On the oxygen abundances of M 67 stars from the turn-off point through the red giant branch†

Yoichi TAKEDA1,2,* and Satoshi HONDA3

1National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
2The Graduate University for Advanced Studies, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
3Nishi-Harima Astronomical Observatory, Center for Astronomy, University of Hyogo, 407-2 Nishigaichi, Sayo-cho, Sayo, Hyogo 679-5313, Japan

*E-mail: takeda.yoichi@nao.ac.jp

Received 2014 October 8; Accepted 2014 December 18

Abstract

With an aim to examine whether the surface oxygen composition suffers any appreciable change due to evolution-induced mixing of nuclear-processed material in the envelope of red giants, abundance determinations for O/Fe/Ni based on the synthetic spectrum-fitting method were performed by using the moderate-dispersion spectra in the 7770–7792 Å region (comprising O I 7771–5, Fe I 7780, and Ni I 7788 lines) for 16 stars of the old open cluster M 67 in various evolutionary stages from the turn-off point through the red giant branch. We could not find any meaningful difference in the oxygen abundances between the non-giant group (Teff > 5000 K) and the red-giant group (Teff < 5000 K), which are almost consistent with each other on average (despite that both have rather large dispersions of a few tenths dex caused by insufficient data quality), though only one giant star (S 1054) appears to show an exceptionally low O abundance and thus needs a more detailed study. This result may suggest that oxygen content in the stellar envelope is hardly affected (or any changes are insignificant) by the mixing of H-burning products in the red giant phase, as far as M 67 stars of low mass (∼1.3 M⊙) are concerned, which is consistent with the prediction from the conventional stellar evolution theory of first dredge-up.

Key words: open clusters and associations: individual (M 67) — stars: abundances — stars: atmospheres — stars: evolution — stars: late-type

1 Introduction

As a star evolves off the main sequence after exhaustion of hydrogen fuels in the core, it increases its radius while the surface temperature drops down, and the deep convection zone is developed. As a result, some portion of the H-burning (CNO cycle) product in the interior may be salvaged and mixed to alter the surface abundances of red giants. According to the canonical stellar evolution calculation, it is essentially the CN-cycled (C→N reaction) material that is dredged up, while the product of ON-cycle (O→N reaction; occurring in deeper region of higher T) is unlikely to cause any significant abundance change because mixing is not expected to substantially penetrate into such a deep layer; thus the predicted surface abundances are characterized by a deficit in C as well as an enhancement in N (with its peculiarity degree increasing with mass/luminosity), while O

† Based on data collected by using the NAYUTA Telescope of the Nishi-Harima Astronomical Observatory.
is practically unaffected (see, e.g., figure 24 in Mishenina et al. 2006).

While such expected tendency has been almost confirmed observationally for C and N, the behavior of O is still controversial and unsettled.

— Mishenina et al. (2006) reported that the oxygen abundances (determined based on the [O i] forbidden line at 6300 Å) in red-clump giants of \( \sim 1-3 M_\odot \) are almost normal (\( ([O/Fe]) \approx 0 \)), in agreement with the theoretical prediction.

— Further, Tautvaisiënë et al.’s (2010) similar study on red-clump giants resulted in essentially the same conclusion as Mishenina et al.’s.

— However, Takeda, Sato, and Murata (2008) reported in their extensive spectroscopic analysis of 322 late-G and early-K giants (\( 4500 \lesssim T_{\text{eff}} \lesssim 5500 K, 1.5 \lesssim \log g \lesssim 3.5, 1 \lesssim M/M_\odot \lesssim 5 \)) that \([O/Fe] \) determined from the [O i] 5577 line shows a subsolar tendency with the extent of peculiarity increasing with M (cf. their figure 12), which implies that a mass-dependent dredge-up of (not only CN-cycle but also) ON-cycle products may take place in the envelope of red giants. So, if this is real, it would require a revision of the standard theory for the dredge-up in the envelope of red giants. (See, however, Note added in proof appended at the end of this paper.)

The best approach to check whether or not stellar surface abundances suffer changes during the evolutionary paths from the main sequence to the red giant phase is to investigate a number of stars (of various types) belonging to an open cluster. That is, since all such member stars are considered to have the same age as well as the same initial composition, detection of any systematic abundance differences along the evolutionary sequence would provide direct evidence for the existence of evolution-induced build-up of chemical peculiarity. Above all, the well-known old open cluster M 67 (NGC 2682) is especially suitable for this purpose, since (unlike many other comparatively young clusters) it has the particular merit of including a wealth of stars (not only on the main sequence but also) on the continuous evolutionary sequence from the turn-off point through the red giant branch.

This well-known old Galactic cluster has been repeatedly studied and several reports on the oxygen abundances of M 67 member stars are already available; e.g., Brown (1985) for three giants; Shetrone and Sandquist (2000) for 10 blue-straggler and turn-off stars; Tautvaisiënë et al. (2000) for 10 giants; Yong, Carney, and Teixera de Almeida (2005) for three giants; Randich et al. (2006) for 10 dwarfs/subgiants of late F- and early G-type; Pace, Pasquini, and François (2008) for five solar-type stars; and Pancino et al. (2010) for three giants.1 However, any trial of systematic oxygen abundance studies in a consistent manner for a wide range of M 67 stars from near-main sequence (F type) through red giants (K type) has never been made so far to our knowledge.

Motivated by this situation, we decided to conduct a spectroscopic study on M 67 stars in various stages from less evolved (near to turn-off points) through fully evolved (red giants), in order to determine their oxygen abundances based on O i 7771–5 triplet lines (by making use of the fact that these O i lines are visible in a wide range of stars from spectral types A through K) and to see if any systematic oxygen abundance peculiarity (e.g., a comparative deficit of O in red giants) is observed. This was our primary purpose.

Somewhat disappointingly, we realized in the course of the analysis that the spectral data we obtained for the relevant M 67 stars of \( V \lesssim 13 \) mag with the 2-m NAYUTA telescope (used for this study) were of insufficient quality (i.e., S/N ratios were from only several tens to \( \sim 100 \)) to carry out reliable abundance determinations. Yet, we positively considered that this is a good opportunity for us to learn how much abundance information is gained by carefully studying rather noisy spectra of medium resolution, since such circumstances may be encountered in astronomical spectroscopy of faint objects. Accordingly, we paid special attention to quantitatively estimating errors involved in the resulting abundances. This challenge forms another aim of the investigation.

The remainder of this article is organized as follows. After describing our observations in section 2, we explain the assignments of stellar parameters in section 3. The procedure of our abundance determination based on the spectrum-fitting method is illustrated in section 4, followed by section 5 where abundance errors are evaluated in various respects. The resulting abundances are discussed in section 6, and the conclusion is summarized in section 7.

