text{eff}}$ or $v_{\text{sin}i}$, while Am and HgMn stars appear to show comparatively higher [Si/H] than normal stars. Although it is not straightforward to explain these observational facts, different physical processes (gas–dust separation and atomic diffusion) are likely to be intricately involved in producing these characteristic behaviors of Si composition in the surface of late A through late B dwarfs.

Key words: physical processes: diffusion – stars: abundances – stars: atmospheres – stars: chemically peculiar – stars: early-type

1. Introduction

It is known that a significant fraction of late A through late B-type main-sequence stars show anomalous spectra indicative of surface abundance anomalies. Those chemically peculiar (CP) stars are divided into several groups according to their features as summarized in the review paper by Preston (1974). So far, the abundance characteristics of many elements in CP stars have been investigated in comparison with normal stars to discuss the origin of their anomalies.

However, regarding silicon, an important abundant element used as the fiducial reference in geo- or cosmo-chemistry, its abundance behavior in upper main-sequence stars is not yet well understood. While conspicuous overabundance of
Si is known to be observed in magnetic CP stars (CP2; the group 2 in CP stars classified by Preston 1974), how it behaves in non-magnetic CP stars (CP1 — Am stars; CP3 — HgMn stars) or in normal stars is not clear. As a matter of fact, we still do not know whether any Si anomaly ever exists in these stars. According to the atomic diffusion theory (see, e.g., Michaud et al. 2015), which is considered to be a promising mechanism to explain the origin of abundance characteristics in CP stars, Si is expected to be somewhat underabundant (Richer et al. 2000; Talon et al. 2006). Meanwhile, such a trend is not necessarily seen in spectroscopically determined Si abundances of A- and late B-type dwarfs, which are rather diversified around the normal (solar) abundance (somewhat overabundant or underabundant depending on cases; e.g., Niemczura et al. 2015; Ghazaryan, Alecian 2016; Mashonkina et al. 2020b; Saffe et al. 2021), though Si abundance determination significantly depends upon which line is to be used.

Another noteworthy aspect characterizing the importance of Si abundance is that this element is a typical refractory species (being easily fractionated into dust) in contrast to the volatile elements such as C, N, and O. Interestingly, Holweger and Stüenenburg (1993) reported that even normal early A-type stars (like λ Boo-type stars) show anti-correlation between the abundances of Si and C ([C/Si] systematically decreases with [Si/H]), which means that some kind of gas–dust separation process (its degree being different from star to star) would have operated in the star formation phase and altered the primordial composition of gas. Is such an effect observed also stars of other types (i.e., late A through late B stars including CP1 and CP3 stars)? This is an interesting problem to be clarified.

Conveniently, Takeda et al. (2018; hereinafter referred to as T18) recently published the C, N, and O abundances for a large sample of 100 main-sequence stars (comprising normal as well as non-magnetic CP stars) covering $7000 < T_{\text{eff}} < 11000$ K. It would be worthwhile, therefore, to determine the Si abundances for these stars. This would enable to clarify the behaviors of both [Si/H] and [C/Si], by which the nature of abundance peculiarity of Si (if any exists) in late A through late B-type stars and the involved physical process may be investigated. This is the aim of the present study.

In the past Si abundance determinations in upper main-sequence stars so far, it appears that neutral Si i lines were mainly used in late–mid A-type stars (including classical Am stars) while once-ionized Si ii lines were primarily employed in early A and late B stars (because Si i lines quickly fade out with an increase in $T_{\text{eff}}$). Since the mixed use of lines of different ionization stages is not advantageous because of inevitable line-by-line abundance discrepancies (see, e.g., Mashonkina 2020a), we decided to invoke in this study only the Si ii doublet lines at 6347 and 6371 Å, which are of high quality (i.e., almost free from blending) and sufficiently strong over the whole relevant $T_{\text{eff}}$ range. Nevertheless, some disadvantages are involved in using these strong Si ii lines; that is, the resulting Si abundances suffer an appreciable non-LTE affect and are
Si abundances of upper main-sequence stars

2. Observational data

Regarding the program stars in this study, all the 101 targets (including the reference star Procyon) in T18 (cf. Section 2 therein) were adopted without change. In addition, in order to back up the range of $11000 \lesssim T_{\text{eff}} \lesssim 14000$ K (which was not covered in T18), 19 late B-type stars (among which $\sim 40\%$ are CP3 stars) were newly included. As such, our targets are 120 late B-type through early F-type stars on or near to the main sequence (luminosity classes of III–V) which have slow to moderately-high rotational velocities ($0 \text{ km s}^{-1} \lesssim v_{\text{e sin } i} \lesssim 100 \text{ km s}^{-1}$). Among these, about $\sim 1/3$ are non-magnetic CP stars: 25 Am stars, 13 HgMn (or Mn) stars, and 2 $\lambda$ Boo stars. Besides, our sample includes 16 Hyades A-type stars. The list of these 120 stars is given in Table 1, while the data source and the basic information of the observational materials are summarized in Table 2.

Figure 1. The 120 program stars are plotted on the theoretical HR diagram ($\log (L/L_\odot)$ vs. $\log T_{\text{eff}}$), where $T_{\text{eff}}$ was derived from colors (cf. Section 3) and $L$ was evaluated from visual magnitude (corrected for interstellar extinction by following Arenou et al. 1992), Hipparcos parallax (van Leeuwen 2007), and bolometric correction (Flower 1996). Theoretical solar-metallicity tracks for 7 different masses (1.5, 1.7, 2, 2.5, 3, 4, and 5 $M_\odot$), which were computed by Lejeune and Schaerer (2001), are also depicted by solid lines for comparison.
| HD# | Name | Sp.Type | T eff | log g | [Fe/H] | B V | Am | Group | Remark |
|-----|------|---------|-------|-------|-------|-----|-----|-------|--------|
| 17380 | v Cas | B9I ... | 14028 | 3.91 | 0.11 | 3.73 | 0.11 | B | SB2, H |
| 17363 | v Cet | B10IV | 13520 | 3.86 | 0.13 | 3.69 | 0.13 | B | SB2, H |
| 17355 | ζ Boo | B9V | 12999 | 3.83 | 0.14 | 3.66 | 0.14 | B | SB2, H |
| 17348 | 15 Boo | A2IV | 12775 | 3.80 | 0.15 | 3.63 | 0.15 | B | SB2, H |
| 17340 | 14 Boo | A2IV | 12698 | 3.77 | 0.16 | 3.60 | 0.16 | B | SB2, H |
| 17332 | 13 Boo | A2IV | 12621 | 3.74 | 0.17 | 3.57 | 0.17 | B | SB2, H |
| 17324 | 12 Boo | A2IV | 12547 | 3.72 | 0.17 | 3.54 | 0.17 | B | SB2, H |
| 17317 | 11 Boo | A2IV | 12479 | 3.70 | 0.17 | 3.51 | 0.17 | B | SB2, H |
| 17310 | 10 Boo | A2IV | 12413 | 3.68 | 0.17 | 3.49 | 0.17 | B | SB2, H |
| 17303 | 9 Boo | A2IV | 12349 | 3.66 | 0.17 | 3.47 | 0.17 | B | SB2, H |
| 17297 | 8 Boo | A2IV | 12284 | 3.64 | 0.17 | 3.45 | 0.17 | B | SB2, H |
| 17290 | 7 Boo | A2IV | 12222 | 3.62 | 0.17 | 3.43 | 0.17 | B | SB2, H |
| 17283 | 6 Boo | A2IV | 12162 | 3.60 | 0.17 | 3.41 | 0.17 | B | SB2, H |
| 17276 | 5 Boo | A2IV | 12103 | 3.58 | 0.16 | 3.40 | 0.16 | B | SB2, H |
| 17270 | 4 Boo | A2IV | 12047 | 3.56 | 0.16 | 3.39 | 0.16 | B | SB2, H |
| 17263 | 3 Boo | A2IV | 11992 | 3.54 | 0.16 | 3.38 | 0.16 | B | SB2, H |
| 17256 | 2 Boo | A2IV | 11939 | 3.52 | 0.16 | 3.37 | 0.16 | B | SB2, H |
| 17250 | 1 Boo | A2IV | 11888 | 3.50 | 0.16 | 3.36 | 0.16 | B | SB2, H |

