High-Dispersion Spectroscopic Study of Solar Twins: HIP 56948, HIP 79672, and HIP 100963*

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Abstract

An intensive spectroscopic study was performed for three representative solar twins (HIP 56948, HIP 79672, and HIP 100963) as well as for the Sun (Moon; reference standard), with intentions of (1) quantitatively discussing the relative-to-Sun similarities based on the precisely established differential parameters and (2) investigating the reason that causes the Li abundance differences, despite their similarities. It was concluded that HIP 56948 most resembles the Sun in every respect, including the Li abundance (though not perfectly similar) among the three, and deserves the name of “closest-ever solar twin”, while HIP 79672 and HIP 100963 have a somewhat higher effective temperature and appreciably higher surface Li composition. While there is an indication of Li being rotation-dependent, because the projected rotation in HIP 56948 (and the Sun) is slightly lower than the other two, the rotational difference alone does not seem to be so large as to efficiently produce a marked change in Li. Rather, this may be more likely to be attributed (at least partly) to a slight difference in $T_{\text{eff}}$ via some $T_{\text{eff}}$-sensitive Li-controlling mechanism. Since the abundance of Be was found to be essentially solar for all stars irrespective of Li, any physical process causing the Li diversity should work only on Li without affecting Be.

Key words: stars: abundances — stars: atmospheres — stars: individual (HIP 56948, HIP 79672, HIP 100963) — stars: rotation — stars: solar analog

1. Introduction

Can we find such a star that indiscernibly resembles our Sun in every respect? This “solar twin” survey, an ever-attracting subject for stellar astronomers, has made significant progress since the 1990s, thanks to an improvement in the precision of stellar parameter determinations.

Since Porto de Mello and da Silva (1997) reported on the remarkable similarity of HIP 79672 (= 18 Sco = HR 6060 = HD 146233; $V = 5.50$) to the Sun, this star has maintained the status of best solar twin candidate for almost a decade (see also Soubiran & Triaud 2004). In the meantime, by using a numerical technique developed by Takeda (2005; hereinafter referred to as Paper I) for establishing the parameter differences between two similar stars with high precision, Takeda et al. (2007; hereinafter Paper II) conducted a comprehensive study of solar analog stars, and found that HIP 100963 (= HD 195934; $V = 7.09$) is an equally good (or even better) solar twin as HIP 79672.

Yet, there is one concern. While these HIP 79672 and HIP 100963 are certainly very similar to the Sun in terms of the stellar parameters and the general appearance of the spectra, one marked dissimilarity exists in a particular part of the spectrum: the strength of the Li line at 6707.8 Å in these two stars is appreciably stronger compared to the solar case (cf. figure 3 in Soubiran & Triaud 2004 and figure A.2 in Paper II). This decisive difference in the surface Li abundance is actually “a fly in the ointment”, which makes us somewhat hesitate to regard them as being “real” solar twins.

Interestingly, however, Meléndez and Ramírez (2007) recently reported that HIP 56948 (= HD 101364; $V = 8.70$) appears to be an ideal solar twin in the sense that it has essentially solar parameters and a low Li abundance, similarly to the Sun. If this is confirmed, this star may deserve being called as a genuine solar twin. It would thus be worth carrying out an independent check analysis in order to ascertain whether HIP 56948 really resembles our Sun on every point, including the Li abundance.

Another related subject of interest is the cause of such a difference in the Li abundance among these superficially very similar solar twins. It was concluded in Paper II, based on an analysis of 118 solar-analog dwarfs around early-G type, that the surface Li abundance is closely correlated with the macroscopic line-broadening parameter (comprising macroturbulence plus rotation); i.e., the surface Li tends to be higher (i.e., less depleted) as the line-width becomes broader (cf. figure 13 therein). Since the macroturbulence (due to the granular motion of stellar convection origin) is unlikely

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* Based on data collected at Subaru Telescope, which is operated by the National Astronomical Observatory of Japan. The electronic tables E1 and E2 are available at [http://pasj.asj.or.jp/v61/i3/610309/](http://pasj.asj.or.jp/v61/i3/610309/).

1 We use the term “solar twin” for those special solar-type stars which have particularly high similarity to the Sun with respect to spectra as well as stellar parameters. See Appendix A of Takeda et al. (2007) and the references therein for the literature concerning this theme.
to differ much among similar solar-type stars, this observational fact suggests that the most decisive factor controlling the surface Li abundance is stellar rotation, or the angular momentum (i.e., faster rotation tends to suppress the envelope mixing and leads to less depletion of Li). Then, is the distinction between the Li-strong (HIP 79672 and HIP 100963) and Li-weak (HIP 56948 and naturally the Sun itself) solar twins simply caused by the difference in the rotational velocity? This point should be checked by careful determinations of the projected rotational velocities of these stars.