2 Observational data

The list of our 16 targets of M 67 cluster is presented in table 1, which were selected to cover the evolutionary status from the turn-off point through the red giant branch. Spectroscopic observations of these stars were carried out in 2014 January and February using the Medium And Low-dispersion Longslit Spectrograph (MALLS; cf. Ozaki & Tokimasa 2005) installed on the Nasmyth platform of the 2-m NAYUTA telescope at Nishi-Harima Astronomical Observatory (NAHAO). Equipped with a 2 K × 2 K CCD detector (13.5 µm pixel), MALLS can record a spectrum

\footnote{1 We do not pay attention here to the pioneering studies done in the 1970s based on photographic plates because they are less reliable; see, e.g., section 1 of Tautvaisiënë et al. (2000).}
covering ~ 400 Å (7600–8000 Å) in the medium-resolution mode with the resolving power of $R \sim 12000$. Since we had to limit the maximum exposure time of one frame to 20 minutes (because of enhanced dark level), a number of spectral frames were co-added in order to reduce the spectrum noise as much as possible. The reduction of the spectra (bias subtraction, flat-fielding, spectrum extraction, wavelength calibration, co-adding of frames to improve the S/N (measured)), and the average $(\langle c_k \rangle)$ of the spectrum at each of the eight selected line-free windows $(k)$ of several Å width, which gives the local $S/N$ for region $k$ as $(S/N)_k \equiv \langle c_k \rangle / \sigma_k$. We then averaged each $(S/N)_k$ to obtain $S/N$(measured) while weighting according to $w_k(\sigma_k^2)^{-1}$. The correlation between $S/N$(predicted) and $S/N$(measured) is shown in figure 1, where we can see that both are reasonably correlated with each other (though quantitative agreement is not necessarily good). From a modest standpoint, we adopted (the rounded value of) the smaller one of these two $S/N$ ratios for each star. Unfortunately, the finally achieved $S/N$ ratios were not satisfactory. While moderate values of $\sim 100$ were realized for brighter giant stars, we could gain only several tens for the case of fainter turn-off stars of $V \gtrsim 12.5$. Accordingly, since the spectrum quality is not sufficient for reliable abundance determination, we must carefully check how much

### Table 1. Basic data of observed M 67 stars.*

| Star | WEBDA | RA (J2000.0) | Dec (J2000.0) | $V$ | $B - V$ | $t_{exp}$ | $S/N$ | Date (2014,UT) | Remark |
|------|-------|--------------|--------------|-----|---------|-----------|------|----------------|---------|
| S 1279 | 164 | 08 51 28.99 | +11 50 33.13 | 10.5379 | 1.1144 | 7200 | 130 | Jan04 | RGC |
| S 1010 | 141 | 08 51 22.804 | +11 48 01.78 | 10.4675 | 1.0946 | 7200 | 70 | Jan28 | RGC |
| S 1074 | 84 | 08 51 12.697 | +11 52 42.44 | 10.5221 | 1.0924 | 9600 | 120 | Jan29+30 | RGC |
| S 1084 | 151 | 08 51 26.181 | +11 53 51.96 | 10.4929 | 1.0853 | 3600 | 75 | Feb01 | RGC |
| S 1054 | 104 | 08 51 17.028 | +11 50 46.40 | 11.1393 | 1.0810 | 4800 | 95 | Jan31 | RGC |
| S 1288 | 217 | 08 51 42.363 | +11 51 23.09 | 11.2502 | 1.0714 | 9600 | 55 | Feb02+03 | RGC |
| S 989 | 135 | 08 51 21.565 | +11 46 06.20 | 11.4291 | 1.0702 | 8400 | 120 | Feb22 | Low GB |
| S 1277 | 218 | 08 51 42.314 | +11 50 07.82 | 11.6221 | 1.0367 | 4800 | 25 | Feb03 | Low GB |
| S 1293 | 3035 | 08 51 39.386 | +11 51 45.66 | 12.1223 | 0.9952 | 7200 | 65 | Jan31 | RGC |
| S 1245 | 227 | 08 51 44.741 | +11 46 46.03 | 12.9475 | 0.8925 | 6000 | 45 | Jan31 | SG |
| S 1056 | 96 | 08 51 15.639 | +11 50 56.22 | 13.0015 | 0.8379 | 7200 | 20 | Jan27 | SG |
| S 489 | 7489 | 08 50 16.296 | +11 53 48.00 | 12.7600 | 0.6800 | 13200 | 25 | Jan28 | TO gap |
| S 1034 | 115 | 08 51 18.541 | +11 49 21.52 | 12.6530 | 0.6056 | 14400 | 25 | Jan04 | SG |
| S 1083 | 157 | 08 51 27.423 | +11 53 26.56 | 12.7547 | 0.5678 | 6000 | 50 | Jan27 | TO |
| S 1270 | 241 | 08 51 49.143 | +11 49 43.59 | 12.6843 | 0.5378 | 10800 | 40 | Jan31 | SG |
| S 1456 | 255 | 08 51 33.54 | +11 48 20.89 | 12.7160 | 0.5181 | 10800 | 25 | Jan28 | TO |

* Most columns are self-explanatory. Each M 67 star, designated with the serial number assigned by Sanders (1995) and the reference number of WEBDA database (Mermilliod 1995, available at [http://www.univie.ac.at/webda/]), is arranged as in table 2 (decreasing order in $B - V$, or increasing order in $T_{eff}$). The positional data are taken from the SIMBAD database, while the photometric data $(V, B - V)$ are from Sandquist (2004). See section 2 for the derivation of $S/N$ ratios presented in column 8. Given in column 10 is the evolutionary status classified by Sandquist (2004).

---

2 IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc. under cooperative agreement with the National Science Foundation.
Besides, we also observed Pollux (K0 III), Procyon (F5 IV–V), and Ganymede (substitute for the Sun) as the reference stars, for which the spectra turned out to be of sufficiently high quality (S/N of more than several hundreds). Our spectra in the 7680–7820 Å region are displayed in figure 3 for each of the 19 program stars.

3 Stellar parameters

Regarding the common properties of M 67 member stars, we adopted [Fe/H] = +0.02 (metallicity), $E(B-V) = +0.04$ (color excess), and $(m–M)_0 = 9.60$ (true distance modulus), following Sandquist (2004). The effective temperature ($T_{\text{eff}}$) was evaluated from dereddened $(B-V)_0 = [(B-V) - E(B-V)]$ by invoking Alonso, Arribas, and Martínez-Roger’s (1996) equation (1) as well as Alonso, Arribas, and Martínez-Roger’s (1999) table 2 for seven non-giants $(B-V < 0.9)$ and nine giants $(B-V > 0.9)$, respectively. The bolometric luminosity $(L)$ was derived from the absolute magnitude $M_V = [(V - (m-M)_0) - 3.1E(B-V)]$ and the bolometric correction (B.C.) calibrated by Alonso, Arribas, and Martínez-Roger (1995) as well as Alonso, Arribas, and Martínez-Roger (1999) for non-giants and giants, respectively. As such, our M 67 targets are plotted on the log $L$ vs. log $T_{\text{eff}}$ diagram shown in figure 2b, where Demarque et al.’s (2004) Yale–Yonsei theoretical solar-metallicity evolutionary tracks (Y2_tracks_a0o2newOS.gz) as well as the 4-Gyr isochrone (YYiso_v2.tar.gz) are also drawn.

The surface gravity $(\log g)$ of each star was then calculated as

$$\log(g/g_\odot) = \log(M/M_\odot) - \log(L/L_\odot) + 4\log(T_{\text{eff}}/T_{\text{eff}})$$

where terms with subscript “$\odot$” are the solar values and we adopted $M = 1.3 M_\odot$ (cf. figure 2b).