**Table 1.** Program stars and the results of the analysis.
### Table 1. (Continued.)

| HD#  | Name     | Sp. Type  | T_{eff} | log g | [Fe/H] | v\_sin\_k | v\_hel | [α/H] | [Si/H] | v\_rot | Refit | Group | Remark  |
|------|----------|-----------|---------|-------|--------|------------|--------|--------|--------|--------|-------|-------|---------|
| 192640 | 29 Cyg     | A2V       | 8845    | 4.66  | +0.66  | 1.44       | +0.08  | 3.48   | +1.52  |       |       |       | B      |
| 193432 | π Cap     | B9V       | 10180   | 3.91  | +0.02  | 23        | 23     | 2.78   | –1.47  | +0.01  | D     |
| 193452 | θ Cap     | B9.5IV/V  | 10543   | 4.15  | +0.39  | 3         | 0.06   | 1.39   | –0.09  | 1.24   | –0.81 | C     |
| 195725 | ζ Cep     | A0III     | 7416    | 3.74  | +0.16  | 49        | 15     | 2.98   | –0.14  | 4.13   | –0.15 | D     |
| 196385 | Ψ V       | A9V       | 6919    | 4.23  | –0.21  | 15        | 0.07   | 2.98   | –0.14  | 4.13   | –0.15 | D     |
| 196426 | Δ Hhl     | B9.5IV    | 12899   | 3.89  | –0.10  | 6         | 1.00   | –0.61  |        |       |       |       | F      |
| 197392 | δ Hhl     | B9III     | 13166   | 3.46  | –0.01  | 30        | 1.00   | –0.66  |        |       |       |       | C      |
| 198039 | 56 Cyg     | A1V       | 7921    | 4.69  | +0.02  | 59        | 0.38   | 3.09   | –0.23  | 2.39   | +0.08 | B     |
| 198667 | 5 Aqr     | B9III     | 11125   | 3.42  | +0.01  | 26        | 0.24   | 1.00   | –0.10  |       |       | C      |
| 200499 | π Cap     | A5V       | 8081    | 3.55  | –0.17  | 62        | 0.31   | 3.99   | –0.34  | 4.26   | –0.30 | B     |
| 201433 | B9V       | 12193    | 4.24   | +0.00  | 15        | 1.00   | 0.00   |        |       |       |       | C      |
| 202671 | 30 Cap    | B5.5IV    | 13566   | 3.36  | +0.45  | 25        | 1.00   | –0.22  |        |       |       |       | C      |
| 204188 | Apm       | 7622     | 4.21   | +0.02  | 36        | 0.43   | 3.87   | –0.18  | 2.22   | +0.13 | B     |
| 207098 | δ Cap     | A0V2 (IV) | 7312    | 4.66  | –0.21  | 81        | 2.00   | 3.57   | –0.02  | B     |
| 209635 | 32 Aqr    | A0m      | 7708    | 3.87  | +0.24  | 7         | 0.72   | 3.92   | +0.02  | 4.09   | +0.07 | F      |
| 211256 | A0V/AV    | 7448     | 3.96   | –0.21  | 13        | 0.59   | 3.76   | –0.20  | 4.11   | –0.25 | D     |
| 212061 | ζ Aqr    | A0V      | 10384   | 3.95  | –0.08  | 54        | 0.49   | 1.55   | –0.42  | 2.48   | –0.46 | B     |
| 214994 | ζ Peg     | A1V      | 9453    | 3.64  | +0.18  | 6         | 0.73   | 2.71   | –0.18  | 2.57   | –0.69 | A,V   |
| 216627 | δ Aqr    | A3V      | 8587    | 3.59  | –0.25  | 79        | 0.45   | 3.73   | –0.63  | 3.87   | –0.57 | B,V   |
| 218396 | A5V       | 7091     | 4.06   | –0.59  | 41        | 0.11   | 3.27   | –0.49  | 3.54   | –0.44 | B     |
| 219485 | A0V       | 9577     | 3.81   | –0.85  | 27        | 0.38   | 2.55   | –0.33  | 1.82   | –0.15 | D     |
| 223245 | ω Aqr    | A1V      | 7487    | 3.88  | –0.07  | 86        | 0.32   | 3.76   | –0.18  | 3.11   | –0.62 | B     |
| 224003 | ψ Per     | A7V      | 7777    | 3.59  | –0.17  | 56        | 0.27   | 3.95   | –0.25  | 2.58   | +0.02 | B     |
| 224995 | 31 Per    | A0V      | 7779    | 3.64  | –0.13  | 99        | 0.23   | 3.96   | –0.26  |       |       | D     |

(1) HD number. (2) Bayer/Flamsteed name. (3) Spectral type taken from Hipparcos catalogue (ESA 1997). (4) Effective temperature (in K). (5) Logarithm of surface gravity (log g in dex, where g is in unit of cm s⁻²). (6) Fe abundance relative to Procyon. (7) Projected rotational velocity (in km s⁻¹). (8) Non-LTE carbon abundance relative to Procyon determined by Takeda et al. (2012). (9) Standard microturbulent velocity (in km s⁻¹), derived by Equation (1). (10) Non-LTE silicon abundance relative to Procyon corresponding to ξ_{Si/H}. (11) Directly determined microturbulence (in km s⁻¹) as a result of spectrum rotation. (12) Non-LTE silicon abundance relative to Procyon corresponding to ξ_{Si/H} refit. (13) Group of the data source (cf. Table 2). (14) Specific remark [spectroscopic binary (SB, "o" denotes the case where orbital elements are available) or radial velocity variable (V), chemical peculiarity (Am, Hg)].