Besides, we should also pay attention to two other related viewpoints in connection with this “rotation–mixing–surface Li” relationship. The first is the stellar activity, which tends to diminish/enhance as the rotation becomes slower/faster. If the rotation is the key factor affecting the surface Li, do the Li-strong solar twins show higher activity than Li-weak ones? The second is the surface abundance of Be, which is destroyed when conveyed into the hot stellar interior by envelope mixing, similarly to Li at a temperature of \( T \gtrsim 3.5 \times 10^6 \) K (higher than the case of Li, which is burned at \( T \gtrsim 2.5 \times 10^6 \) K). It is interesting to see whether any difference is observed in the surface abundance of Be between the Li-strong and Li-weak groups, which may provide us with an observational constraint on the origin of Li discrepancies among these solar twins.

Motivated by these considerations, we decided to conduct an intensive spectroscopic study for these representative solar twins (HIP 56948, HIP 79672, and HIP 100963 along with the Sun/Moon as the comparison standard) based on high-dispersion spectra obtained by the Subaru Telescope with HDS, in order to (1) quantitatively discuss the reason/mechanism causing the difference between the Li-strong and Li-weak groups by examining the rotational velocity, the degree of stellar activity, and the Li as well as Be abundance. This is the purpose of this study.

2. Observational Data

Observations of HIP 56948, HIP 79672, HIP 100963 and the Moon (substitute for the Sun) were carried out on the night of 2008 June 15 (Hawaii Standard Time) by using the High Dispersion Spectrograph (HDS: Noguchi et al. 2002) placed at the Nasmyth platform of the 8.2-m Subaru Telescope, which can record high-dispersion spectra covering a wavelength portion of \( \sim 1600 \) Å (blue cross disperser) or \( \sim 2600 \) Å (red cross disperser) with two CCDs of 2 K \( \times 4 \) K pixels at a time.

In order to cover the wide wavelength range from near-UV (\( \sim 3000 \) Å) to red (\( \sim 7000 \) Å), each star was observed at two different wavelength settings (standard Ub with blue cross disperser for \( \sim 3000–4500 \) Å and standard Yc with red cross disperser for \( \sim 4400–7000 \) Å). With the slit width set at 0.4 (200 \( \mu m \)) and no on-chip binning of pixels, the resolving power of the obtained spectra is \( R \approx 90000 \).

The integrated exposure times for each star at the Ub/Yc settings are 64 min/32 min, 18 min/7 min, 32 min/16 min, and 2 min/0.5 min for HIP 56948, HIP 79672, HIP 100963 and the Moon, respectively.

3. Parameter Determination

3.1. Standard Stellar Parameters

Following the procedure described in sub-subsection 3.1.1 of Paper II, we measured the equivalent widths (EW) of selected spectral lines. The reduction of the spectra (bias subtraction, flat-fielding, scattered-light subtraction, spectrum extraction, wavelength calibration, continuum normalization) was performed by using the “echelle” package of the software IRAF\(^2\) in a standard manner. The estimated S/N ratios at each of the wavelengths calculated as the square root of the resulting photoelectron counts (ADN \( \times \) gain) are graphically depicted in figure 1. We can see from this figure that sufficiently high S/N ratios of \( \sim 500–1000 \) were achieved in the most sensitive red region, though this value is considerably reduced, even by a factor of \( \sim 10 \) at \( \sim 3100 \) Å of near-UV where the Be II lines are located.

![Fig. 1. Distribution of S/N ratios (estimated as the square root of photoelectron counts) of the spectra used for this study, which are divided into four wavelength regions: \( \sim 3000–3700 \) Å (blue CCD) and \( \sim 3700–4600 \) Å (red CCD) in the Ub setting; \( \sim 4400–5700 \) Å (blue CCD) and \( \sim 5700–7000 \) Å (red CCD) in the Yc setting. The absence of data at \( \sim 3700 \) Å and \( \sim 5700 \) Å corresponds to the joint of mosaicked CCDs. Spurious spikes seen at several wavelengths are due to bad columns of CCDs. (a) HIP 56948, (b) HIP 79672, (c) HIP 100963, and (d) Moon.](https://academic.oup.com/pasj/article-abstract/61/3/471/2898217)
the Fe I and Fe II lines on the “Yc setting” spectra covering ~ 4400–7000 Å. Based on these EW values, the four standard atmospheric parameters \( T_{\text{eff}} \) \( \log g \), \( v_t \) \( \xi \) and \( \text{Fe/He} \) \( \log L \) \( M \) \( \log a e \) \( (v_t) \) \( EW_{\text{OAO}} \) \( \Lambda_{\text{NLTE}}^{\text{Fe/H}} \). (a) HIP 79672 (Paper II), (b) HIP 100963 (Paper II), (c) Moon (Paper II), and (d) Moon (Paper I).