Regarding the microturbulence $(v_t)$, Takeda et al.’s (2013) empirical formula [cf. equations (1) and (2) therein] was adopted for non-giants $(T_{\text{eff}} > 5000 \text{ K})$. As to giants $(T_{\text{eff}} < 5000 \text{ K})$, we assumed a log $g$-dependent relation

$$v_t = 0.01 + 1.30 \log g - 0.31(\log g)^2$$

(where $v_t$ is in km s$^{-1}$ and $g$ is in cm s$^{-2}$), which we found to represent (within $\sim 0.1-0.2$ km s$^{-1}$) the $v_t$ data derived by Takeda, Sato, and Murata (2008; cf. figure 1c therein) well for giants in the parameter range of $4600 < T_{\text{eff}} < 4900 \text{ K}$ and $2.3 < \log g < 3.3$.

---

Figure 2. (a) M 67 stars plotted on $V$ vs. $B-V$ diagram, based on the photometric data taken from Sandquist (2004). Filled circles: our 16 targets (from the turn-off point through the red giant branch). Open circles: other M 67 member stars which we did not observe. (b) M 67 stars plotted on the log $L$ vs. log $T_{\text{eff}}$ diagram, with the same meanings of symbols as in panel (a). The Yale–Yonsei theoretical solar-metallicity evolutionary tracks (corresponding to 1.1, 1.3, and 1.5 $M_\odot$) as well as the 4-Gyr isochrone (Demarque et al. 2004) are also depicted by solid lines and crosses, respectively. (Color online)

---

3.1 Stellar parameters

Regarding the common properties of M 67 member stars, we adopted $[\text{Fe/H}] = +0.02$ (metallicity), $E(B-V) = +0.04$ (color excess), and $(m–M)_0 = 9.60$ (true distance modulus), following Sandquist (2004). The effective temperature ($T_{\text{eff}}$) was evaluated from dereddened $(B-V)_0 = [(B-V) - E(B-V)]$ by invoking Alonso, Arribas, and Martínez-Roger’s (1996) equation (1) as well as Alonso, Arribas, and Martínez-Roger’s (1999) table 2 for seven non-giants $(B-V < 0.9)$ and nine giants $(B-V > 0.9)$, respectively. The bolometric luminosity $(L)$ was derived from the absolute magnitude $M_V = [(V - (m-M)_0) - 3.1E(B-V)]$ and the bolometric correction (B.C.) calibrated by Alonso, Arribas, and Martínez-Roger (1995) as well as Alonso, Arribas, and Martínez-Roger (1999) for non-giants and giants, respectively. As such, our M 67 targets are plotted on the log $L$ vs. log $T_{\text{eff}}$ diagram shown in figure 2b, where Demarque et al.’s (2004) Yale–Yonsei theoretical solar-metallicity evolutionary tracks (Y2_tracks_a0o2newOS.gz) as well as the 4-Gyr isochrone (YYiso_v2.tar.gz) are also drawn.

The surface gravity $(\log g)$ of each star was then calculated as

$$\log(g/g_\odot) = \log(M/M_\odot) - \log(L/L_\odot) + 4\log(T_{\text{eff}}/T_{\text{eff}})$$

where terms with subscript “$\odot$” are the solar values and we adopted $M = 1.3 M_\odot$ (cf. figure 2b).

Regarding the microturbulence $(v_t)$, Takeda et al.’s (2013) empirical formula [cf. equations (1) and (2) therein] was adopted for non-giants $(T_{\text{eff}} > 5000 \text{ K})$. As to giants $(T_{\text{eff}} < 5000 \text{ K})$, we assumed a log $g$-dependent relation

$$v_t = 0.01 + 1.30 \log g - 0.31(\log g)^2$$

(where $v_t$ is in km s$^{-1}$ and $g$ is in cm s$^{-2}$), which we found to represent (within $\sim 0.1-0.2$ km s$^{-1}$) the $v_t$ data derived by Takeda, Sato, and Murata (2008; cf. figure 1c therein) well for giants in the parameter range of $4600 < T_{\text{eff}} < 4900 \text{ K}$ and $2.3 < \log g < 3.3$.

---

Figure 2. (a) M 67 stars plotted on $V$ vs. $B-V$ diagram, based on the photometric data taken from Sandquist (2004). Filled circles: our 16 targets (from the turn-off point through the red giant branch). Open circles: other M 67 member stars which we did not observe. (b) M 67 stars plotted on the log $L$ vs. log $T_{\text{eff}}$ diagram, with the same meanings of symbols as in panel (a). The Yale–Yonsei theoretical solar-metallicity evolutionary tracks (corresponding to 1.1, 1.3, and 1.5 $M_\odot$) as well as the 4-Gyr isochrone (Demarque et al. 2004) are also depicted by solid lines and crosses, respectively. (Color online)
Concerning the reference stars, we assigned \((T_{\text{eff}}, \log g, [\text{Fe/H}], \text{and} \nu_t)\) as follows: (4904 K, 2.84, +0.06, and 1.3 km s\(^{-1}\)) for Pollux (Takeda et al. 2008), (6612 K, 4.00, −0.02, and 2.0 km s\(^{-1}\)) for Procyon (Takeda et al. 2005), and (5780 K, 4.44, 0.00, and 1.0 km s\(^{-1}\)) for the Sun. These finally adopted atmospheric parameters for each star are summarized in Table 2. Also, how the \(\log g\) and \(\nu_t\) of our M 67 targets depend characteristically upon \(T_{\text{eff}}\) is displayed in Figure 4.
such assigned parameters are compared in table 3 with those adopted in previous investigations on oxygen abundances in M 67 (cf. section 1), where five M 67 stars common to our sample were analyzed in four studies. We can see from this table that both are reasonably consistent with each other in terms of $T_{\text{eff}}$ and log $g$, since the differences are $\lesssim 50$ K and $\lesssim 0.1$ dex, respectively, in most cases (except that Pancino et al.'s spectroscopic log $g$ for S 1010 is higher by $\sim$ 0.4 dex while their photometric log $g$ is in agreement with ours). Regarding $v_1$, for giants, Tautvaisiene et al. (2000) used systematically higher values ($1.7$–$1.8$ km s$^{-1}$) than that ($1.3$ km s$^{-1}$) adopted by us, while Yong, Carney and Teixeira de Almeida's (2005) $v_1$ ($1.34$ km s$^{-1}$ for S 1010) is consistent with ours.