### Table 2. Basic information of the observational data.

| Group | *Instr* | Obs. Time | Resolution | Number | Star Type | Reference |
|-------|---------|-----------|------------|--------|-----------|-----------|
| A     | HIDES  | 2008 Oct  | 100000     | 7      | A type    | Takeda et al. (2012) |
| B     | BOES   | 2008 Jan/Sept, 2009 Jan | 45000 | 56 | A type    | Takeda et al. (2008, 2009) |
| C     | HIDES   | 2012 May  | 70000     | 8      | late B type | Takeda et al. (2014) |
| D     | HIDES    | 2017 Aug/Nov | 100000 | 29 | A type    | Takeda et al. (2018) |
| E     | HIDES   | 2001 Feb  | 70000     | 1      | Procyon   | Takeda et al. (2005a) |
| F     | HIDES   | 2006 Oct  | 70000     | 19     | late B type | Takeda et al. (2010) |

1 Only for HD 172617 (Vega), Takeda et al.'s (2007) OAO/HIDES spectrum of high-S/N (~ 2000) and high-resolution (~10000) observed in 2006 May was adopted.

2 HIDES and BOES denote "High Dispersion Echelle Spectrograph" at Okayama Astrophysical Observatory and "Bohynsaur Observatory Echelle Spectrograph" at Bohynsaur Optical Astronomy Observatory, respectively.

### 3. Stellar parameters

As in T18, the effective temperature (T_{eff}) and the surface gravity (log g) for each star were determined from colors of Strömgren's uvby/b' photometric system by using Napiwotzki et al.'s (1993) calibration.

Especially important parameter we should care about is the microturbulence (ξ). We basically adopted (as done in T18) the analytical T_{eff}-dependent relation.
derived by Takeda et al. (2008)

\[ \xi = 4.0 \exp\left\{ -\log(T_{\text{eff}}/8000)/A \right\}^2 \]  
(1)

(where \( A \equiv [\log(10000/8000)]/\sqrt{\ln 2} \), \( \xi \) is in km s\(^{-1}\), and \( T_{\text{eff}} \) is in K) for stars with \( T_{\text{eff}} < 11000 \) K, while \( \xi = 1 \) km s\(^{-1}\) was assumed at \( T_{\text{eff}} > 11000 \) K (where this equation yields \( \xi < 1 \) km s\(^{-1}\)). Such formula-based values are called as the “standard” microturbulence (designated as \( \xi_{\text{std}} \)) in order to clarify the difference from another choice of microturbulence described later (cf. Section 6.2).

The only exception is the standard star Procyon (HD 61421),\(^1\) for which we used Takeda et al.’s (2005b) spectroscopically determined values (\( T_{\text{eff}} = 6612 \) K, \( \log g = 4.00 \), and \( \xi_{\text{std}} = 1.97 \) km s\(^{-1}\)) to maintain consistency with Takeda et al. (2008).

The adopted values of \( T_{\text{eff}}, \log g, [\text{Fe/H}], \)\(^2\) and \( \xi_{\text{std}} \) are summarized in Table 1.

All the program stars are plotted on the \( \log L \) vs. \( \log T_{\text{eff}} \) diagram (theoretical HR diagram) in Fig. 1, where theoretical evolutionary tracks corresponding to different stellar masses are also depicted. This figure indicates that the masses of our sample stars are in the range between \( \sim 1.5 \) \( M_\odot \) and \( \sim 5 \) \( M_\odot \). More detailed data regarding the targets and their stellar parameters are given in the electronic table (tableE.dat).

The model atmosphere corresponding to each star was constructed by interpolating Kurucz’s (1993a) ATLAS9 model grid (for \( \xi = 2 \) km s\(^{-1}\)) in terms of \( T_{\text{eff}}, \log g, \) and [Fe/H].

4. Non-LTE calculation for Si

The statistical-equilibrium calculations for silicon atom were carried out by using the non-LTE code described in Takeda (1991). The atomic model of Si adopted in this study was constructed based on Kurucz and Bell’s (1995) compilation of atomic data (\( g_f \) values, levels, etc.), which consists of 34 Si \( \text{i} \) terms (up to \( 4d^1\text{F}^o \) at 58893.4 cm\(^{-1}\)) with 222 Si \( \text{i} \) radiative transitions, 31 Si \( \text{ii} \) terms (up to \( 3p^3\text{S}^o \) at 123033.5 cm\(^{-1}\)) with 109 Si \( \text{ii} \) radiative transitions, and 23 Si \( \text{iii} \) terms (up to \( 4p^3\text{P} \) at 248073 cm\(^{-1}\); included only for conservation of total Si atoms).

\(^1\)The reason why Procyon was chosen as the reference standard (as done in our previous studies) is to carry out abundance determination by “differential analysis” where the resulting relative abundances are unaffected by uncertainties in the \( g_f \) values of spectral lines. That is, Procyon (F5 IV–V) is more suitable than the Sun (whose \( T_{\text{eff}} \) is too low in comparison with those of A and late B stars to be used for such a purpose), while its chemical abundances are practically the same as those of the Sun (cf. the references quoted in Section IV(c) of Takeda et al. 2008).

\(^2\)These Fe abundances were already established in our previous papers (cf. the references given in Table 2) based on the spectrum-fitting method in the wavelength region (\( \sim 20–30\) Å wide) centered around \( \sim 6155\) Å (where the Fe \( \text{ii} \) 6147/6149 doublet lines are the important indicators of Fe abundance).
Regarding evaluations of photoionization rates, the cross-section data taken from TOPbase (Cunto, Mendoza 1992) were used for the lower 10 Si I terms and 10 Si II terms (while hydrogenic approximation was assumed for higher terms). As to the collisional rates, the theoretical results of Aggarwal and Keenan (2014) were invoked for the bound-bound electron impact rates between the lower 10 Si II terms. Otherwise, the recipe described in Sect. 3.1.3 of Takeda (1991) was followed (inelastic collisions due to neutral hydrogen atoms were formally included as described therein, though insignificant in the atmosphere of early-type stars under question).

The calculations were done on a grid of 44 (= 11 \times 4) solar-metallicity ([Fe/H] = 0) model atmospheres resulting from combinations of eleven \(T_{\text{eff}}\) values (6500, 7000, 7500, 8000, 8500, 9000, 9500, 10000, 11000, 12000, 13000, and 14000 K) and four \(\log g\) values (3.0, 3.5, 4.0, and 4.5) while assuming \(\xi = 2 \text{ km s}^{-1}\) and the Si abundance of \(A(\text{Si}) = 7.55\) (solar Si abundance adopted in ATLAS9 models). The depth-dependent non-LTE departure coefficients to be used for each star were then evaluated by interpolating this grid in terms of \(T_{\text{eff}}\) and \(\log g\).

5. Abundance determination

The non-LTE Si abundances were determined (as done in T18 for CNO abundances) based on Takeda’s (1995) numerical algorithm by accomplishing the best fit between the synthetic and observed spectra in the 6340–6380 Å region while varying the abundances of Si and some other elements showing appreciable lines (especially Fe, plus other elements such as Mg, Mn, Zn depending on cases), \(v_M\) (macrobroadening velocity corresponding to instrumental/rotational broadening and macroturbulence) and \(\Delta \lambda\) (radial velocity or wavelength shift) but the microturbulence being fixed at \(\xi_{\text{std}}\). Since the relevant wavelength region of the raw spectra is more or less contaminated by weak telluric lines, they were removed in advance by dividing by the spectrum of a rapid rotator as demonstrated in Fig. 2. The atomic data of spectral lines comprising in this region were exclusively taken from Kurucz and Bell’s (1995) compilation (those of relevant Si II doublet lines are summarized in Table 3), though some pre-adjustments were necessary in order to achieve an satisfactory fit. The accomplished fit in the neighborhood of both lines for each star is displayed in Fig. 3.