**3.2. Rotational Velocity**

In order to evaluate the stellar projected rotational velocity \( v_{\text{rot}} \), we determined the total macrobroadening parameter, which is the \( e \)-folding width of the Gaussian macrobroadening function, \( f_M(v) \propto \exp\left[-(v/v_M)^2\right] \), by way of the line-profile fitting as done in subsection 4.2 of Paper II. Unlike the previous case (where the fitting was applied to the spectrum portion at the 6080–6089 Å region), however, we performed the fitting analysis to each of the “individual” Fe I and Fe II lines (the same lines as used for the EW measurements in subsection 3.1) as Takeda (1995) did for the solar flux spectrum, because the macroturbulence (to be subtracted from the total macrobroadening) is considered to be different from line to line because of its depth-dependence (cf. Takeda 1995).

We used the line-broadening model adopted by Takeda et al. (2008). That is, the total macrobroadening function, \( f_M(v) \), is assumed to be the convolution of three Gaussian component functions \( f_\alpha \propto \exp\left[-(v/v_\alpha)^2\right] \), where \( \alpha \) is any of “ip”
Fig. 3. Line-broadening parameters (derived by the profile-fitting method applied to blend-free Fe lines) plotted against the mean-depth of line formation \((\log \tau_{5000})\), where green open circles, blue filled circles, and red dots represent \(v_{r+m}\) (rotation+macroturbulence), \(v_{int}\) (macroturbulent velocity parameter, supposed to be depth-dependent as \(v_{int} = 1.60 - 0.11 \log \tau_{5000} - 0.19 \log \tau_{5000}^{2}\); cf. subsection 3.2) and \(v_{rt}\) (rotational broadening parameter obtained as \(v_{rt}^2 = v_{int}^2 - v_{ip}^2\)) respectively. The blue horizontal line indicates the average value of \(v_{rt}\) \((\langle v_{rt} \rangle); \text{cf. table 1}\) calculated for the lines of \((\log \tau_{5000}) \leq -0.7\). (a) HIP 56948, (b) HIP 79672, (c) HIP 100963, and (d) Moon.

While the detailed results of \(v_{r+m}\) and \(v_{rt}\) (along with the assigned \((\log \tau_{5000})\)) for each line are presented in electronic table E2, these \(v_{r+m}\), \(v_{int}\), and \(v_{rt}\) are plotted against \(\tau_{5000}\) in figure 3. We can see from this figure that the depth-dependent tendency of \(v_{r+m}\) is almost removed in \(v_{int}\) by subtracting the effect of \(v_{rt}\). Finally, we obtained \((\langle v_{rt} \rangle)\) as the parameter representing \(v_\text{rot} \sin i^5\) by averaging the \(v_{rt}\)’s with \((\log \tau_{5000}) \leq -0.7\) (deep-forming lines with \((\log \tau_{5000}) \geq -0.7\) were not used for the averaging because of the larger uncertainties due to the weakness of the line-strength), as given in table 1.

3.3. Li Abundance

The portion of the observed spectrum (6706.3–6709.3 Å) comprising the Li I resonance doublet at \(\sim 6707.8\) Å, along with Kurucz et al.’s (1984) solar flux spectrum, is shown in figure 4 (left panels). We can recognize from this figure that the strengths of the Li line for HIP 79672 and HIP 100963 are markedly larger than those for HIP 56948 and the Sun/Moon, classifying these four into Li-strong and Li-weak groups. As in Paper II, the Li abundance \((A_{\text{Li}})\) was determined from the Li I doublet lines at \(\sim 6707.8\) Å in the same manner as described in Takeda and Kawanomoto (2005). Namely, we first established the LTE abundance \((A_{\text{Li}}^{\text{LTE}})\) by applying the method of synthetic profile fitting to the spectrum feature of Fe I + Li I lines (see the right panels in figure 4). Then, the EW(Li I 6708) was inversely calculated from such obtained \(A_{\text{Li}}^{\text{LTE}}\). Finally,  

Admittedly, we can not hope to relate the “exact” value of \(v_\text{rot} \sin i\) to \((\langle v_{rt} \rangle)\) within the framework of such a rough modeling of line-broadening functions (all assumed to be the Gaussian form). However, we may reasonably expect that \((\langle v_{rt} \rangle)\) is proportional to \(v_\text{rot} \sin i\) with a factor not much different from unity. This is sufficient for our present purpose, because what we want to know is the “differential” characteristics (i.e., the ratio of \((\langle v_{rt} \rangle)\) between two stars is considered to be the ratio of actual \(v_\text{rot} \sin i\)). At any rate, it is encouraging that the resulting \((\langle v_{rt} \rangle)\) value of 2.13 km s\(^{-1}\) for the Sun/Moon is quite close to the actual solar \(v_\text{rot} \sin i\) value of 1.9 km s\(^{-1}\), by which we may regard that our approximation (suggesting \(v_{rt} \approx 0.94 v_\text{rot} \sin i\)) is not bad.
while taking into account the non-LTE effect, $A_{\text{Li}}^\text{NLTE}$ was calculated from $EW$(Li I 6708). The resulting $A_{\text{Li}}^\text{LTE}$ for each star is presented in table 1. In all four cases studied, the non-LTE correction $\Delta (= A_{\text{Li}}^\text{NLTE} - A_{\text{Li}}^\text{LTE})$ turned out to be $+0.07$. The solar Li abundance of 0.91 derived in this study based on the spectrum of Moon (Subaru/HDS) is in excellent agreement with the result of 0.92 concluded by Takeda and Kawanomoto (2005) based on the spectrum of Moon (OAO/HIDES) as well as the solar flux spectrum (Kurucz et al. 1984).