### 4 Abundance determinations

#### 4.1 Model atmospheres and spectral line data

The model atmosphere for each star to be used for abundance derivations was constructed by three-dimensionally interpolating Kurucz's (1993) ATLAS9 model grid in terms of $T_{\text{eff}}$, log $g$, and [Fe/H]. Regarding the atomic parameters of spectral lines, we basically invoked the extensive compilation by Kurucz and Bell (1995), while applying appropriate adjustments to log $g$ values when necessary (see footnote 5 and note in table 4). By using these atmospheric models, we simulated the theoretical spectra in the $7680$–$7820$ Å region while assuming the metallicity-scaled solar abundances for all elements (and convolved them with the Gaussian broadening function corresponding to $R \sim 12000$), which are overplotted in figure 3.\(^5\)

\(^5\) In this computation, we basically adopted Kurucz and Bell's (1995) compilation for the atomic data. We noticed, however, that their original $g_f$ values were not necessarily appropriate for quite a few lines in this wavelength region, to which adequate adjustments must be applied in order to accomplish a satisfactory match between theory and observation. Accordingly, we estimated the necessary corrections ($\Delta \log g_f$) for the following 17 lines by comparing the observed spectrum of Ganymede and the theoretical solar flux spectrum simulated with the standard solar abundances: NiI 7715.583 (by $+1.0$ dex), SiI 7725.046 (by $-0.7$ dex), FeI 7742.885 (by $-0.3$ dex), SII 7745.101 (by $-0.5$ dex), MgI 7746.345 (by $-1.3$ dex), SiI 7750.010 (neglected), FeI 7770.279 (by $-0.7$ dex), CaI 7771.239 (neglected), FeI 7771.427 (by $-0.7$ dex), FeI 7772.597 (by $-0.1$ dex), TiI 7773.904 (neglected), FeI 7774.001 (by $+1.5$ dex), CaI 7774.965 (neglected), CaI 7775.763 (neglected), FeI 7776.952 (by $+2.3$ dex; see also table 4), SiI 7799.180 (neglected), and SiII 7799.996 (by $+1.5$ dex). Besides these, six additional CN lines in the 7770–7777 Å region used by Takeda, Sadakane, and Kawanomoto (1998) were also included with Eriksson and Toff's (1979) $g_f$ values.

---

### Table 2. Stellar parameters and the resulting abundances.*

| Star   | $T_{\text{eff}}$ | log $g$ | [Fe/H] | $v_1$ | $A_{\text{Ni}}^L$ | $A_{\text{Ni}}^N$ | $A_{\text{Ni}}^O$ | EW_{Ni} | EW_{Fe} | EW_{Fe} | EW_{Fe} | EW_{Ni} |
|--------|-----------------|--------|--------|-------|-------------------|-------------------|-------------------|--------|--------|--------|--------|--------|
| Pollux | 4904            | 2.84   | +0.06  | 1.3   | 8.53             | -0.10            | 8.43              | 25     | 7.47   | 135    | 6.56   | 133    |
| S 1279 | 4668            | 2.45   | +0.02  | 1.3   | 8.58             | -0.09            | 8.49              | 20     | 7.54   | 140    | 5.94   | 109    |
| S 1010 | 4705            | 2.44   | +0.02  | 1.3   | 8.57             | -0.09            | 8.48              | 21     | 6.90   | 116    | 5.64   | 91     |
| S 1074 | 4709            | 2.47   | +0.02  | 1.3   | 8.74             | -0.10            | 8.64              | 25     | 7.11   | 119    | 6.08   | 116    |
| S 1084 | 4722            | 2.46   | +0.02  | 1.3   | 8.34             | -0.08            | 8.26              | 16     | 7.78   | 162    | 6.95   | 172    |
| S 1054 | 4731            | 2.73   | +0.02  | 1.3   | 7.43             | -0.06            | 7.37              | 3      | 7.78   | 162    | 6.77   | 154    |
| S 1288 | 4749            | 2.78   | +0.02  | 1.2   | —                | —                | —                | —      | 8.20   | 200    | 6.39   | 124    |
| S 0989 | 4751            | 2.85   | +0.02  | 1.2   | 8.53             | -0.08            | 8.45              | 18     | 7.75   | 154    | 6.73   | 144    |
| S 1277 | 4816            | 2.96   | +0.02  | 1.2   | 8.97             | -0.10            | 8.87              | 30     | 7.70   | 149    | 6.61   | 134    |
| S 1293 | 4900            | 3.21   | +0.02  | 1.0   | 8.74             | -0.08            | 8.66              | 26     | 7.49   | 125    | 6.47   | 112    |
| S 1245 | 5044            | 3.58   | +0.02  | 0.9   | 8.64             | -0.07            | 8.57              | 25     | 7.99   | 165    | 6.10   | 82     |
| S 1056 | 5199            | 3.68   | +0.02  | 1.0   | —                | —                | —                | —      | —      | 7.22   | 147    |
| S 0489 | 5703            | 3.79   | +0.02  | 1.2   | 8.72             | -0.15            | 8.57              | 57     | —      | —      | 5.93   | 54     |
| S 1034 | 5975            | 3.84   | +0.02  | 1.4   | 9.49             | -0.35            | 9.14              | 128    | 7.07   | 80     | 6.80   | 90     |
| S 1083 | 6123            | 3.93   | +0.02  | 1.5   | 8.45             | -0.16            | 8.29              | 63     | 6.89   | 67     | 6.29   | 45     |
| S 1270 | 6163            | 3.92   | +0.02  | 1.6   | 9.62             | -0.44            | 9.18              | 155    | 7.96   | 130    | 6.96   | 94     |
| S 1456 | 6329            | 3.98   | +0.02  | 1.7   | 8.19             | -0.16            | 8.03              | 56     | 8.13   | 137    | 6.29   | 45     |
| Procyon| 6612            | 4.00   | -0.02  | 2.0   | 9.21             | -0.37            | 8.84              | 148    | 7.38   | 87     | 6.53   | 47     |
| Sun    | 5780            | 4.44   | 0.00   | 1.0   | 8.69             | -0.09            | 8.60              | 46     | 7.84   | 124    | 6.61   | 81     |

*In columns 1 through 5 are given the name (M 67 stars are indicated by Sanders numbers), effective temperature (in K), logarithmic surface gravity (in cm s$^{-2}$), metallicity (logarithmic Fe abundance relative to the Sun; in dex), and microturbulent velocity dispersion (in km s$^{-1}$) for each star. The LTE abundances ($A^L$) resulting from our spectrum fitting analysis and the corresponding equivalent widths (EW; in mÅ) evaluated for O I 7774.17, Fe I 7780.55, and Ni I 7788.94 lines are presented in the remaining columns, where the non-LTE corrections ($A^N$) and the non-LTE abundances ($A^O$) are also given regarding oxygen. All abundance results are expressed in the usual normalization of $A_{\text{H}} = 12.00$.\(^5\)
Fe I 7780, and Ni I 7788 lines). The adopted atomic data of the relevant O I, Fe I, and Ni I lines are summarized in table 4, for which we invoked Kurucz and Bell’s (1995) compilation. However, only the log gf value (−0.066) for the Fe I line at 7780.55 Å was exceptionally taken from Kurucz and Peytremann’s (1975) old database as done by Takeda and Sadakane (1997), since the value (−2.361) given in Kurucz and Bell (1995) is too small and apparently inappropriate (it would lead to an unrealistically large solar Fe abundance).

Since we could not arrive at any converged solution for S 1288 and S 1056 because the lines are overwhelmed by noise, we abandoned A(O) determinations for these two stars. The eventually accomplished fit for each spectrum is shown in figure 5, and the results of A(O), A(Fe), and A(Ni) are given in table 2.

(ii) Secondly, the equivalent width (EW) of the O I line at 7774.17 Å (the middle line of the triplet) was inversely computed from such established solution of A(O) by using the same model atmosphere. Similarly, EW 7780 and EW 7788 for Fe I 7770.55 and Ni I 7788.94 lines were derived from A(Fe) and A(Ni).

