HIGH-RESOLUTION SPECTROSCOPY OF EXTREMELY METAL-POOR STARS FROM SDSS/SEGUE. II. BINARY FRACTION

WAKO AOKI 1,2, TAKUMA SUDA 1,3, TIMOTHY C. BEERS 4, and SATOSHI HONDA 5

1 National Astronomical Observatory, Mitaka, Tokyo 181-8588, Japan; aoki.wako@nao.ac.jp, takuma.suda@nao.ac.jp
2 Department of Astronomical Science, School of Physical Sciences, The Graduate University of Advanced Studies (SOKENDAI), 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
3 Research Center for the Early Universe, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
4 Department of Physics and JINA Center for the Evolution of the Elements, University of Notre Dame, 225 Nieuwland Science Hall, Notre Dame, IN 46656, USA; tbeers@nd.edu
5 Center for Astronomy, University of Hyogo, 407-2, Nishigaiachi, Sayo-cho, Sayo, Hyogo 679-5313, Japan; honda@nhao.jp

Received 2014 July 24; accepted 2014 September 19; published 2015 January 7

ABSTRACT

The fraction of binary systems in various stellar populations of the Galaxy and the distribution of their orbital parameters are important but not well-determined factors in studies of star formation, stellar evolution, and Galactic chemical evolution. While observational studies have been carried out for a large sample of nearby stars, including some metal-poor Population II stars, almost no constraints on the binary nature for extremely metal-poor (EMP; [Fe/H] < −3.0) stars have yet been obtained. Here we investigate the fraction of double-lined spectroscopic binaries and carbon-enhanced metal-poor (CEMP) stars, many of which could have formed as pairs of low-mass and intermediate-mass stars, to estimate the lower limit of the fraction of binary systems having short periods. The estimate is based on a sample of very metal-poor stars selected from the Sloan Digital Sky Survey and observed at high spectral resolution in a previous study by Aoki et al. That survey reported 3 double-lined spectroscopic binaries and 11 CEMP stars, which we consider along with a sample of EMP stars from the literature compiled in the SAGA database. We have conducted measurements of the velocity components for stacked absorption features of different spectral lines for each double-lined spectroscopic binary. Our estimate indicates that the fraction of binary stars having orbital periods shorter than 1000 days is at least 10%, and possibly as high as 20% if the majority of CEMP stars are formed in such short-period binaries. This result suggests that the period distribution of EMP binary systems is biased toward short periods, unless the binary fraction of low-mass EMP stars is significantly higher than that of other nearby stars.

Key words: binaries: general – Galaxy: halo – stars: abundances – stars: Population II

1. INTRODUCTION

Understanding the nature of the first generation of stars born in the Galaxy, at zero metallicity, is a key requirement for exploration of the formation of structure, stellar evolution, nucleosynthesis, and chemical evolution in the early universe. While searches for metal-poor stars in the Milky Way and its satellite galaxies have detected a large number of stars with very low metallicity, no object with zero metallicity has yet been found (Beers & Christlieb 2005; Frebel & Norris 2013; Keller et al. 2014). This might indicate that only intermediate-to high-mass stars were formed from metal-free gas clouds, which would have already exploded as supernovae or evolved to white dwarfs. Indeed, recent numerical simulation of star formation from gas clouds with no metals predict that the typical mass of first stars to be several tens of solar masses or higher (e.g., Hirano et al. 2014; Susa et al. 2014).

Some models of star formation from metal-free gas clouds, however, predict the possible formation of low-mass stars (e.g., Nakamura & Umemura 2002). Among such studies, the formation of low-mass stars as multiple systems has also been investigated. For example, Machida (2008) predicted that the binary frequency is higher in low-mass stars formed from gas clouds with extremely low metallicity because the probability of fragmentation is larger at lower metallicity, even with expected smaller rotation energy of such clouds. A high frequency of binaries with short periods is also predicted.