3.4. Be Abundance

The spectrum portion of 3129.5–3131.5 Å comprising Be II lines at 3130.42 Å and 3131.07 Å is shown in figure 5, where each stellar spectrum is compared with Kurucz et al.’s (1984) solar flux spectrum. A glance at this figure allows us to be convinced that the Be line features are essentially the same as in the solar case for all stars. According to the theoretical simulation shown in the lowest panel of this figure, the agreement of $A_{\text{Be}}$ with the solar value appears to be very good, presumably to within $\sim 0.1$ dex (though the uncertainty may be somewhat larger for HIP 56948 where the spectrum quality is comparatively poor). This fact clearly suggests that Be makes a clear distinction from Li (showing an appreciable difference from star to star) in spite of their rather similar characters being comparatively easily destroyed in the stellar interior, as far as these solar twin stars are concerned. This result is consistent with what Randich et al. (2002) concluded for early-G dwarf stars in open clusters.
### 3.5. Differential Analysis

Now that the “standard” atmospheric parameters are established in subsection 3.1, we can derive the “differential” parameters, $Δp_{i,j}$ ($p$ is any of $T_{eff}$, $log$ $g$, $v_{t}$, and $A_{FeK}$), of star $i$ relative to any other arbitrary comparison star $j$ by using a method described in Paper I, where several practical quantities were defined such as (i) the average of the direct solution, $Δp_{i,j}$ (average of $Δp_{i,j}$ and $-Δp_{j,i}$), (ii) the intermediary solution via star $k$, $Δp_{i,kj} = (Δp_{ik}) + (Δp_{jk})$, and (iii) the average of the intermediary solution, $Δp_{ijk}$ (average of $Δp_{ijk}$ over various $k$).

Since we are interested in the parameter differences relative to the Sun, we take $i = 1, 2, 3$ and $j = 0$ (see table 1 for the numbering of each star), and two intermediary stars can be assigned for any pair (e.g., for the case of $i = 1$ and

### Table 2. Differential analysis of HIP 56948 relative to the Sun.*

|          | $ΔT$ | $Δ\log g$ | $Δv_t$ | $ΔA$ | $\epsilon_T$ | $\epsilon_g$ | $\epsilon_v$ | $\epsilon_{A_1}$ | $\epsilon_{A_2}$ | $\sigma_{A_1}$ | $\sigma_{A_2}$ | $N_1$ | $N_2$ |
|----------|------|-----------|--------|------|--------------|--------------|--------------|-----------------|----------------|---------------|---------------|-------|-------|
| 056948 – Sun | +4.3 | 0.015 | -0.02 | +0.015 | 5.0 | 0.010 | 0.04 | 0.007 | 0.008 | 0.021 | 0.021 | 196 | 18   |
| —(Sun – 056948) | +1.3 | -0.027 | -0.01 | +0.012 | 5.0 | 0.010 | 0.04 | 0.006 | 0.007 | 0.020 | 0.018 | 189 | 16   |
| (056948 – Sun) | +2.8 | -0.021 | -0.01 | +0.013 | 5.0 | 0.010 | 0.04 | 0.007 | 0.008 | 0.021 | 0.021 | 196 | 18   |

### Table 3. Differential analysis of HIP 79672 relative to the Sun.*

|          | $ΔT$ | $Δ\log g$ | $Δv_t$ | $ΔA$ | $\sigma_T$ | $\sigma_g$ | $\sigma_v$ | $\sigma_{A_1}$ | $\sigma_{A_2}$ | $N_1$ | $N_2$ |
|----------|------|-----------|--------|------|------------|------------|------------|-----------------|---------------|-------|-------|
| 079672 – Sun | +48.9 | +0.008 | +0.03 | +0.056 | 5.0 | 0.010 | 0.03 | 0.006 | 0.006 | 0.018 | 0.016 | 194 | 17   |
| —(Sun – 079672) | +48.1 | +0.009 | +0.03 | +0.053 | 5.0 | 0.010 | 0.03 | 0.006 | 0.006 | 0.019 | 0.017 | 193 | 17   |
| (079672 – Sun) | +48.5 | +0.008 | +0.03 | +0.054 | 5.0 | 0.010 | 0.03 | 0.006 | 0.006 | 0.019 | 0.017 | 193 | 17   |

### Notes

* The results of differential analyses for the case of $(i = 1$ and $j = 0)$. The brief description of the data in the table is given below while Paper I should be consulted for more detailed explanations. (Note that the effective temperature $T_{eff}$ and the Fe abundance $A_{FeK}$ are abbreviated as $T$ as $A$, respectively, in this table 2 along with the following tables 3 and 4.