(iii) Finally, regarding oxygen, the non-LTE correction for O I 7774.17 (ΔN7774) was evaluated from EW 7774 by following the procedure described in Takeda (2003), which was applied to A(O) [derived in step (i)] to obtain AN(O) (non-LTE oxygen abundance) as

\[ A^N(O) = A^O(O) + \Delta N_{7774}. \]

Such obtained results of AN(O) and A(O) are also presented in table 2.

5 Error analysis

In the present case where spectra of insufficient quality are used, the primary source of errors accompanying our abundance results is noise. We estimated this kind of abundance error by two independent ways: (1) based on expected

| Figure 4. T_eff-dependence of (a) log g and (b) v_t for our 16 targets of M 67. |

---

6 Actually, this computation was done also for the other two lines of the triplet at 7771.94 and 7775.39 Å. These EW 7771 and EW 7775 are well correlated with EW 7774 through the following relations: E W 7771 = 0.1 + 1.18 E W 7774 + 5.81 \times 10^{-4} E W 7774 and E W 7775 = 0.3 + 0.76 E W 7774 + 7.70 \times 10^{-4} E W 7774, where EW is expressed in m Å. Naturally, the inequality relation EW 7771 > EW 7774 > EW 7775 always holds between these three EW values, reflecting the difference of log gf.

7 We may regard the oxygen abundance derived from the O I 7774.17 line (the middle component) as practically equivalent to that corresponding to the O I 7771–5 triplet as a whole for the following reason. The non-LTE abundance for the triplet (the mean of A^N_{7771}, A^N_{7774}, and A^N_{7775}) is expressed as (A^N) = A^O + (\Delta N_{7771} + \Delta N_{7774} + \Delta N_{7775})/3, where the inequality relation |\Delta N_{7771}| > |\Delta N_{7774}| > |\Delta N_{7775}| generally holds for the extents of (negative) non-LTE correction according to Takeda (2003) because of the difference in the component strengths (EW 7771 > EW 7774 > EW 7775, cf. footnote 6). We actually found the following equations regarding the AN values of each lines derived for our the program stars: AN 7771 = 1.10AN_{7774} and AN 7775 = 0.85AN_{7774}. Given this situation, the difference between \Delta N_{7774} and (\Delta N_{7771} + \Delta N_{7774} + \Delta N_{7775})/3 turned out to be very small and negligible (< 0.01 dex for all stars), by which we can state that A^N_{7774} is essentially equivalent to (A^N).
Table 3. Comparison of the atmospheric parameters with the literature values.

| Star   | $T_{\text{eff}}$ (K) | log $g$ (cm s$^{-1}$) | $v_t$ (km s$^{-1}$) | Reference                  |
|--------|----------------------|------------------------|---------------------|----------------------------|
| S 1279 (F164) | 4700 2.50 1.8     |                        |                     | Tautvaisiene et al. (2000) |
|         | 4668 2.45 1.3     |                        |                     | This study                 |
| S 1010 (F141) | 4730 2.40 1.8     |                        |                     | Tautvaisiene et al. (2000) |
|         | 4700 2.30 1.34    |                        |                     | Yong, Carney and Teixera de Almeida (2005) (spectroscopic) |
|         | 4640 2.30         |                        |                     | Yong, Carney and Teixera de Almeida (2005) (photometric) |
|         | 4650 2.80 1.3     |                        |                     | Pancino et al. (2010) (spectroscopic) |
|         | 4590 2.42 1.2/1.8 |                        |                     | Pancino et al. (2010) (photometric) |
|         | 4705 2.44 1.3     |                        |                     | This study                 |
| S 1074 (F84) | 4750 2.40 1.8     |                        |                     | Tautvaisiene et al. (2000) |
|         | 4709 2.47 1.3     |                        |                     | This study                 |
| S 1084 (F151) | 4760 2.40 1.7     |                        |                     | Tautvaisiene et al. (2000) |
|         | 4722 2.46 1.3     |                        |                     | This study                 |
| S 1034  | 6019 4.00 1.5     |                        |                     | Randich et al. (2006)      |
|         | 5975 3.84 1.4     |                        |                     | This study                 |

Table 4. Atomic data of the spectral lines used for abundance determinations.

| Species | $\lambda_{\text{air}}$ (Å) | $\chi_{\text{low}}$ (eV) | log $gf$ (dex) | Gammar (dex) | Gammas (dex) | Gammaw (dex) |
|---------|-----------------------------|---------------------------|----------------|--------------|--------------|--------------|
| O I     | 7771.944                    | 9.146                     | +0.324         | 7.52         | −5.55        | (−7.65)      |
| O I     | 7774.166                    | 9.146                     | +0.174         | 7.52         | −5.55        | (−7.65)      |
| O I     | 7775.388                    | 9.146                     | −0.046         | 7.52         | −5.55        | (−7.65)      |
| Fe I    | 7780.552                    | 4.473                     | −0.066         | 7.88         | −6.13        | −7.80        |
| Ni I    | 7788.936                    | 1.951                     | −2.420         | 8.00         | −6.31        | −7.85        |

The first four columns are self-explanatory. Presented in columns 5–7 are the damping parameters: Gammar is the radiation damping width (s$^{-1}$) [log $\gamma_{\text{rad}}$], Gammas is the Stark damping width (s$^{-1}$) per electron density (cm$^{-3}$) at $10^8$ K [log $(\gamma_{\text{e}}/\rho_e)$], and Gammaw is the van der Waals damping width (s$^{-1}$) per hydrogen density (cm$^{-3}$) at $10^4$ K [log $(\gamma_{\text{H}}/\rho_{\text{H}})$]. Most of these data were taken from the compilation of Kurucz and Bell (1995), though Kurucz and Peytremann’s (1973) log $gf$ value was adopted for Fe I 7780.552 as done in Takeda and Sadakane (1997) (cf. subsection 4.2). The parenthesized damping parameters are the default values computed by the WIDTH9 program, since the data are not available in Kurucz and Bell (1995).

uncertainties in the equivalent widths, and (2) directly analyzing a number of mock spectra (with artificially added noise) in the same spectrum-fitting method. Besides this, we also have to evaluate errors due to ambiguities in the adopted atmospheric parameters ($T_{\text{eff}}$, log $g$, and $v_t$).

5.1 Noise-related error #1: based on equivalent widths

Regarding the error in $EW$, we invoked the formula derived by Cayrel (1988),

$$\delta EW \simeq 1.6(w \delta x)^{1/2} \epsilon,$$

where $\delta x$ is the pixel size (0.21 Å), $w$ is the full-width at half maximum (corresponding to $\simeq 25$ km s$^{-1}$ or $R \simeq 12000$), and $\epsilon \equiv (S/N)^{-1}$. We thus determined the abundances for each of the perturbed $EW_+ (\equiv EW + \delta EW)$ and $EW_- (\equiv EW - \delta EW)$, respectively, from which the differences from the standard $A$ were derived as $\delta A_+ (> 0)$ and $\delta A_- (< 0)$.