The importance of obtaining observational estimates of the binary fraction of stars is generally recognized. In addition to the studies of stars in the Solar neighborhood (e.g., Duquennoy & Mayor 1991), the binary nature of metal-poor stars has been investigated by multi-epoch spectroscopic approaches (e.g., Carney et al. 1994; Jorissen et al. 1998; Goldberg et al. 2002) and by speckle interferometric observations of relatively wide systems (e.g., Rastegaev 2010).

However, there is almost no constraint on the binary frequency for extremely metal-poor (EMP; [Fe/H] < −3.0) stars, which might be compared with theoretical predictions for the low-mass stellar binary formation at zero or extremely low metallicity. Although the number of known EMP stars has been greatly increased by recent large spectroscopic surveys, it will take some time to obtain a full estimate of their binary fraction based on radial-velocity monitoring studies, as have already been carried out for less metal-poor stars (Carney et al. 1994; Latham et al. 2002).

In this paper, we estimate a lower limit on the binary fraction for EMP stars based on the frequency of double-lined spectroscopic binaries and carbon-enhanced metal-poor (CEMP) stars exhibiting overabundances of heavy neutron-capture elements (the CEMP-s stars; Beers & Christlieb 2005). We investigate the sample of very metal-poor stars reported by Aoki et al. (2013, hereafter Paper I), who obtained high-resolution spectra for 137 stars selected from the Sloan Digital Sky Survey (SDSS; York et al. 2000) and the stellar sub-survey SEGUE (Yanny et al. 2009), providing a homogeneous sample of very metal-poor stars with [Fe/H] < −2.5, particularly near the main-sequence turnoff. We also consider samples...
of double-lined spectroscopic binaries and CEMP-s stars reported in literature, based on the SAGA database compilation (Suda et al. 2008). Although the sample size of EMP stars is still insufficient for deriving definitive conclusions, this is the first attempt to provide a constraint on their binary frequency and orbital periods.

2. DOUBLE-LINED SPECTROSCOPIC BINARIES

The sample discussed in Paper I includes three double-lined spectroscopic binaries. The velocity components of these systems are analyzed in Section 2.1 below.

In order to estimate the fraction of binaries among EMP stars, we investigate the detection probability of double-lined spectroscopic binaries as a function of the quality of our spectra for stars close to the main-sequence turnoff (Sections 2.2 and 2.3). For this purpose, the sample is modeled using stellar density distributions based on isochrones, assuming an initial mass function and adopting an appropriate stellar age (Section 2.3.2).

2.1. Double-lined Spectroscopic Binaries in the SDSS/SEGUE Subaru Sample

The three double-lined spectroscopic binaries found in Paper I are listed in Table 1. Two spectra obtained at different epochs are available for each object, including the spectrum of SDSS J0817+2641 studied by Aoki et al. (2008). The quality of the data obtained by the "snapshot" spectroscopy technique (which employs shorter exposure times than most high-resolution followup approaches) is only moderate signal-to-noise ratio (S/N ~ 30). In order to measure the velocity components of the systems, we stacked absorption features of different spectral lines. The spectral lines used in this analysis are Mg I λ 5172.68 Å, Mg I λ 5183.60 Å, Fe I λ 4383.55 Å, Ca I λ 4226.73 Å, and Ba II λ 4554.03 Å. The lines used for the stacking of each spectrum are listed in the table. Note that the Ba II line was used only for the first-epoch spectrum of SDSS J0817+2641. The Ca I, Fe I, and Ba II lines were not used for the second-epoch spectrum of this object because the data quality at shorter wavelengths was not sufficient.

Figure 1 shows the stacked spectra for individual exposures. We identified two or three components in these spectra. The velocity difference from the primary component, which is indicated as “A” in the figure, were measured for each spectrum. The spectrum of SDSS J1108+1747, obtained on 2008 March 8, exhibits three components, indicating that this is (at least) a triple system. The other spectrum of this star, obtained on 2008 March 10, exhibits only two components. A comparison of line strengths found in the two spectra indicates that one of the two velocity components, B or C, overlaps the primary, A, in the 2008 March 10 spectrum. The heliocentric radial velocities of individual components measured for the stacked spectra are given in Table 1.