† 1st row: the results of $(ΔT_{i,j}$, $Δ\log g_{i,j}$, $Δv_{t,i,j}$, $ΔA_{i,j}$), the possible errors ($\epsilon_T$, $\epsilon_g$, and $\epsilon_v$) involved in these solutions (estimated by the procedure described in subsection 5.2 of Takeda et al. 2002), the root-mean-square errors ($\epsilon_{A_1}$, $\epsilon_{A_2}$) on the differential abundances $(ΔA_{i,j})$ from Fe i and Fe ii lines corresponding to these ambiguities in atmospheric parameters, the standard deviations ($\sigma_{A_1}$ and $\sigma_{A_2}$) around the means of $ΔA_{i,j}$ and $ΔA_{j,i}$, and the numbers ($N_1$ and $N_2$) of the used Fe i and Fe ii lines.

2nd row: the same as the 1st row, but for the inverse case of $j < i$; i.e., presented are the parameter differences of $-ΔT_{j,i}$, $-Δ\log g_{j,i}$, $-Δv_{t,j,i}$, and $-ΔA_{j,i}$ and the corresponding errors ($\epsilon_T$, $\epsilon_g$, $\epsilon_v$, $\epsilon_{A_1}$, $\epsilon_{A_2}$).

3rd row: averaged solutions of the parameter differences given in the 1st and 2nd rows; i.e., $(ΔT_{ij})$, $(Δ\log g_{ij})$, $(Δv_{t,ij})$, and $(ΔA_{ij})$.

‡ The first row gives $(Δp_{i,j})$ (equation (15) in Paper I) and $(\sigma_{Δp_{i,j}})$ (equation (16) in Paper I), where $p$ denotes each of $T$, $\log g$, $v_{t}$, and $A$.

Meanwhile, in the following two rows are presented the individual $(Δp_{i,kj})$ values (equation (14) in Paper I) for each intermediary star $k$ (from which the $(Δp_{i,j})$ and $(\sigma_{Δp_{i,j}})$ values in the first row were computed). (Inset in the lower-right space:)

The $(i – j)$ differences of the standard parameters $(T$, $\log g$, $v_{t}$, and $A$) given in table 1.
Δ two direct and intermediary solutions may provide us with an appreciation of these

ΔSun (i = 3 and j = 0). The detailed results for HIP 56948 (i = 1), HIP 79672 (j = 2), HIP 100963 (j = 3) are presented in tables 2, 3, and 4, respectively. (Note that these three tables are formatted in the same manner as in tables 2–9 of Paper I.) The values of \( \Delta T_{\text{eff}} \) (direct solution) and \( \langle \Delta P_{\text{rot}} \rangle \) (average of the intermediary solution) are separately summarized in table 5, where the differences in \( v_{\text{rot}} \) and \( A_{\text{Li}} \) are also given. It is worth noting that the comparison of these two direct and intermediary solutions may provide us with an opportunity for checking/estimating the accuracy of the results.

4. Discussion

4.1. Which Is the Best Solar Twin?

When we compare the parameter differences (relative to the Sun) for HIP 79672 and HIP 100963 given in table 5 with those of Paper II (see table A.1 therein), we can see a notable discrepancy in the values of \( \Delta T_{\text{eff}} \), despite that other \( \Delta \log g \), \( \Delta v_{\text{t}} \), and \( \Delta A_{\text{Fe}} \) are mostly in good agreement. Namely, while Paper II derived a very small \( \Delta T_{\text{eff}} \) \(+1.7 \text{K}/-1.6 \text{K}\) for HIP 79672/100963), the present results \(+48.5 \text{K}/+38.2 \text{K}\) for the direct solution) indicate appreciably larger values by \sim 40–50 \text{K}\) than these. Although the reason for this \( \Delta T_{\text{eff}} \) discrepancy is not clear, it would presumably be ascribed to the difference in the used EW data set. At any rate, because of the reasonable consistency between the direct and intermediary solutions (compare the values in the upper and lower rows in table 5) and the use of the spectrum data of much higher quality (in terms of both the S/N ratio and the spectrum resolving power), we would place larger weight in the present results.