Then, the equivalent widths \((W_{6347} \text{ and } W_{6371})\) of the Si II 6347 and 6371 lines were inversely evaluated from the best-fit solution of \(A_{\text{Nld}}^N(\text{Si})\) with the same model and atmospheric parameters as used in the spectrum-fitting analysis. From such evaluated \(W\), the non-LTE abundance \((A^N)\), LTE abundance \((A^L)\) and non-LTE correction \((\Delta \equiv A^N - A^L)\) were derived for each line. Besides, \(W\) can be further used to estimate the abundance uncertainties due to typi-
Figure 2. Examples of how the telluric lines (mostly due to H₂O vapor) are removed in the 6340–6380 Å region comprising Si ii 6347/6371 lines. Dividing the raw stellar spectrum (middle, black) by the spectrum of a rapid rotator (bottom, red) results in the final spectrum (top, blue). The left (a) and right (b) panel show the cases of HD 12111 (weaker telluric contamination) and HD 20149 (stronger contamination), respectively. No Doppler correction is applied to the wavelength scale of these spectra.

6. Discussion and conclusion

6.1. Characteristics of the non-LTE effect

As seen from the results derived in Section 5, the Si ii 6347/6371 lines suffer an appreciable non-LTE effect. According to Fig. 4b, their non-LTE abundance corrections (Δ) are negative (which means that the non-LTE effect strengthens the lines) and typically a few tenths dex (|Δ_{6347}| ∼ 0.2–0.5 dex, |Δ_{6371}| ∼ 0.1–0.4 dex; naturally the former is larger because of the stronger line forming in comparatively shallower layer). The maximum of |Δ| is around T_{eff} ∼ 10000 K.
Si abundances of upper main-sequence stars

Figure 3. Synthetic spectrum fitting analysis for Si abundance determination from Si\textsc{ii} 6347/6371 lines. In the left, middle, and right panels are shown the results for 40 stars in $6500 \text{K} < T_{\text{eff}} < 8000 \text{K}$, 39 stars in $8000 \text{K} < T_{\text{eff}} < 9500 \text{K}$, and 41 stars in $9500 \text{K} < T_{\text{eff}} < 14000 \text{K}$, respectively. The best-fit theoretical spectra (in the selected ranges of 6344–6350 \text{Å} and 6367.5–6375 \text{Å} comprising the relevant Si\textsc{ii} lines) are depicted by blue solid lines, while the observed data are plotted by pink symbols (the masked data excluded in judging the goodness of fit are highlighted in green). In each panel, the spectra are arranged in the descending order of $v_s \sin i$, and an offset of 0.2 is applied to each spectrum (indicated by the HD number) relative to the adjacent one. The case of Procyon (standard star) is separately displayed at the bottom of the left panel.
Figure 4. Silicon abundances and the related quantities plotted against $T_{\text{eff}}$. (a) Equivalent widths of Si ii 6347 ($W_{6347}$, filled symbols) and Si ii 6371 ($W_{6371}$, open symbols). (b) Non-LTE corrections for Si ii 6347 ($\Delta_{6347}$, filled symbols) and Si ii 6371 ($\Delta_{6371}$, open symbols) (c) $A_{\text{std}}^{\text{N}}$(Si) (standard non-LTE Si abundance corresponding to $\xi_{\text{std}}$), where the error bar denotes $\pm \delta T_{\text{g}},$ (root-sum-square of $\delta T$, $\delta g$, and $\delta \xi$, where $\delta T$ is the mean of $|\delta T_+|$ and $|\delta T_-|$; etc.), (d) $\delta T_+$ and $\delta T_-$ (abundance variations for Si ii 6347 in response to $T_{\text{eff}}$ changes of $+3\%$ and $-3\%$), (e) $\delta g_+$ and $\delta g_-$ (abundance variations for Si ii 6347 in response to log $g$ changes by $+0.1$ dex and $-0.1$ dex), and (f) $\delta \xi_+$ and $\delta \xi_-$ (abundance variations for Si ii 6347 in response to perturbing the $\xi_{\text{std}}$ value by $+30\%$ and $-30\%$). The abundance of Procyon ($A_{\text{std}}^{\text{N}} = 7.367$), which is adopted as the reference, is indicated by the horizontal dashed line in panel (c).
Table 3. Adopted atomic data of Si ii 6347 and 6371 lines.

| Multiplet No. | λ (Å) | χ<sub>low</sub> (eV) | log g<sub>f</sub> (dex) | Gammar (dex) | Gammas (dex) | Gammaw (dex) |
|--------------|-------|----------------------|----------------------|--------------|--------------|-------------|
| 2            | 6347.109 | 8.121 | +0.297 | 9.09 | -5.04 | (-7.68) |
| 2            | 6371.371 | 8.121 | -0.003 | 9.08 | -5.04 | (-7.68) |

Note: These data are were taken from Kurucz and Bell’s (1995) compilation, while those parenthesized are the default values calculated by Kurucz’s (1993a) WIDTH9 program. Followed by first four self-explanatory columns, damping parameters are given in the last three columns: Gammar is the radiation damping width (s<sup>-1</sup>), log<sub>γ<sub>rad</sub></sub>. Gammas is the Stark damping width (s<sup>-1</sup>) per electron density (cm<sup>-3</sup>) at 10<sup>4</sup> K, log(γ<sub>e</sub>/N<sub>e</sub>). Gammaw is the van der Waals damping width (s<sup>-1</sup>) per hydrogen density (cm<sup>-3</sup>) at 10<sup>4</sup> K, log(γ<sub>w</sub>/N<sub>H</sub>).

In Fig. 5 are shown the \(l_{0}^{NLTE}/l_{0}^{LTE}(τ)\) (the non-LTE-to-LTE line-center opacity ratio; almost equal to \(b_{1}\)) and \(S_{L}(τ)/B(τ)\) (the ratio of the line source function to the Planck function; nearly equal to \(b_{2}/b_{1}\)) for the transition relevant to the Si ii 6347/6371 lines (\(b_{1}\) and \(b_{2}\) are the non-LTE departure coefficients for the lower and upper terms), which were computed on the models of representative \(T_{\text{eff}}\) and log<sub>g</sub> values. As seen from this figure, while \(l_{0}^{NLTE}/l_{0}^{LTE} > 1\) (overpopulation) holds in the line-forming region at \(T_{\text{eff}} \lesssim 10000\) K (A-type tars), this inequality suddenly turns to be reversed (underpopulation) at higher \(T_{\text{eff}}\) (late B-type stars) because of the beginning of Si ii overionization (once-ionized Si is not the dominant ionization stage any more in such a higher \(T_{\text{eff}}\) regime). Although the non-LTE effect still acts to intensify lines (\(Δ\) remains negative) at 10000 K \(\lesssim T_{\text{eff}} \lesssim 14000\) K due to the dilution of \(S_{L}(< B)\) (see the lower panels in Fig. 5), |\(Δ\)| progressively decreases with an increase in \(T_{\text{eff}}\) (see also the Appendix A where the behavior of \(Δ\) in B-type stars is further discussed).