The properties of these stars are summarized in Table 2. The effective temperature ($T_{\text{eff}}$) and the iron abundances are taken from Paper I. The $T_{\text{eff}}$ is approximately that of the primary star, as discussed in Paper I. Assuming similar spectral features for the two or three components in a given system, the ratios of the line strengths (depths) in Figure 1 approximately indicate that the luminosity ratios of the components are smaller than 4/1. According to theoretical isochrones of metal-poor stars (e.g., Kim et al. 2002), this luminosity ratio corresponds to a pair of main-sequence stars having a 400 K difference in $T_{\text{eff}}$, or a stellar pair comprising a subgiant and a main-sequence star having almost the same effective temperature.

The above situation is demonstrated by Aoki et al. (2012) for the double-lined spectroscopic binary G 166−45, which is a very metal-poor ([Fe/H] = −2.5) system of two main-sequence stars with 6300 and 5900 K, with similar colors to SDSS J1410+5350. Figure 2 of Aoki et al. (2012) shows that there are two cases of a main-sequence stars’ pair and a pair of main-sequence and subgiant stars that satisfy the system’s color as well as the mass ratio determined by long-term radial-velocity monitoring of the system (Goldberg et al. 2002). Although the mass ratio of the binary SDSS J1410+5350 is still unknown, we estimate that the system consists of two main-sequence stars with $T_{\text{eff}} = 6300$ K and 5800 K, or of a subgiant primary with 5900 K and a main-sequence secondary with 6500 K. The combined synthetic spectra of the Mg I λ 5183.6 Å line for the two cases of the system is shown in Figure 2, adopting the flux ratio of 4/1 as estimated from the isochrone for very low metallicity (Figure 3). Both cases account well for the observed spectrum and are not distinguished by the current data quality. This indicates that the above approach to estimate the components of the binary system is basically appropriate, although the stellar parameters of the two stars in the system are not fully constrained by the fitting. In the case of a subgiant–main-sequence pair, the mass ratio is about 0.9, while it is closer to unity in the case of a pair of main-sequence stars. The Mg abundance assumed in the calculation of the synthetic spectra is log ε(Mg) = 4.9([Mg/H] = −2.7). Adopting [Mg/Fe] = +0.56 estimated for SDSS J1410+5350 by Aoki et al. (2013), this object is confirmed to be extremely metal-poor ([Fe/H] < −3).

### Table 1

| Object     | Object Name               | Obs. Date    | $V_{\text{helio}}$ (km s$^{-1}$) | #1  | #2  | #3  |
|------------|---------------------------|--------------|----------------------------------|-----|-----|-----|
| SDSS J0817+2641 | SDSS J081754.93+264103.8 | 2007 Feb 10  | −0.6                       | +73.5 | ... | 1,2,3,5 |
| SDSS J0817+2641 | SDSS J081754.93+264103.8 | 2008 Mar 10  | +2.7                       | +72.0 | ... | 1,2,3,5 |
| SDSS J1410+5350 | SDSS J141001.77+53018.2  | 2008 Mar 8   | −88.7                      | −25.4 | −9.27 | 1,2,3,4 |
| SDSS J1410+5350 | SDSS J141001.77+53018.2  | 2008 Mar 10  | −28.4                      | −70.6 | ... | 1,2,3,4 |
| SDSS J1108+1747 | SDSS J110821.68+174746.6 | 2008 Mar 8   | −138.6                     | −164.5 | ... | 1,2,3,4 |
| SDSS J1108+1747 | SDSS J110821.68+174746.6 | 2008 Mar 10  | −135.1                     | −168.4 | ... | 1,2,3,4 |

* 1: Mg I λ 5172.68 Å; 2: Mg I λ 5183.60 Å; 3: Fe I λ 4383.55 Å; 4: Ca I λ 4226.73 Å; 5: Ba II λ 4554.03 Å.
Assuming a binary system with equal masses and zero eccentricity as the simplest case, the two components would exhibit a radial velocity variation with sine curves of the same amplitude. The fraction of the orbital phase during which the velocity difference between the two components is larger than 10 km s\(^{-1}\) is greater than 50% if the amplitude (of each component) is larger than 7.5 km s\(^{-1}\). The corresponding orbital periods are about 1000 days or shorter. Hence, the double-lined spectroscopic binaries detectable in our sample have rather small separations (at most several AU). If a larger eccentricity is assumed, binary systems having longer periods are detectable near their periastron. However, the fraction of the orbital phase during which the velocity difference becomes large is limited and the probability of detecting such systems is small.