By inspecting table 5, we can summarize as follows concerning the similarity or dissimilarity of these three program stars to the Sun in terms of each checkpoint. (In the discussion of the parameter differences given below, we refer to the averaged values of the direct and intermediary solutions for convenience.):

- \( \Delta T_{\text{eff}} \): HIP 56948 is manifestly more solar like \(+10 \pm 10 \text{K}\) than other HIP 79672 and HIP 100963 \(+40 \pm 10 \text{K}\).

| Star   | \( \Delta T_{\text{eff}} \) (K) | \( \Delta \log g \) (dex) | \( \Delta v_{\text{t}} \) (km s\(^{-1}\)) | \( \Delta A_{\text{Fe}} \) (dex) | \( \Delta A_{\text{Li}} \) (dex) | \( v_{\text{rot}} \) / \( v_{\text{rot}}^{\odot} \) |
|--------|-------------------------------|----------------------------|---------------------------------|-------------------------------|---------------------------------|-----------------------------|
| HIP 56948 | \(+2.8\)                          | \(-0.021\)                   | \(-0.01\)                         | \(+0.013\)                     | \(+0.22\)                             | \(1.02\)                     |
|        | \(+17.0\)                          | \(+0.006\)                   | \(+0.01\)                         | \(+0.020\)                     |                                  |                             |
| HIP 79672 | \(+48.5\)                          | \(+0.008\)                   | \(+0.03\)                         | \(+0.054\)                     | \(+0.69\)                             | \(1.08\)                     |
|        | \(+39.3\)                          | \(+0.013\)                   | \(+0.04\)                         | \(+0.048\)                     |                                  |                             |
| HIP 100963 | \(+38.2\)                          | \(+0.023\)                   | \(+0.00\)                         | \(+0.004\)                     | \(+0.77\)                             | \(1.07\)                     |
|        | \(+33.2\)                          | \(+0.018\)                   | \(+0.01\)                         | \(+0.004\)                     |                                  |                             |

* The results of differential analyses for the case of \( i = 3 \) and \( j = 0 \). See the notes in table 2 for the details.
D log g: All three stars do not show appreciable differences from the solar value, if we consider the nominal uncertainty of ±0.01 dex.

Δv_t: HIP 79672 shows slightly higher v_t than the Sun by ±0.03–0.04 km s\(^{-1}\); HIP 56948 and HIP 100963 are essentially solar.

ΔA_{Li}: Regarding the metallicity, HIP 100963 is almost indiscernible from the Sun (±0.01 dex) and HIP 56948 (∼ +0.01–0.02 dex) is also near-solar (or very slightly metal-rich?), while HIP 79672 appears to be somewhat metal-rich (∼ +0.05 dex).

A_{Li}: HIP 79672 and HIP 100963 are markedly overabundant in Li compared to the Sun by ∼ +0.7–0.8 dex (by a factor of ∼5–6), while the difference from A_{Li,⊙} is much milder for HIP 56946 (only ∼ +0.2 dex or ∼60%).

(v_t) (equivalent to v_e sin i): HIP 56948 has almost the same projected rotational velocity as the Sun, while HIP 79672 and HIP 100963 show slightly higher values by ∼5%–10%.

A_{Fe}: All of three stars (HIP 56948, HIP 79672, and HIP 100963) have essentially the same Be abundances as the Sun, which means that Be does not conform to the behavior of Li showing a diversity. Consequently, whichever mechanism changing the surface Li abundance of these solar twins can not influence Be; e.g., if the variation of A_{Fe} is caused by an envelope mixing, it should not be so deep as to affect Be (see also Randich et al. 2002).

Taking all these results into consideration, we can draw the following conclusions.

HIP 56948 is surely most similar to the Sun among these three stars, not only from the similarity of stellar parameters but also from the viewpoint of surface Li abundance; it may thus deserve the name of “closest ever solar twin”. However, unlike the argument of Meléndez and Ramírez (2007) who derived ΔA_{Li} = −0.02 (±0.13), since the atmospheric Li abundance of this star is marginally higher than the solar value by ∼0.2 dex, we still can not call it a “genuine” solar twin. Another concern about this star is that its luminosity derived from the Hipparcos parallax appears to be somewhat larger than the solar luminosity, which in effect makes the age older (cf. table 1). We suspect that this inconsistency is attributed to an error in the parallax, because HIP 56948 is comparatively distant. The possibility that its actual π is by ∼10% larger than the catalogued value may as well be considered, since the similarity of T_{eff}, log g, and A_{Fe} should guarantee the equality of L (cf. Appendix A of Paper II).

Regarding HIP 79672 and HIP 100963, they have by ∼40 K higher T_{eff} than T_{eff,⊙} by ∼0.7–0.8 dex larger A_{Li} than A_{Li,⊙}, and by ∼5%–10% larger v_e sin i than v_e sin i. Apart from these considerable differences, the parameters of HIP 100963 quite resemble the solar values. Meanwhile, HIP 79672 shows other noticeable differences from the Sun with respect to v_t (by +0.03–0.04 km s\(^{-1}\)) and A_{Fe} (∼ +0.05 dex), which makes this star comparatively lower ranked as a solar twin among the three.