How the theoretical \(W\) and \(Δ\) computed for these two Si ii lines depend upon the atmospheric parameters (\(T_{\text{eff}}, \log g, \) and \(ξ\)) is illustrated in Fig. 6, which reasonably explains the trends observed in Figs. 4a and 4b (the maximum of \(W\) is seen around \(T_{\text{eff}} \sim 8000\) K because the peak of \(ξ\) is attained there).

6.2. Consistency check of microturbulence

As is evident from the lower three panels (d–f) of Fig. 4, an uncertainty \(ξ\) has the most significant impact on the Si abundance among the three atmospheric parameters especially at \(T_{\text{eff}} \lesssim 10000\) K, since the Si ii 6347/6371 lines are strong and saturated (on the flat part of the curve of growth). Therefore, particular attention should be paid to whether or not an appropriate choice of \(ξ\) has be done. As a matter of fact, Takeda et al. (2009) reported that considerably underestimated Na abundance would result from the strongly saturated Na i
Figure 5. The non-LTE-to-LTE line-center opacity ratio (upper panels a–c) and the ratio of the line source function ($S_L$) to the local Planck function ($B$) (lower panels d–f) for the Si $\text{ii}$ $4s^2 S - 4p^2 P^o$ transition (corresponding to Si $\text{ii}$ 6347/6371 lines) of multiplet 2, plotted against the continuum optical depth at 5000 ˚A. Computations were done with $\xi = 2 \text{ km s}^{-1}$ on the solar-metallicity models ([Fe/H] = [Si/Fe] = 0) of $T_{\text{eff}}$ = 7000 K (left panels a, d), 10000 K (middle panels b, e), and 13000 K (right panels c, f). At each panel are shown the results for three log $g$ values of 3.5, 4.0, and 4.5 depicted by different colors (red, blue, and green, respectively).

5889/5895 D lines if the microturbulence given by Equation (1) is used, which may be attributed to the depth-dependence of $\xi$ (cf. Section 5 therein) Does such an inadequacy similarly exist also for the case of Si $\text{ii}$ 6347/6371 lines?

In order to examine this problem, another solution of microturbulence was determined from these doublet lines themselves by taking the advantage that their log $g_f$ strengths are different by 0.3 dex. That is, spectrum fitting analysis was retried (taking $A_{\text{Si}}^N$ and $\xi_{\text{std}}$ as the starting solutions) while allowing both $A_{\text{Si}}^N$ and $\xi$ to vary. These refit solutions (which are referred to as $A_{\text{Si}}^N$ and $\xi_{\text{refit}}$) were successfully converged for 97 stars (about ∼ 80%), though failed for the remaining 23 stars.

The resulting $A_{\text{Si}}^N$ and $\xi_{\text{refit}}$ (given in Table 1) are compared with $A_{\text{Si}}^N$ and $\xi_{\text{std}}$ in Fig. 7, where the following characteristics are observed.

— Fig. 7a indicates that consistency between $\xi_{\text{refit}}$ (dots) and $\xi_{\text{std}}$ (solid line) is
Figure 6. The non-LTE and LTE equivalent widths ($W^N$ and $W^L$) for the Si II 6347/6371 lines and the corresponding non-LTE corrections ($\Delta$), which were computed on the non-LTE grid of models described in Section 4, are plotted against $T_{\text{eff}}$. Each figure set consists of two panels; the upper panel is for $W^N$ (solid lines) and $W^L$ (dashed lines), while the lower panel is for $\Delta$. The upper sets (a+b, e+f) show the case of fixed $\xi$ (2 km s$^{-1}$) but different log $g$ (3.0, 3.5, 4.0, and 4.5), while the lower sets (c+d, g+h) are for the case of fixed log $g$ (4.0) but different $\xi$ (1, 2, 3, and 4 km s$^{-1}$). The left-hand figures show the results for the Si II 6347 line, while the right-hand ones for the Si II 6371 line.
not necessarily bad, though considerable discrepancy (quite a few \( \xi_{\text{refit}} \) values tending to be appreciably lower than \( \xi_{\text{std}} \)) is seen around \( T_{\text{eff}} \sim 8000 \) K.\(^4\)

— As a result, \( A_{\text{std}}^N \) tends to be lower than \( A_{\text{refit}}^N \) at \( T_{\text{eff}} \sim 8000 \) K. The differences are typically a few tenths dex (four stars show especially large discrepancies of \( \sim 0.5-0.6 \) dex (cf. Fig. 7c).

— It is worth noting that the \([\text{Si/H}]_{\text{std}}^N\) values also exhibit similar discrepancies when compared with Takeda et al.’s (2009) \([\text{Si/H}]\) results derived from the spectrum fitting in the 6140–6170 Å region comprising Si I lines (Fig. 7d).

— Accordingly, we may state that the abundances derived from Si I 6347/6371 lines by using Equation (1)-based \( \xi_{\text{std}} \) are apt to be underestimated around \( T_{\text{eff}} \sim 8000 \) K corresponding to late-to-mid A-type stars.

— However, this problem is not so serious as the case of Na I 5889/5895 lines addressed by Takeda et al. (2009). Actually, the appearance of \( A_{\text{refit}}^N \) vs. \( T_{\text{eff}} \) plot (Fig. 7b) is not significantly different from the case of \( A_{\text{std}}^N \) (Fig. 4c). In the figures illustrating the behaviors of Si abundances to be discussed in the next section, both (“std” and “refit”) results will be shown, so that they may be compared with each other.

6.3. Observed trend of Si abundances

The relative abundances of Si ([Si/H]) and the C-to-Si ratios ([C/Si] = [C/H]−[Si/H]) for the 120 stars are plotted against the stellar parameters (and the corresponding [C/H] or [Si/H]) in Fig. 8, where two kinds of results based on \( A_{\text{std}}^N \) and \( A_{\text{refit}}^N \) are presented in parallel in each panel. Besides, the same correlation plots as Fig. 8 but only for the selected 16 Hyades stars are depicted in Fig. 9. The following characteristics can be read from these figures.

• The resulting Si abundances (relative to Procyon) for most stars are in the range of \(-0.5 < [\text{Si/H}] < +0.3\) (tending to be rather Si-deficient than Si-rich).

• As for the relation to stellar parameters, any clear dependence upon \( T_{\text{eff}} \) or \( v_c \sin i \) is not observed in [Si/H] (Figs. 9a and 9b).

• Am stars and HgMn stars appear to show somewhat higher [Si/H] than normal stars, while λ Boo stars are naturally Si-deficient. The mean \([\text{Si/H}]_{\text{std}}\) values for each star group are −0.23 (normal), −0.03 (Am), −0.18 (HgMn),\(^5\) and −1.08 (λ Boo).