### 2.3. Detection Probability: Luminosity Ratios

#### 2.3.1. Detectable Luminosity Ratios

Another requirement to detect a double-lined spectroscopic binary is that the flux ratio between the two components is not so large that the absorption lines in the spectrum of the secondary are completely swamped by continuum light from the primary. In our spectra, with S/N of 25–30, absorption lines with depths of 6%–8% are clearly identifiable. Assuming the strengths of deep absorption features, such as the Mg I b lines (intrinsic absorption depth of ∼50%) are the same between the two components, we can identify a double-lined spectroscopic binary when the ratio of continuum flux between the primary and secondary is 5/1 or smaller. Indeed, the continuum flux ratios estimated for the three binaries in our sample are 4/1 or smaller. Since the two components should have similar spectral types when they are observed as a double-lined spectroscopic binary, the flux ratio should be a good approximation of the luminosity ratio (see Section 2.1).

In the following subsections, the probability of detecting binary systems based on stellar models that can explain the distribution of effective temperatures of stars in our sample is explored.

#### 2.3.2. Stellar Models

Since the luminosity of a red giant is very sensitive to the mass for a given stellar age, the probability of finding a double-lined spectroscopic binary for red giants is negligible. Hence, we here estimate the probability of detecting a double-lined spectroscopic binary for turnoff stars as a function of \(T_{\text{eff}}\), adopting the stellar models of Kim et al. (2002).

For the first step, we estimate the probability of observing objects as a function of evolutionary stages among turnoff stars. Figure 3 (upper panel) shows the isochrones of Kim et al. (2002) for [Fe/H] = -3.0, with enhanced \(\alpha\)-elements for the ages of 13 and 15.5 Gyr. The probability of observing objects in a flux-limited sample is proportional to \(N \times L^{3/2}\), where \(N\) and \(L\) indicate the stellar number density (calculated assuming a Salpeter initial mass function) and stellar luminosity (here we ignore bolometric corrections).

The probability is calculated for each \(T_{\text{eff}}\) bin of 250 K for \(T_{\text{eff}} > 5500\) K. Since main-sequence stars and subgiants are not distinguished for our turnoff sample, we sum up the probabilities for the two cases for each \(T_{\text{eff}}\) bin. We note that the probabilities to observe main-sequence stars and subgiants are comparable for \(T_{\text{eff}} \geq 6000\) K, while the probability of
observing subgiants is significantly higher than main-sequence stars for lower temperatures (see below).

The lower panel of Figure 3 shows the results of the above estimates for two cases of stellar ages (the solid line: 15.5 Gyr; the dotted line: 13 Gyr). As seen from their comparison, the distribution of the highest \( T_{\text{eff}} \) bin is sensitive to the adopted age for the isochrone. The fraction of observed objects as a function of \( T_{\text{eff}} \) in our sample are shown by filled circles. We find that the distribution for the 15.5 Gyr case agrees well with the observed data for \( T_{\text{eff}} \geq 6000 \) K. Hence, we here adopt the 15.5 Gyr isochrone for the following estimates of the detection probability for double-lined spectroscopic binaries. We note that although this age is higher than the currently adopted age of the universe (~13.8 Gyr; Planck Collaboration et al. 2014), there could well be systematic offsets in the calculations of stellar evolution and/or in the estimates of \( T_{\text{eff}} \) for our sample, which are not of consequence for the current discussion. We also note that the number of stars with \( T_{\text{eff}} < 6000 \) K in our sample is smaller than expected from the number of objects with \( T_{\text{eff}} > 6000 \) K and the probability distribution. Since, in our flux-limited sample, subgiants are expected to dominate main-sequence stars in this temperature range, this result indicates that subgiants with \( T_{\text{eff}} < 6000 \) K are deficient in our sample compared to the prediction. This could, however, also be due to the bias that our original sample of Paper I includes a relatively small number of giants compared to turnoff stars, which also partially affects the numbers of subgiants in the sample.