4.2. What Controls Lithium? — Roles of Rotation and T_{eff}

Let us turn our attention to the question posed in section 1: “why do these solar twins show a diversity in the Li line strength in spite of their similarity to one another?” Is this attributed to the difference in the rotational velocity, as suggested in Paper II? According to tables 1 and 5, the values of v_t (v_e sin i) for the Li-strong group (HIP 79672 and HIP 100963) are somewhat larger by ∼5%–10% than those for the Li-weak group (HIP 56948 and the Sun/Moon), which can also be visually recognized in figure 3. Considering that i = 90° for the Sun, while i is unknown for the three stars, we can assure that the equatorial rotational velocities (v_e) of Li-strong HIP 79672 and HIP 100963 are anyhow larger than the solar value (v_e), which may be just favorable for the working hypothesis of Paper II.

Yet, we feel it still premature to conclude that the stellar rotation is the only decisive factor to influence the surface Li abundance of these solar twin stars. Inspecting the core features of the Ca II H and K lines of the program stars shown in figure 6, which are sensitive to the chromospheric activity closely related to the stellar rotation rate,\(^6\) we see in any of these stars almost no appreciable differences in comparison to the solar H and K cores of Kurucz et al.’s (1984) solar spectrum. [Actually, the largest difference relative to

\[^6\] The strength of the Ca II H+K core emission is known to roughly scale with the rotational rate (e.g., Noyes et al. 1984), though its exact relationship is still under discussion (see, e.g., Giampapa 2005). This means, for example, that a solar-type star rotating with v_e ∼ 10 km s\(^{-1}\) would show a stronger core emission by several times than the Sun.
the Sun among the four is seen in the “Moon” spectrum, which is presumably due to the difference in the solar activity phase, because the year of 2008 corresponds to the almost minimum activity.] Besides, according to Giampapa (2005; cf. figure 36 therein), the Li-strong HIP 79672 exhibits stellar activity (inferred from Ca ii H and K line cores; amplitude of ~10% with period of 8–9 years) quite similar to the solar activity. We thus consider that a “substantially” large difference in the rotational rate is not very likely between Li-strong (HIP 79672 and HIP 100963) and Li-weak (HIP 56948 and the Sun) groups.

We rather suspect that the difference in $T_{\text{eff}}$ may also play a significant role in producing this Li-diversity. As reported in Paper II, there is a slanted “lower boundary line” at $+100 \text{ K} \geq \Delta T_{\text{eff}} \geq 0 \text{ K}$ in the $A_{\text{Li}}$ vs. $\Delta T_{\text{eff}}$ diagram, below which no stars are found (cf. figure 9 therein). Interestingly, when we plot HIP 79672 and HIP 100963 (both have $\Delta T_{\text{eff}} \approx +50 \text{ K}$ and $A_{\text{Li}} \sim 1.6$) on this diagram, they almost fall on this boundary line, $A_{\text{Li}} \simeq 1 + 1(\Delta T_{\text{eff}}/100 \text{ K})$, which we regard to be a significant fact worthy of attention.

That is, as speculated in Paper II, we consider that the diversity of $A_{\text{Li}}$ (at a given $T_{\text{eff}}$) is due to the difference in the rotational velocity (i.e., slower rotators tend to show lower Li abundances presumably caused by an enhanced envelope-mixing). On the other hand, since the existence of a steeply slanted lower boundary of $A_{\text{Li}}$ means that all slow rotators should settle on this boundary line, the $A_{\text{Li}}$ values of such slow rotators would naturally show a marked $T_{\text{eff}}$-dependence of $dA_{\text{Li}}/dT_{\text{eff}}$ (100 K) $\sim 1$. This scenario may reasonably explain (at least to an order of magnitude) the difference in $A_{\text{Li}}$ by $0.6–0.7$ dex between HIP 79672/100963 and Sun/HIP 79672, all showing superficially slow rotation as the Sun, while $T_{\text{eff}}$ for the former is slightly higher than the latter by $\sim 40–50 \text{ K}$. Consequently, the Li-strong nature of HIP 79672 and HIP 100963 may be naturally explained by the fact that they belong to the “boundary-line stars” (which seem to have higher possibilities of hosting planets; cf. subsection 5.1 in Paper II). In this sense, we would suggest that $T_{\text{eff}}$ is another significant factor (along with rotational velocity $v_r$) in controlling the Li abundances of solar twins, especially for slowly-rotating ones.

Anyway, this is nothing but a phenomenological explanation, and a number of tasks are still left until the real physical mechanism involved in determining the surface Li abundance is clarified. Hence, investigations especially on the theoretical side) on the inter-relations between rotation, $T_{\text{eff}}$, and $A_{\text{Li}}$ in solar-analog stars are desirably awaited, so that the confronted problems could be settled:

— Why does such a slanted lower boundary exist in the $A_{\text{Li}}$ vs. $T_{\text{eff}}$ diagram of solar-analog stars, below which stars do not exist (“forbidden zone”)? Any $T_{\text{eff}}$-sensitive physical mechanism is acting so as to suppress the further Li depletion?