• A positive correlation exists between [Si/H] and [Fe/H] (Fig. 8c), which is also observed for the selected sample of Hyades stars (Fig. 9c). Actually, the

\(^4\)Besides, two \( \xi_{\text{refit}} \) values around \( T_{\text{eff}} \sim 13000 \) K are apparently two large; but they are not reliable and should not be seriously taken, because determination becomes more difficult for the case of weaker Si II lines at higher \( T_{\text{eff}} \).

\(^5\)HD 106625 (γ Crv) was excluded in the averaging process because of its exceptionally low \([\text{Si/H}]_{\text{std}}\) of −1.49 for this HgMn group.
Figure 7. (a) Microturbulence directly determined by spectrum refitting ($\xi_{\text{refit}}$) plotted against $T_{\text{eff}}$ by dots, while the $T_{\text{eff}}$-dependent standard microturbulence ($\xi_{\text{std}}$) given by Equation (1) is shown by the red solid line. (b) Non-LTE Si abundance ($A_{\text{N refit}}^\text{Si}$) resulting from refitting (corresponding to $\xi_{\text{refit}}$) plotted against $T_{\text{eff}}$. (c) Difference between “std” and “refit” abundances ($A_{\text{N std}}^\text{Si} - A_{\text{N refit}}^\text{Si}$) plotted against $T_{\text{eff}}$. (d) Difference between [Si/H]$_{\text{std}}$ (derived in this study based on Si ii 6347/6371 lines by using the standard $\xi_{\text{std}}$) and [Si/H]$_{\text{Si I}}$ (derived by Takeda et al. 2009) based on the spectrum fitting applied to the region comprising Si i lines) plotted against $T_{\text{eff}}$.

- Correlation coefficients calculated between [Si/H]$_{\text{std}}$ and [Fe/H] are +0.65 (all sample) and +0.82 (Hyades sample).

- The C-to-Si ratio ([C/Si]) tends to decrease systematically with an increase in [Si/H] (Fig. 8h) indicating that C and Si are anti-correlated, though the nature of anti-correlation between [Si/H] and [C/H] is not very clear (Fig. 8d).

How can we interpret these results? As mentioned in Section 1, two physical processes may be considered for the possible cause of chemical abundance anomalies: (i) atomic diffusion and (ii) gas–dust separation. Regarding the former diffusion process, although considerable uncertainties still exist, available
Figure 8. Graphical display of how [Si/H] and [C/Si] for the 120 program stars are related to stellar parameters (or abundances). Left panels: [Si/H] (Si abundance relative to Procyon) plotted against (a) $T_{\text{eff}}$, (b) $v_{\text{e} \sin i}$, (c) [Fe/H], and (d) [C/H]. Right panels: [C/Si] (logarithmic C-to-Si abundance ratio) plotted against (e) $T_{\text{eff}}$, (f) $v_{\text{e} \sin i}$, (g) [Fe/H], and (h) [Si/H]. Each panel consists of two similar diagrams constructed from different Si abundances $A_N^{\text{std}}$ (left) and $A_N^{\text{refit}}$ (right) corresponding to $\xi_{\text{std}}$ and $\xi_{\text{refit}}$, respectively. Stars of different $v_{\text{e} \sin i}$ classes are discriminated by the types of symbols: circles ($0 < v_{\text{e} \sin i} < 30$ km s$^{-1}$), triangles ($30 \leq v_{\text{e} \sin i} < 70$ km s$^{-1}$), and squares ($70 \leq v_{\text{e} \sin i} < 100$ km s$^{-1}$). Normal stars are shown by open symbols, while those classified as chemically peculiar are highlighted by filled symbols (red-filled symbols for Am stars, blue-filled ones for HgMn stars, and purple-filled ones for $\lambda$ Boo stars).
Si abundances of upper main-sequence stars

theoretical calculations predict a deficiency of C, a slight underabundance of Si, and an overabundance of Fe (cf. Richer et al. 2000; Talon et al. 2006). As to the latter gas–dust separation process, Si as well as Fe (both are refractory elements and should behave similarly) are expected to be anti-correlated with C (volatile species).

Although \([C/Si]\) apparently decreases with an increase in \([Si/H]\), this trend can not be simply explained by the gas–dust separation alone, because the (negative) gradient of \(d[C/Si]/d[Si/H]\) in Fig. 8h is too steep to be identified with Holweger and Stürenburg’s (1993) Fig. 2 (the slope is \(\sim -45^\circ\)). Actually, the considerably wide range of \([C/Si]\) (\(\sim 2\) dex) is mainly due to the diversified deficiency of C (\(-1.5 \lesssim [C/H] \lesssim 0\) especially seen in Am stars of lower \(T_{\text{eff}}\); cf. Fig. 8d) while the contribution of \([Si/H]\) is comparatively minor. Therefore, the main cause of C deficiency is attributed to (not the dust–gas separation but) to atomic diffusion as discussed in T18.

Regarding the cause for the dispersion of \([Si/H]\), the fact that \([Si/H]\) and \([Fe/H]\) correlate well with each other (Fig. 8c, Fig. 9c; just like Holweger and Stürenburg’s Fig. 3) may indicate that the gas–dust separation process (acting both Si and Fe in a same direction) is involved at least partly, because atomic diffusion would differently affect Si and Fe according to the currently available calculations. However, it is unlikely that the diffusion process does not play any role in affecting the surface abundances of Si and Fe, since Takeda and Sadakane (1997) reported the \(v_{\text{sin}i}\)-dependence of over-/under-abundance of Fe/O in Hyades A-type stars (cf. Fig. 7 therein) which is reasonably interpreted as the result of atomic diffusion being more effective for slower rotators.

Consequently, given the available information alone, it is hardly possible to find any satisfactory interpretation regarding the observed behavior of Si abundances (particularly in relation to the abundances of C and Fe). It may be possible that both processes (atomic diffusion and gas–dust separation) concurrently operate in an intricate manner (the former being more significant?). Unfortunately, the current diffusion calculations appear to still suffer considerable uncertainties (e.g., in the choice of parameters concerning turbulent mixing or mass loss). Further progress in this field is desirably awaited, so that it may shed light to this complicated situation.

Acknowledgements.

This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France.