### References

(1) Paper I, (2) Aoki et al. (2008), (3) Spite et al. (2000), (4) Norris et al. (2000), (5) González Hernández et al. (2008), (6) Aoki et al. (2009), (7) Sbordone et al. (2010), (8) Depagne et al. (2000).

---

**Table 2**

| Object            | Position (R.A., Decl.) | \( V_0 \) | \( T_{\text{eff}}(K) \) | [Fe/H] | \( \Delta v \) (km s\(^{-1}\)) | Remarks\textsuperscript{a} |
|-------------------|------------------------|----------|-------------------------|--------|-----------------------------|---------------------------|
| **Objects in the SDSS/SEGUE Subaru Sample** |
| SDSS J0817+2641   | 08:17:54.93 +26:41:03.8 | 16.012   | 6050                    | −2.85  | 69−70                       | 1, 2                      |
| SDSS J1108+1747   | 11:08:21.68 +17:47:46.6 | 15.525   | 6050                    | −3.17  | 42−79                       | 1                         |
| SDSS J1410+5350   | 14:10:01.77 +53:50:18.2 | 16.015   | 6100                    | −3.42  | 23−33                       | 1                         |
| **Objects from the Literature (SAGA Database)** |
| CS 22873−139      | 20:05:55.15 −59:17:11.4 | 13.83    | 6300                    | −3.37  | 53                          | \( P = 19.166 \) days; 3  |
| CS 22876−032      | 00:07:37.46 −35:31:16.7 | 12.84    | 6500                    | −3.66  | 32                          | \( P = 425 \) days; 4, 5  |
| HE 1148+0037      | 11:51:49.8 +00:54:11.1  | 13.61    | 5900                    | −3.51  | 15                          | 6, 7                      |
| HE 1353−2735      | 13:56:42.53 −27:49:54.0 | 14.7     | 5900                    | −3.2   | 30                          | 8                         |

\textsuperscript{a} References. (1) Paper I, (2) Aoki et al. (2008), (3) Spite et al. (2000), (4) Norris et al. (2000), (5) González Hernández et al. (2008), (6) Aoki et al. (2009), (7) Sbordone et al. (2010), (8) Depagne et al. (2000).
The fraction of detected double-lined spectroscopic binaries in our turnoff sample is 2.84 ± 1.69% (3 objects among 109 stars). Although the sample size is still too small to derive any definitive conclusion, here we attempt to give a constraint on the binary fraction of EMP stars.

Given the above estimate for detection probability (Section 2.3), the fraction of binaries in which the secondary is also a turnoff star is ∼5%–6%. Taking into account the orbital phase for which the binary system is detectable (Section 2.2), this fraction could be as high as 10%. This value indicates the fraction of binary systems that have similar masses and orbital period of about 1000 days or shorter.

If a random distribution of the inclinations of binary systems, relative to the line-of-sight (θ), is assumed, a correction of the detection probability is estimated to be \( \int_0^{\pi/2} \cos \theta d\theta \int_0^{T_{\text{eff}} \text{bin}} \cos \theta d\theta = 2\pi T_{\text{eff}} \). Hence, the correction to the fraction of binary systems is the inverse of this ratio, about 3/2.

On the other hand, the fraction of binary systems in a flux-limited sample could be enhanced by the effect that a binary system that is not spatially resolved is brighter than a single star that has the same brightness of the primary star (Opik effect: Trimble 1990). If we assume that the contribution of the secondary star to the flux in the optical bands (e.g., the SDSS g band) is typically 30% of the primary, the volume covered by the flux-limited sample is \( 1.33/2 \sim 1.5 \). Hence, the correction to the fraction of binary systems is about two-thirds, which is mostly compensated for by the correction for the effect of inclination.