— $A_{\text{Li}}$ appears to be positively correlated with both $v_r \sin i$ and $T_{\text{eff}}$. What does this mean? These two factors happen to act independently on $A_{\text{Li}}$ in the same direction? Or this is nothing but a superficial effect caused by a tight relationship between $v_r \sin i$ and $T_{\text{eff}}$?

— Whichever $v_r \sin i$ or $T_{\text{eff}}$ may be the relevant key, the physical mechanism working in the envelope of these solar-analog stars must satisfy the condition of changing the surface Li without affecting Be. What kind of process is that?

— Finally, from the observational side, the number of well-studied solar twins/analogs is still so insufficient as to clearly reveal the behavior of Li in Sun-like stars. If we could considerably increase the number of the sample stars (e.g., $\sim 10^3$ or even more), it would surely give us a new insight to this field (in addition, a nearly-perfect solar twin might as well be detected). Besides, given that field solar-type stars are diverse in their age (cf. figure 10 in Paper II), intensively studying the early-G dwarfs in old solar-age clusters (e.g., M 67) would also be beneficial for disentangling the roles of various stellar parameters on this Li problem.

5. Conclusion

An intensive spectroscopic study based on high-quality spectra obtained with Subaru/HDS was performed for HIP 56948, HIP 79672, and HIP 100963 (along with the Sun/Moon as the reference standard), known to be the representative solar twins, in order to (1) clarify which of the three most resembles the Sun by precisely establishing the various differential parameters relative to the Sun and (2) investigate the reason why appreciable differences in the surface Li abundance are observed for these superficially very similar stars.

The standard atmospheric parameters ($T_{\text{eff}}^{\text{std}}, \log g^{\text{std}}, v_r^{\text{std}}, \text{and } [\text{Fe/H}]^{\text{std}}$) were first evaluated by using the equivalent widths of the Fe i and Fe ii lines, the rotational velocity parameter ($v_r$; which is nearly equivalent to $v_r \sin i$) was derived from the line-profile width by eliminating the effect of the macroturbulence, and the Li abundance ($A_{\text{Li}}$) was determined from the Li i doublet line at $\sim 6707.8 \text{ Å}$. Further, the differences of the atmospheric parameters ($\Delta T_{\text{eff}}, \Delta \log g, \Delta v_r$, and $\Delta A_{\text{Li}}$) relative to the Sun were established by using the method of precision differential analysis (Paper I).

While we could confirm that HIP 79672/100963 have appreciably higher Li content by a factor of $\sim 5–6$, as compared to Sun/HIP 56948, the Be abundances for all the program stars (HIP 56948/79672/100963) turned out to be essentially the same as the solar value, which indicates that Be is not affected by any mechanism causing the variation of Li.

We found that HIP 56948 is most similar to the Sun among the three, not only due to the similarity of the stellar parameters (including rotation), but also from the weakness of the Li line (however, $A_{\text{Li}}$ for this star is still slightly larger than $A_{\text{Li,M}}$ by $\sim 0.2$ dex; i.e., not perfectly the same). It may thus deserve the name of “closest ever solar twin”. Meanwhile, some remarkable differences from the solar parameters are recognized in HIP 79672 and HIP 100963, which show a somewhat higher $T_{\text{eff}}$ (by $\sim 40 \text{ K}$), a considerably larger $A_{\text{Li}}$ (by $\sim 0.7–0.8$ dex) and a slightly higher rotational velocity (by $\sim 5\%–10\%$).

We can see a tendency that the Li-strong HIP 79672 and HIP 100963 have somewhat larger rotational velocities by $\sim 5\%–10\%$ than Li-weak HIP 56948 and the Sun, which is consistent with the suggestion of Paper II that $A_{\text{Li}}$ is closely correlated with the stellar rotational velocity. However, it does not seem to be very likely that a substantial difference exists in the rotational velocity between these two groups, because no essential differences are seen in their chromospheric activities.
(sensitive to stellar rotation) inferred from the Ca II H+K line cores. We rather suspect that the overabundance of Li in HIP 79672 and HIP 100963 (by ~0.6–0.7 dex) is attributed to the difference in $T_{\text{eff}}$ (by ~+50 K) relative to the Sun, since these two stars fall on the $T_{\text{eff}}$-sensitive slanted lower boundary in the $A_{\text{Li}}$ vs. $T_{\text{eff}}$ distribution, as reported in Paper II for solar-analog stars. However, it is not clear whether and how these two factors (rotational velocity and effective temperature) are mutually related in affecting the surface Li abundance, which remains to be further clarified.

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