5.2 Noise-related error #2: based on artificial spectra

We first calculated the reference spectrum corresponding to the standard solutions of $A_0$(O), $A_0$(Fe), $A_0$(Ni), and $v_{M0}$ for each star (obtained in subsection 4.2). Then, randomly generated noise of normal distribution (corresponding to the $S/N$ ratio) was added to this standard spectrum, and this process was repeated 100 times. In this way, 100 artificial spectra were generated, as shown in figure 6. Next, we tried abundance determinations in exactly the same manner.
as described in subsection 4.2, and obtained $A_i$(O), $A_i$(Fe), and $A_i$(Ni) for each spectrum $i$ ($i = 1, 2, \ldots, 100$). The distributions of the resulting $A_i$(O) are illustrated in figure 7. Then, from this ensemble of $A_i$, the average $\langle A \rangle$ and the standard deviation $\sigma_A$ were computed. We can regard this $\sigma_A$ (representing the dispersion of $A_i$) as an estimate of abundance errors caused by noise.

5.3 Effect of atmospheric parameters
The uncertainties in $A$ due to errors of atmospheric parameters were evaluated by repeating the analysis on $EW$ while perturbing the standard values of atmospheric parameters interchangeably by $\pm 2\%$ in $T_{\text{eff}}$ (typical differences between various determinations; cf. Takeda et al. 2005, 2008), $\pm 0.1\text{ dex in log } g$ (typical differences between spectroscopic log $g$ and directly determined log $g$ as adopted in this study; cf. Takeda et al. 2005, 2008), and $\pm 20\%$ in $v_t$ (typical scatter around the analytical formula used by us). We call these six kinds of abundance variations as $\delta_T$, $\delta_g$, $\delta_v$, $\delta_T$, $\delta_g$, and $\delta_v$, respectively.

5.4 Trend of each error source
These abundance errors derived in the last three subsections $\{[(\delta A_-, \delta A_+), (-\sigma_A, +\sigma_A), (\delta T_+, \delta T_-), (\delta g_+, \delta g_-), (\delta v_+, \delta v_-)]\}$ along with equivalent widths (EW) are graphically shown as functions of $T_{\text{eff}}$ in figures 8 (O), 9 (Fe), and 10 (Ni). We can see from these figures the following trends:

— The noise-related errors $\delta A$ or $\sigma_A$ are quantitatively more significant than the parameter-related ones in the present case.
— Reflecting the fact that they are of the same origin, $|\delta A|$ and $\sigma_A$ are almost of the same extent, though the former tends to be somewhat larger than the latter.
— Regarding the parameter-related errors, $\delta_T$ values are more or less appreciable (particularly for O in red giants), $\delta_g$ values are negligibly small, and $\delta_v$ values are important only for Fe and Ni (especially in red giants).
— The extents of (negative) non-LTE correction for O $\simeq 0.1\text{ dex (red giants)}$ and $\sim 0.4–0.5\text{ dex (turn-off stars)}$. 

Fig. 5. Synthetic spectrum fitting in the 7770–7792Å region comprising O: 7771.94, 7774.17, 7775.39, Fe: 7780.55, and Ni: 7788.94 lines. The best-fitting theoretical spectra are shown by blue solid lines. The observed data are plotted by red symbols connected by lines, where those rejected in the fitting are highlighted in green. The spectra of M 67 stars are arranged (from top to bottom) in the order of increasing $T_{\text{eff}}$. Note that the ordinate scale is twice as large in the left-hand panel (giant stars) as in the right-hand panel (non-giant stars). For the A(O)-indeterminable cases of S 1288 and S 1056, the theoretical spectra shown here were simulated with the fixed oxygen abundances at the metallicity-scaled solar composition. (Color online)
For evaluating the total error budget, we adopt $\sigma_A$ (which is more preferable than $\delta A$ from the viewpoint of authenticity in the derivation procedure) for $S/N$-related error and $\delta_{T \text{eff}} [\equiv (\delta_T^2 + \delta_g^2 + \delta_v^2)^{1/2}]$ for parameter-related error (where $\delta_T$ is the average of $|\delta_{T+}|$ and $|\delta_{T-}|$; and the same applies also for $\delta_g$ and $\delta_v$). That is, we regard $\pm \sqrt{\sigma_A^2 + \delta_{T \text{eff}}^2}$ as the error bars attached to the abundance results obtained in section 4 (cf. table 2). Our final abundances of O, Fe, and Ni (with such estimated error bars) are plotted against $T_{\text{eff}}$ in figure 11, where the results for Pollux, Procyon and the Sun are shown for comparison.

### 6 Discussion

#### 6.1 Abundances of Fe and Ni

We first review the abundances of Fe and Ni (iron-group elements representative of the metallicity) for M 67 stars shown in figures 11b and 11c. Dividing all 16 stars into a giant group ($T_{\text{eff}} < 5000$ K; nine stars) and a non-giant group ($T_{\text{eff}} > 5000$ K; seven stars), we obtain $\langle A(\text{Fe}) \rangle_{\text{giant}} = 7.57(\pm 0.39)$, $\langle A(\text{Fe}) \rangle_{\text{non-giant}} = 7.61(\pm 0.58)$, and $\langle A(\text{Fe}) \rangle_{\text{all}} = 7.59(\pm 0.44)$ as the averaged abundances of Fe for each group (values in parentheses after $\pm$ are the standard deviations). Meanwhile, the results for Ni are $\langle A(\text{Ni}) \rangle_{\text{giant}} = 6.40(\pm 0.43)$, $\langle A(\text{Ni}) \rangle_{\text{non-giant}} = 6.44(\pm 0.55)$, and $\langle A(\text{Ni}) \rangle_{\text{all}} = 6.42(\pm 0.47)$. These results suggest that (i) $A(\text{Fe})$ and $A(\text{Ni})$ do not show any systematic dependence upon $T_{\text{eff}}$, and (ii) they are more or less consistent with those of the standard stars (Pollux, Procyon, and the Sun) within the dispersion, which can also be recognized by eye-inspection of figures 11b and 11c, even though appreciable scatters amounting to $\pm 0.4–0.5$ dex are seen. Accordingly, we may state that the derived abundances of Fe and Ni for M 67 stars do not show any systematic trend, which does not contradict the uniformity in
Fig. 7. Histogram of oxygen abundance deviations, which are defined as the differences between the apparent $A_{\text{H}}(\text{O})$ solutions (resulting from the fitting-analysis of 100 mock spectra with artificial noise; cf. figure 6) and the given $A_{\text{H}}(\text{O})$ used for modeling of the standard spectrum.

the metallicity within this cluster. This, in turn, may imply that the atmospheric parameters which we assigned to each star are almost reasonable.