The estimate is dependent on the assumption of the eccentricity of binary systems. However, the typical eccentricity (e) of binaries with P < 1000 days is 0.3 (Duquennoy & Mayor 1991), and the fraction of stars that have e > 0.5 is quite small (see also Goldberg et al. 2002). Hence, the effect of the eccentricity assumed in the estimate should not have a significant impact.

The estimate is also dependent on the assumption of the mass distribution of secondaries. The secondary stars considered here are, however, turnoff stars that have masses from 0.58 to 0.76 M☉. Hence, the result does not significantly change unless there is a very sharp change of the mass ratio within such a small mass range. Our calculation limits the lower mass of the secondary to be 0.58 M☉ because we here consider only turnoff stars. If lower-mass stars are included as possible secondaries, the probability of detecting the secondary as a component of a double-lined spectroscopic binary in our observation would become higher for cooler main-sequence cases. However, as the fraction of such objects included in our sample is small, the effect is also not expected to be large.

### 2.4. The Fraction of Double-lined Spectroscopic Binaries

2.3.3. Probability to Detect Double-lined Spectroscopic Binaries

We now estimate the probability of detecting double-lined spectroscopic binaries as a function of \( T_{\text{eff}} \) of the primary star, assuming a flat (constant) mass distribution of the secondary. Under this assumption, the probability is just the fraction of the mass range that satisfies the secondary luminosity criterion (one-fifth of the primary; see above). To simplify the calculation, we here consider \( T_{\text{eff}} > 5375 \text{ K} \) for both the primary and secondary.

The probability estimated for each \( T_{\text{eff}} \) bin (for the primary) is given in Table 3. The result is given separately for the main-sequence and subgiant cases. The probability becomes lower with increasing luminosity of the primary. Since the luminosity of a subgiant is significantly higher than a main-sequence star, the mass range of the secondary detectable as a double-lined spectroscopic binary is narrower. This results in a lower probability for cooler subgiants. We also give the fractions of main-sequence and subgiant stars expected to be included in each \( T_{\text{eff}} \) bin, which are proportional to \( N \times L^{3/2} \) (see above). The combined probability for main-sequence and subgiant stars, weighted by the fractions of each, is given for each \( T_{\text{eff}} \) bin (see the table section labeled “Total”). While the probability of detecting the secondary as a component of a double-lined spectroscopic binary is higher for cooler main-sequence stars, the fraction of main-sequence stars in a \( T_{\text{eff}} \) bin is lower than that of subgiants. As a result, the highest probability is found in the \( T_{\text{eff}} \) bins for 6000 and 6250 K. Indeed, the three double-lined spectroscopic binaries found in our sample have \( T_{\text{eff}} \geq 5500 \text{ K} \), as well as having the required short period.

#### Table 3: Probabilities to Detect Double-lined Spectroscopic Binaries

| \( T_{\text{eff}} \) (K) | 5500 | 5750 | 6000 | 6250 | 6500 |
|------------------------|------|------|------|------|------|
| probability\(^a\)       | 1.00 | 1.00 | 1.00 | 0.92 | 0.59 |
| fraction\(^b\)          | 0.13 | 0.35 | 0.52 | 0.55 | 0.47 |

\(^a\) The probability of detecting a double-lined spectroscopic binary that has a turnoff star as secondary.

\(^b\) The fraction of main-sequence or subgiant stars among the listed \( T_{\text{eff}} \) bin.

3. CARBON-ENHANCED METAL-POOR STARS

The above estimate assumes that the currently observed object includes two (or more) stars, the primary and secondary, that are still shining. However, when performing counts of the frequency of low-mass star binaries, one should also account for systems in which we are now observing the erstwhile secondary star, those that had companions of higher mass that have already evolved to become faint white dwarfs. In general, to estimate the fraction of such objects, long-term monitoring for radial-velocity variations is required. However, another useful probe for such systems is the chemical peculiarity of...
stars, particularly the observed excesses of carbon and neutron-capture elements, which would be expected to be provided by mass transfer to the currently observed star from a companion asymptotic giant branch (AGB) star in a relatively close orbit. At very low metallicities, these stars are known as CEMP-s stars (Beers & Christlieb 2005). The initial mass of AGB stars that most efficiently yield s-process elements are estimated to be 1–3 \( M_\odot \) (Busso et al. 1999), although the operation of the s-process in EMP stars is still under discussion (e.g., Suda et al. 2004; Lugaro et al. 2012).