6In this context, Takeda et al. (2012) pointed out that \([Na/H]\) well correlate with \([Fe/H]\) in A-type stars, which contradicts the prediction from the diffusion theory (Na is expected to be almost normal or slightly underabundant unlike Fe). That situation is quite similar to the present case of \([Si/H]\).
References

Aggarwal K. M., Keenan F. P., 2014, MNRAS, 442, 388
Arenou F., Grenon M., Gómez A., 1992, A&A, 258, 104
Cunto W., Mendoza C., 1992, Rev. Mex. Astron. Astrofis., 23, 107
ESA, 1997, The Hipparcos and Tycho Catalogues, ESA SP-1200, available from NASA-ADC or CDS in a machine-readable form (file name: hip_main.dat)
Flower P. J., 1996, ApJ, 469, 355
Ghazaryan S., Alecian G., 2016, MNRAS, 460, 1912
Hoffleit D., Jaschek C., 1991, The Bright Star Catalogue, 5th revised ed. (New Haven, Conn.: Yale University Observatory)
Holweger H., Stürenburg S., 1993, in Peculiar Versus Normal Phenomena in A-Type and Related Stars, ASP Conf. Ser. 44, eds. M. M. Dworetsky, F. Castelli, and R. Faraggiana (Astronomical Society of the Pacific: San Francisco), p. 356
Kurucz R. L., 1993a, Kurucz CD-ROM, No. 13 (Harvard-Smithsonian Center for Astrophysics)
Kurucz R. L., 1993b, Kurucz CD-ROM, No. 14 (Harvard-Smithsonian Center for Astrophysics)
Kurucz R. L., Bell B., 1995, Kurucz CD-ROM, No. 23 (Harvard-Smithsonian Center for Astrophysics)
Lejeune T., Schaerer D., 2001, A&A, 366, 538
Mashonkina L., 2020a, MNRAS, 493, 6095
Mashonkina L., Ryabchikova T., Alecian G., Sitnova T., Zatsarinny, O., 2020b, MNRAS, 499, 3706
Michaud G., Alecian G., Richer J., 2015, Atomic Diffusion in Stars (Switzerland: Springer International Publishing)
Napiwotzki R., Schönberner D., Wenske, V., 1993, A&A, 268, 653
Niemezcza ein, Murphy S. J., Smalley B., Uytterhoeven K., Pigulski A., Lehmann H., Bowman D. M., Catanzaro G., van Aarle E., et al., 2015, MNRAS, 450, 2764
Preston G. W., 1974, ARA&A, 12, 257
Richer J., Michaud G., Turcotte S., 2000, ApJ, 529, 338
Saffe C., Miquelarena P., Alacoria J., Flores M., Jaque Arancibia M., Calvo D., Martín Girardi G., Grossi M., Collado A., 2021, A&A, 647, A49
Takeda Y., 1991, A&A, 242, 455
Takeda Y., 1995, PASJ, 47, 287
Takeda Y., Han I., Kang D.-I., Lee B.-C., Kim K.-M., 2008, JKAS, 41, 83
Takeda Y., Kambe E., Sadakane K., Masuda S., 2010, PASJ, 62, 1239
Takeda Y., Kang D.-I., Han I., Lee B.-C., Kim K.-M., 2009, PASJ, 61, 1165
Si abundances of upper main-sequence stars

Takeda Y., Kang D.-I., Han I., Lee B.-C., Kim K.-M., Kawanomoto S., Ohishi N., 2012, PASJ, 64, 38
Takeda Y., Kawanomoto S., Ohishi N., 2007, PASJ, 59, 245
Takeda Y., Kawanomoto S., Ohishi N., 2014, PASJ, 66, 23
Takeda Y., Kawanomoto S., Ohishi N., Kang D.-I., Lee B.-C., Kim K.-M., Han I., 2018, PASJ, 70, 91 (T18)
Takeda Y., Ohkubo M., Sato B., Kambe E., Sadakane K., 2005b, PASJ, 57, 27
Takeda Y., Sadakane K., 1997, PASJ, 49, 367
Takeda Y., Sato B., Kambe E., Masuda S., Izumiura H., Watanabe E., Ohkubo M., et al., 2005a, PASJ, 57, 13
Talon S., Richard O., Michaud G., 2006, ApJ, 645, 634
van Leeuwen F., 2007, Hipparcos, the New Reduction of the Raw Data, Astrophysics and Space Science Library, Vol. 350 (Berlin: Springer)
Figure 9. Graphical display of how [Si/H] and [C/Si] for the 16 Hyades cluster stars are related to stellar parameters (or abundances). Otherwise, the same as in Fig. 8.
Appendix. Non-LTE effects on Si II 6347/6371 lines in B-type stars

Recently, Mashonkina (2020a) carried out an extensive study on the non-LTE line formation for silicon (Si i, Si ii, and Si iii) in main-sequence stars of A- and B-type covering the $T_{\text{eff}}$ range between 7000 and 20000 K. Mashonkina’s calculation includes the Si ii 6347/6371 lines and the non-LTE corrections for these lines derived by her for late A through late B stars ($T_{\text{eff}} \sim 7000$–13000 K; negative $\Delta$ with extents of several tenths dex) are more or less consistent with the results of this investigation.

However, her calculation failed to explain the formation of these Si ii doublet lines in the early B-type star $\iota$ Her ($T_{\text{eff}} = 17500$ K), because of the positive non-LTE corrections resulting in unacceptably large non-LTE Si abundances ($\Delta_{6347} = +0.60$, $\Delta_{6371} = +0.67$, $A_{6347}^N = 8.38$, $A_{6371}^N = 8.27$; cf. Table 4 in her paper).

Although such an early B-type star is outside of the scope of this study, it is interesting to examine whether similar inconsistency emerges in our calculations at the higher $T_{\text{eff}}$ regime ($> 15000$ K). For this purpose, additional non-LTE calculations were performed for the log $g = 4$ models with extended $T_{\text{eff}}$ up to 20000 K. The resulting runs of $l_{\text{NLTE}}/l_{\text{LTE}}$ and $S_{L}/B$ with depth for the Si i 6347/6371 lines (from $T_{\text{eff}} = 8000$ K through 20000 K) are depicted in Figs. 10a and 10b; and Figs. 10c and 10d display how $W_{6371}$ and $\Delta_{6371}$ (for the weaker line of the doublet) vary with $T_{\text{eff}}$.

Our calculations suggest that the extent of the (negative) non-LTE abundance correction ($|\Delta|$) progressively decreases with an increase of $T_{\text{eff}}$ in the regime of B-type stars ($T_{\text{eff}} \gtrsim 10000$ K), until it eventually reaches $\Delta \sim 0$ at the critical $T_{\text{eff}}$ of $\sim 19000$ K; thereafter $\Delta$ turns into positive (cf. Fig. 10d). In other words, the line is strengthened by the non-LTE effect ($W_{\text{NLTE}} > W_{\text{LTE}}$) at $T_{\text{eff}} < \sim 19000$ K while weakened ($W_{\text{NLTE}} < W_{\text{LTE}}$) at $T_{\text{eff}} \sim 19000$ K, as can be confirmed in Fig. 10c.

As mentioned in Section 6.1, the behavior of $\Delta$ is mainly controlled by the line source function; that is, as long as the inequality $\langle S_{L} \rangle < \langle B \rangle$ (Si dilution) holds in the line-forming region, $\Delta$ remains negative. However, according to Fig. 10b, as $T_{\text{eff}}$ is ever increased, $\langle S_{L} \rangle$ becomes comparable with or even outweighs $\langle B \rangle$, which explains why $\Delta$ approaches zero or even turns into positive at higher $T_{\text{eff}}$ ($\sim 20000$ K).

Fig. 10d suggests that the non-LTE correction for $\iota$ Her ($T_{\text{eff}} = 17500$ K) expected from our calculation is $\Delta_{6371} \sim -0.1$ dex; then, since the LTE abundance is $A_{6371}^L = 7.60$ (cf. Table 4 in Mashonkina 2020a), the non-LTE Si abundance for $\iota$ Her would make $A_{6371}^N \sim 7.5$, which is almost consistent with the solar abundance.