6.2 O abundances in M 67: almost uniform but one exception

Our non-LTE oxygen abundances, which are plotted against $T_{\text{eff}}$ in figure 11a, appear to show nearly the same trend seen for Fe and Ni (figures 11b and 11c). That is, $A(\text{O})$ values do not show any systematic dependence upon $T_{\text{eff}}$ and are almost consistent with those of standard stars, which means that almost the same argument as given in subsection 6.1 may hold also for this case of oxygen. We notice, however, that only one star ($S 1054$) exhibits an anomalously low $A(\text{O})$ (deviating by $\sim 1$ dex from the mean of other M 67 stars). Excluding this $S 1054$, we obtain $\langle A(\text{O}) \rangle$ (giant but $S 1054$) = $8.55(\pm 0.19)$, $\langle A(\text{O}) \rangle$ (non-giant) = $8.63(\pm 0.46)$, and $\langle A(\text{O}) \rangle$ (all but $S 1054$) = $8.59(\pm 0.33)$.$^8$

Such derived mean abundance ($\sim 8.6$) is reasonably consistent with those of Pollux (8.43), Procyon (8.84), and the Sun (8.60) within $\lesssim 0.2$ dex. Accordingly, we may conclude that atmospheric oxygen abundances of M 67 stars studied by us are almost uniform (with one exception) at the near-solar composition,$^9$ irrespective of the evolutionary phase from unevolved turn-off stars through well-evolved red giants. This may be regarded as a significant consequence, given $8$ That the abundance dispersion in the non-giant group ($0.46$ dex) is appreciably larger than that in the giant group ($0.19$ dex) is apparently due to the poor spectrum quality for the former (note that we had to use data with $S/N$ ratios as low as $\sim 20–30$; cf. table 1).

$9$ Regarding two stars ($S 1288$ and $S 1056$), for which $A(\text{O})$ could not be determined, their spectrum feature at the position of O lines (severely affected by noise) does not contradict the normal oxygen composition, as shown in figure 5, where we assumed [O/Fe] = 0 as fixed for these two stars.
that the O I line strengths in our M 67 samples widely differ from each other (by a factor amounting up to ∼10; cf. figure 8a).

6.3 On the nature of S 1054

The outlier behavior of A(O) for S 1054 is curious. Is this an unusual star compared to other M 67 members? While Sandquist (2004) classified this star as “RGB binary?”, its position on the Hertzsprung–Russell diagram is not peculiar as compared to other red giants, which makes it less likely that this star actually is an unresolved binary. This argument is substantiated by the fact that its heliocentric radial velocities (\(V_{hel}\)) at 20 different dates over the time span of ∼5400 d reported by Mathieu et al. (1986) are quite stable; i.e., \(\langle V_{hel}\rangle = 33.5\) km s\(^{-1}\) with a standard deviation of only 0.4 km s\(^{-1}\). Besides, it is almost without doubt that S 1054 is a M 67 member, as this \(\langle V_{hel}\rangle\) is reasonably consistent with those of other such members. Accordingly, we cannot help considering that S 1054 is an ordinary red giant star of M 67. Then, how should we interpret its markedly low \(A(O)\) (7.37) compared with the others (∼8.6 on the average)? Here, we should recall that the error accompanying the \(A(O)\) value of S 1054 derived in subsection 5.4 is appreciably large as \(\pm 0.50 \equiv \pm \sqrt{\sigma_A^2 + \delta_A^2}\) despite that the spectrum S/N ratio of ∼100 is sufficiently high, because the O I 7771–5 lines are considerably weak. Therefore, the disagreement of ∼1.2 dex corresponds to ∼2.4 \(\sigma\), which means that a small probability of a few per cent still remains.
6.4 Does evolution-induced mixing have impact on surface oxygen in red giants?

Let us discuss the implication of this result from the viewpoint of our original motivation (i.e., to check the theoretical prediction in comparison with the observational fact). According to the recent calculation of Lagarde et al. (2012), the logarithmic oxygen abundance ratio \([\text{O}/\text{H}]\) of a solar-metallicity 1.25-\(M_\odot\) star at the red-giant phase is only \(-0.001\) (case 1: standard recipe) and \(-0.0013\) (case 2: including thermohaline convection and rotation-induced mixing); i.e., essentially unaffected by the mixing of H-burning products for both of the cases considered by them. In this sense, our observational consequence (no meaningful difference between the O abundances of evolved red giants and unevolved or less evolved stars) is fully consistent with such theoretical expectations, as far as the present case of a \(\sim 1.3\)-\(M_\odot\) star is concerned.

However, little can be said about higher mass stars based on our result alone. The apparent deficiency of O \((-0.5 \lesssim \text{[O/Fe]} \lesssim 0\) reported by Takeda, Sato, and Murata (2008; cf. figure 12 therein), which appears to be enhanced with mass and correlated with a deficit in C \((-0.5 \lesssim \text{[C/Fe]} \lesssim 0\) as well as an overabundance of Na \(0 \lesssim \text{[C/Fe]} \lesssim 0.4\), was actually derived from red...
gigants of low- through intermediate-mass (1 ≤ M ≤ 5 M⊙).

While Lagarde et al.’s (2012) calculations for solar-metallicity stars suggest a mass-dependent O deficiency ([O/H] = −0.004/−0.02, −0.03/−0.04, −0.04/−0.05, −0.07/−0.07 corresponding to case 1/case 2 for 2, 3, 4, and 6 M⊙, respectively), its extent is marginal and evidently insufficient to account for the trend suggested from Takeda, Sato, and Murata’s (2008) analysis based on the [O i] 5577 line. Whether or not the theoretical prediction also reasonably explains the oxygen abundances for red giants of higher-mass (∼2–5 M⊙) is yet to be investigated. (However, notable progress has recently been made regarding this issue. See Note added in proof appended at the end of this paper.)

6.5 Comparison with previous studies

Finally, we review the results of ([O/H]) (mean of M 67 stars) obtained in this study with comparison to the published data, which are summarized in Table 5. We can recognize from this table that both of our ([O/H]) (giants) and ([O/H]) (non-giants) are ~0.0 and thus consistent with the previous results based on high-quality data obtained by larger telescopes. Yet, we also note that the apparent star-to-star dispersion (standard deviation) of our O abundances is considerably large (0.19 dex for giants excepting S 1054 and 0.46 dex for non-giants) compared to literature values (mostly <0.1 dex). This is apparently due to large errors involved in our abundance analysis where considerably low-quality data had to be invoked, which stems from the fact that our telescope and equipment were comparatively powerless from the viewpoint of the present-day standard.

As mentioned in section 1, it was our alternative aim to check how much information can be gained from our rather noisy spectra of medium resolution. We must admit here that the results we obtained are evidently insufficient for quantitatively discussing the detailed nature of abundances within the cluster (e.g., such as pursuing the degree of chemical homogeneity). We consider, however, that our study could serve as a useful pilot study to clarify the general qualitative tendency (e.g., consistency between the giant and non-giant groups at near-solar oxygen abundances) or to suggest an interesting candidate (S 1054) which may possibly have a peculiar oxygen composition. At any rate, we would stress the necessity of verifying what has been implied in this study, based on new observational data of much higher quality.

7 Conclusion

Despite the considerable progress in the study of abundance changes in the surface of red giants caused by evolution-induced dredge-up of nuclear-processed material, no consensus has ever been accomplished yet about whether oxygen is significantly affected by such envelope mixing.

Give that the best approach to check if surface abundances suffer appreciable changes on the way to the red giant phase is to investigate cluster stars formed with the same composition, we carried out a spectroscopic study for 16 selected stars of M 67 in various evolutionary stages from the turn-off point through the red giant branch,
along with Pollux, Procyon, and the Sun (Ganymede) as reference stars.

The observations were done by using the 2-m NAYUTA telescope and the MALLS spectrograph at the Nishi-Harima Astronomical Observatory, by which we could obtain moderate-dispersion (R ~ 12000) spectra (centered around ~ 7700–7800 Å) for each star.