As reported in Paper I, 9 turnoff stars and 2 red giants turned out to be CEMP-s stars in our total sample of 137 very metal-poor stars. These objects are listed in Table 4. The fraction is about 8\%, both for turnoff stars and giants. This is a lower limit on the fraction of CEMP-s stars because moderately carbon-enhanced (warm) turnoff stars cannot be readily identified by our snapshot spectroscopy.

Most of the CEMP-s stars exhibit very large enhancements of carbon ([C/H] \( \geq \)) in order to explain such large carbon excesses by mass transfer from an AGB star across a binary system, the binary separation would be expected to be relatively short (\( \lesssim 10 \) AU; see Figure 8 of Komiya et al. 2007). The lower limit on the separation of the binary system required to form CEMP-s stars is estimated to be 0.2–1 AU. If the separation was smaller, mass transfer by Roche-lobe overflow would occur before the primary had evolved to an AGB star.

A recent study of the binary nature of CEMP stars (Starkenburg et al. 2014) confirms that almost all CEMP-s stars can be regarded as binaries, with average orbital periods 400–600 days. Hence, our sample of turnoff stars includes binaries with periods < 3000 days (possibly < 1000 days), in which the companion has already evolved to a white dwarf with a fraction of 8\% (or higher).

### Table 4

| Object Name/Position (R.A., Decl.) | \( V_0 \) | \( T_{\text{eff}} \) (K) | [Fe/H] | [C/H] | [Ba/Fe] | Remarks* |
|-----------------------------------|----------|------------------------|--------|-------|---------|----------|
| SDSS J0002+2928                   |          | 6150                   | −3.26  | −0.63 | 1.84    | 1        |
| SDSS J0126+0607                   |          | 6900                   | −3.01  | +0.07 | 3.20    | 1        |
| SDSS J0711+6702                   |          | 5350                   | −2.91  | −0.97 | 0.82    | 1        |
| SDSS J0912+0216                   |          | 6150                   | −2.68  | −0.63 | 1.30    | 1        |
| SDSS J1036+1212                   |          | 5850                   | −3.47  | −1.63 | 1.35    | 1        |
| SDSS J1245+0738                   |          | 6100                   | −3.16  | −0.63 | 2.09    | 1        |
| SDSS J1349+0229                   |          | 6200                   | −3.24  | −0.23 | 2.25    | 1        |
| SDSS J1626+1458                   |          | 6400                   | −2.99  | −0.13 | 1.69    | 1        |
| SDSS J1646+2824                   |          | 6100                   | −3.05  | −0.53 | 1.78    | 1        |
| SDSS J1734+4316                   |          | 5200                   | −2.51  | −0.73 | 1.61    | 1        |
| SDSS J1836+6317                   |          | 5350                   | −2.85  | −0.83 | 2.37    | 1        |

*References. (1) Paper I, (2) Lai et al. (2008), (3) Aoki et al. (2007), (4) Sivarani et al. (2006), (5) Cohen et al. (2006), (6) Aoki et al. (2008), (7) Behara et al. (2010).

### 4. BINARY STARS REPORTED IN THE LITERATURE

We now inspect the frequencies of double-lined spectroscopic binaries and CEMP-s stars with extremely low metallicity, based on the sample of EMP stars included in the SAGA database (Suda et al. 2008), which is a compilation of stars with elemental-abundance data obtained from high-resolution spectroscopy. The version of the SAGA database from which we obtained the sample used for the present study contain data published by 2012. We note that the sample of Paper I was not included in the version of SAGA.