Mashonkina’s (2020a) $\Delta_{6371}$ vs. $T_{\text{eff}}$ relation (taken from Table 9 of her paper) is also overplotted for comparison in Fig. 10d. We can see from this figure that the upturn of Mashonkina’s $\Delta_{6371}$ is considerably steeper and $\Delta_{6371} \sim 0$ is attained already at $T_{\text{eff}} \sim 13000$–14000 K, which is in marked contrast to our calculation (critical $T_{\text{eff}}$ for $\Delta_{6371} \sim 0$ is at $\sim 19000$ K). The reason for this discrepancy is not clear. An inspection of the bottom panel of Mashonkina’s (2020a) Fig. 1 (in comparison with our Fig. 10a) suggests that Si ii levels are largely underpopulated (presumably due to more enhanced Si ii overionization) in her calculation. We suspect that her procedure of evaluating UV photoionizing radiation field may have been rather different, for which we used the opacities included in Kurucz’s (1993a) ATLAS9 program along with Kurucz’s (1993b) line opacity distribution function as described in Section 3.1.2 of Takeda (1991).
Figure 10. Non-LTE calculation results for the Si II 4s 2S–4p 2P^o transition of multiplet 2 (like the case of Figs. 5 and 6), which were derived for log g = 4 models (with ξ = 2 km s^{-1} and [Si/Fe] = [Fe/H] = 0) but T_{eff} extended up to 20000 K (in order to cover early B stars). (a) The non-LTE-to-LTE line-center opacity ratio (vs. τ_{5000}), (b) S_L/B ratio (vs. τ_{5000}), (c) non-LTE and LTE equivalent widths for Si II 6371 (vs. T_{eff}), and (d) non-LTE correction for Si II 6371 (vs. T_{eff}). In panels (a) and (b), T_{eff}/1000 is marked in each curve. In panel (d), the T_{eff}-dependence of Δ_{6371} calculated by Mashonkina (2020a) is also shown for comparison.
Erratum: Photospheric silicon abundances of upper main-sequence stars derived from Si\(\text{II}\) 6347/6371 doublet lines

(2024 July 8 by Yoichi Takeda)

In the article [CAOSP, 52, 5–31 (2022)], Si abundances of 120 late A- through late B-type stars were determined by conducting a non-LTE analysis on Si\(\text{II}\) doublet lines at 6347 and 6371 Å. It has recently revealed, however, that the non-LTE corrections (Δ) and abundances (\(A^\text{N}\)) derived therein were not correct because of an inadvertently erroneous treatment in the non-LTE calculation program. Specifically, the overionization effect of Si\(\text{II}\) atoms (acting to weaken Si\(\text{II}\) lines or shifting Δ towards the positive direction) was underestimated by this mistake. As a consequence, Δ and \(A^\text{N}\) obtained in that paper were more or less undervalued, and this error becomes progressively more significant with an increase in \(T^\text{eff}\) (as the dominant ionization stage of Si atoms changes from Si\(\text{II}\) to Si\(\text{III}\)).

Therefore, the equivalent widths of Si\(\text{II}\) 6347/6371 lines for each star were reanalyzed based on the corrected non-LTE calculations. The resulting new values of Δ and \(A^\text{N}\) are shown in Figs. 11a and 11b, which should be compared with Figs. 4b and 4c of the original article. As seen from these figures, while Δ(old) values range between \(~−0.4\) to \(~0.0\), Δ(new)s are somewhat raised upward by \(~0.2\) dex on the average (i.e., ranging between \(~−0.2\) and \(~+0.2\)). Since the gradual \(T^\text{eff}\)-dependent effect is not so significant in the relevant range of \(7000 \lesssim T^\text{eff} \lesssim 13000\) K, the impact of applying new Δ is almost the overall raise of \(A^\text{N}\) (or [Si/H]) by \(~0.2\) dex, which is not so important as compared to the star-to-star dispersion of the abundances (\(~1\) dex).

Accordingly, the main conclusion of the article (regarding the Si abundances of late A- to late B-stars) is not essentially affected by the revised non-LTE calculations.

In the meanwhile, the inadequate non-LTE calculations had a crucial influence upon the consequence of the Appendix of the paper, where the non-LTE effect on the formation of Si\(\text{II}\) lines in B-type stars in general (covering \(T^\text{eff}\) up to \(~20000\) K) was passingly examined in comparison with Mashonkina’s (2020, MNRAS, 493, 6095) study, because the differences (increasing with \(T^\text{eff}\)) become considerably large at such a high-\(T^\text{eff}\) regime. This situation is illustrated in Fig. 12, which is the revised version of the original Fig. 12. As shown in Fig. 12a, the degree of overionization (\(I^\text{LTE}/I^\text{LTE} < 1\)) is considerable and progressively enhanced with \(T^\text{eff}\) at \(T^\text{eff} \gtrsim 10000\) K, while such a tendency was absent in the old Fig 10a. As a result, the behavior of new Δ\(6371\) (non-LTE correction for Si\(\text{II}\) 6371; red solid line in Fig. 12c) is markedly different as compared to the previous result (black dotted line in Fig. 12c); that is, it is larger by \(~0.2–0.5\) dex and turns into positive already around \(T^\text{eff} \sim 13000\) K.

It was once stated in the Appendix that a reasonable non-LTE Si abundance could be obtained for the B3 IV star \(\epsilon\) Her (\(T^\text{eff} \simeq 17500\) K) due to an application of Δ\(6371 \sim −0.1\) dex, in contrast to Mashonkina’s appreciably positive Δ\(6371 \sim +0.67\) yielding an unacceptably large non-LTE Si abundance. However, this conclusion was wrong, because such a slightly negative Δ\(6371\) was fortuitously derived by incorrect non-LTE calculations. The problem of an unreasonably high non-LTE Si abundance for \(\epsilon\) Her from Si\(\text{II}\) 6347/6371 lines still remains unsettled also in the author’s non-LTE calculations. This means that much more investigation is further required towards correctly understanding the mechanism of Si\(\text{II}\) line formation in B-type stars.
Figure 11. (a) Non-LTE corrections for Si ii 6347 ($\Delta_{6347}$, filled symbols) and Si ii 6371 ($\Delta_{6371}$, open symbols), plotted against $T_{\text{eff}}$. (b) $A_N$(Si) (non-LTE Si abundance derived by averaging those of Si ii 6347/6371 lines), plotted against $T_{\text{eff}}$. Note that panels (a) and (b) are the revised Fig. 4b and Fig. 4c in the original article.

Figure 12. Behaviors of the non-LTE effect on Si ii lines in B-type stars. This figure is the revised version of Fig. 10 in the original paper. See the caption therein for more details. (a) The non-LTE-to-LTE line-center opacity ratio (vs. $\tau_{5000}$), (b) $S_L/B$ ratio (vs. $\tau_{5000}$), (c) non-LTE and LTE equivalent widths for Si ii 6371 (vs. $T_{\text{eff}}$), and (d) non-LTE correction for Si ii 6371 (vs. $T_{\text{eff}}$). In panels (c) and (d), the old (wrong) results are also shown by black dotted lines for comparison.