The atmospheric parameters were evaluated photometrically from colors (T eff), directly from mass and radius (log g), and by using empirical formulas (v t).

We determined the oxygen abundances based on the synthetic spectrum-fitting in the 7770–7792 Å region comprising O I 7771–5, Fe I 7780, and Ni I 7788 lines. The non-LTE correction was further taken into account for deriving the final O abundances.

In estimating abundance ambiguities involved in our analysis, errors due to noise as well as due to uncertainties in the adopted atmospheric parameters were taken into consideration. Regarding noise-related errors, we tried two independent determinations (application of a conventional formula to EW values and simulation by using many mock spectra with artificial noise) and compared with each other.

The abundances of Fe and Ni obtained as by-products were found to be roughly consistent with each other (though with a rather large dispersion) without any systematic trend.

It turned out that the mean oxygen abundances of M 67 stars are quite similar between the giant (T eff < 5000 K) and non-giant (T eff > 5000 K) groups at the near-solar composition (with only one exception of S 1054 which shows a marked O deficiency by ~ 1 dex).

This result implies that oxygen content in the stellar envelope is almost unaffected by the mixing of H-burning products in the red-giant phase, as far as M 67 stars of low mass (~ 1.3 M⊙) are concerned, which is in agreement with the prediction from the conventional stellar evolution theory of first dredge-up.

S 1054 is a puzzling object. Although we cannot completely exclude the possibility that its considerably low O-abundance is spurious (i.e., simply due to random fluctuation), a more detailed re-analysis based on high-quality data is needed.

The results we obtained based on rather noisy spectra of medium resolution (reflecting our use of a smaller telescope) are not sufficient for quantitatively discussing the detailed nature of abundances within the cluster. Still, our study may be regarded as useful for a pilot study to clarify the general qualitative behavior of O abundances in M 67.

Note added in proof (2015 February 23):

Very recently, Takeda et al. (2015) revisited the oxygen abundance problem in red giants and found that the [O I] 5577 line are likely to be inadequately underestimated because the blending of C2 molecular lines was not taken into account in their analysis. That is, since the importance of this blending effect is appreciably different between the C-normal reference Sun and C-deficient red giants, this neglect could have caused an appreciable systematic error in the differential analysis. Accordingly, Takeda et al. (2015) concluded that the surface oxygen abundances of red giant stars practically retain their original composition (in reasonable consistency with the conventional theory of stellar evolution), while retracting the suggestion once made by Takeda, Sato, and Murata (2008).

Acknowledgments

This research has made use of the SIMBAD database (operated at CDS, Strasbourg, France) as well as the WEBDA database (operated at the Department of Theoretical Physics and Astrophysics of the Masaryk University).

References

Alonso, A., Arribas, S., & Martínez-Roger, C. 1995, A&A, 297, 197
Alonso, A., Arribas, S., & Martínez-Roger, C. 1996, A&A, 313, 873
Alonso, A., Arribas, S., & Martínez-Roger, C. 1999, A&AS, 140, 261 [Erratum: 376, 1039]
Brown, J. A. 1985, ApJ, 297, 233
Cayrel, R. 1988, in IAU Symp. 132, The Impact of Very High S/N Spectroscopy on Stellar Physics, ed. Cayrel de Strobel, G., & Spite, M. (Dordrecht: Kluwer Academic Publishers), 345
Demarque, P., Woo, J.-H., Kim, Y.-C., & Sukyoung, K. 2004, ApJS, 155, 667
Eriksson, K., & Toft, S. C. 1979, A&A, 71, 178
Kurucz, R. L. 1993, Kurucz CD-ROM, No. 13, ATLAS9 Stellar Atmosphere Programs and 2 km/s Grid (Cambridge, MA: Harvard-Smithsonian Center for Astrophysics)
Kurucz, R. L., & Bell, B. 1995, Kurucz CD-ROM, No. 23 Atomic Line Data (Cambridge, MA: Harvard-Smithsonian Center for Astrophysics)
Kurucz, R. L., & Peytermann, E. 1975, Smithsonian Astrophys. Obs. Spec. Rept., No. 362
Lagarde, N., Decressin, T., Charbonnel, C., Eggenberger, P., Ekström, S., & Palacios, A. 2012, A&A, 543, A108
Mathieu, R. D., Latham, D. W., Griffin, R. F., & Gunn, J. E. 1986, AJ, 92, 1100
Mermilliod, J.-C. 1995, in Information & On-Line Data in Astronomy, ed. D. Greet & M. A. Albrecht (Dordrecht: Kluwer Academic Publishers), 127
Mishenina, T. V., Bienaymé, O., Gorbaneva, T. I., Charbonnel, C., Soubiran, C., Korotin, S. A., & Kovtyukh, V. V. 2006, A&A, 456, 1109
Ozaki, S., & Tokimasa, N. 2005, Annu. Rep. Nishi-Harima Astron. Obs., 15, 15 (in Japanese)
Pace, G., Pasquini, L., & François, P. 2008, A&A, 489, 403
Pancino, E., Carrera, R., Rossetti, E., & Gallart, C. 2010, A&A, 511, A56
Randich, S., Sestito, P., Primas, F., Pallavicini, R., & Pasquini, L. 2006, A&A, 450, 557

Note added in proof (2015 February 23):

Very recently, Takeda et al. (2015) revisited the oxygen abundance problem in red giants and found that the [O I] 5577 line are likely to be inadequately underestimated because the blending of C2 molecular lines was not taken into account in their analysis. That is, since the importance of this blending effect is appreciably different between the C-normal reference Sun and C-deficient red giants, this neglect could have caused an appreciable systematic error in the differential analysis. Accordingly, Takeda et al. (2015) concluded that the surface oxygen abundances of red giant stars practically retain their original composition (in reasonable consistency with the conventional theory of stellar evolution), while retracting the suggestion once made by Takeda, Sato, and Murata (2008).
Sanders, W. L. 1977, A&AS, 27, 89
Sandquist, E. L. 2004, MNRAS, 347, 101
Shetrone, M. D., & Sandquist, E. L. 2000, AJ, 120, 1913
Takeda, Y. 1995, PASJ, 47, 287
Takeda, Y. 2003, A&A, 402, 343
Takeda, Y., Honda, S., Ohnishi, T., Ohkubo, M., Hirata, R., & Sadakane, K. 2013, PASJ, 65, 53
Takeda, Y., Kawanomoto, S., & Sadakane, K. 1998, PASJ, 50, 97
Takeda, Y., Ohkubo, M., Sato, B., Kambe, E., & Sadakane, K. 2005, PASJ, 57, 27 [Erratum: 57, 415]
Takeda, Y., & Sadakane, K. 1997, PASJ, 49, 367
Takeda, Y., Sato, B., & Murata, D. 2008, PASJ, 60, 781
Takeda, Y., Sato, B., Omiya, M., & Harakawa, H. 2015, PASJ, 67, 24
Tautvaisiene, G., Edvardsson, B., Puzeras, E., Barisevičius, G., & Ilyin, I. 2010, MNRAS, 409, 1213
Tautvaisiene, G., Edvardsson, B., Tuominen, I., & Ilyin, I. 2000, A&A, 360, 499
Yong, D., Carney, B. W., & Teixeira de Almeida, M. L. 2005, AJ, 130, 597