In the SAGA database, we found 82 stars with [Fe/H] < −3.0 and \( T_{\text{eff}} > 5500 \) K, which represent main-sequence turnoff EMP stars. Among them, four double-lined spectroscopic binaries have been identified (Table 2). This fraction (4/82) is comparable to, but somewhat higher than, that in our SDSS/SEGUE Subaru sample (3/109). The reason for the higher fraction found for the SAGA sample might be that high-resolution observations have been repeated for some EMP stars included in the SAGA database, while the bulk of the sample in Paper I is based on a single-epoch observation. That is, if the spectrum of a SDSS/SEGUE Subaru star did not exhibit a clear signature of it being a double-lined spectroscopic binary in the first-epoch observation, it did not receive a second-epoch observation, resulting in our possibly missing some of the bonafide double-lined binaries. If we change the metallicity criterion from [Fe/H] < −3.0 to [Fe/H] < −2.7, the total number of stars increases to 156, but the number of known double-lined spectroscopic binaries does not change. We also suspect that double-lined binaries are sometimes excluded by studies of the chemical abundances of EMP stars due to the...
added complexity (and uncertainty) of the analysis. Further complete assessment of the sample of previously observed stars, including data not published, would be quite useful for obtaining a more accurate estimate of the fraction of double-lined spectroscopic binaries.

There are 149 stars with [Fe/H] < −3 for which [C/Fe] is determined in the SAGA database. There are eight CEMP-s stars with [Fe/H] < −3 among them (Table 4). The fraction (8/149) is comparable to that in our SDSS/SEGUE Subaru sample (11/137). We note that we adopt a criterion of [Fe/H] < −3 in the sample selection from the SAGA database, while the sample of Paper I includes objects with slightly higher metallicity, and indeed five stars among the 11 CEMP-s stars have [Fe/H] > −3. The fraction of CEMP-s stars among the entire sample of CEMP stars is known to be lower in the metallicity regime [Fe/H] < −3, in which the CEMP-no\(^6\) stars dominate (Aoki et al. 2007). The fractions of CEMP-s stars for [Fe/H] < −2.7 and < −2.5 are 25/272 and 39/364, respectively, which are as high as that found for our SDSS/SEGUE Subaru sample.

5. DISCUSSION AND CONCLUSIONS

We have detected three double-lined spectroscopic binaries among the 109 main-sequence turnoff stars studied in Paper I. The frequency of low-mass star binary systems having comparable masses is estimated to be around 10%. Although the sample size is still small, the result is supported by the fraction of double-lined spectroscopic binaries among EMP turnoff stars in the SAGA database (4/82). The orbital periods of these binary systems would be shorter than about 1000 days. In addition, the fraction of CEMP-s stars, which would originally have had low-mass (typically 1.5 M\(_{\odot}\); Busso et al. 1999) star companions, is near 10% in both our Paper I sample and in the SAGA sample. Although the estimate of binary separations (orbital periods) of such CEMP-s stars are dependent on the assumption of the mass transfer and surface mixing of these stars, they could also be short (P < 3000 days), taking into account their high [C/H] ratios (Table 4). Additional measurements of orbital periods for these objects, based on radial-velocity monitoring, is strongly desired.

The binary frequency of metal-rich stars in the Solar neighborhood is estimated to be about 50% or higher, although that is not yet considered well determined. Dzuennouy & Mayor (1991) reported that the fraction of multiple stars in their sample (164 primary stars) is 43%, and the period distribution is unimodal with a median period of 180 years. According to their results, the fraction of binary systems with period shorter than 1000 days is around 10%. The fraction of such short-period binaries among EMP stars estimated above is already as high as 10%, even though the searches for such binaries are clearly incomplete.

Concerning Population II stars, Goldberg et al. (2002) reported 34 double-lined spectroscopic binaries among the 1464 high proper motion stars selected by Carney et al. (1994) (the Carney–Latham sample). A total of 31 systems among these 34 have periods shorter than 1000 days, and the remaining 3 have large eccentricity. The simple fraction is 34/1464 (~2.5%). About half of the double-lined spectroscopic binaries of Goldberg et al. (2002) are, however, cool main-sequence stars (T\(_{\text{eff}}\) < \(\sim\) 5250 K). Such objects are not well covered in previous studies for very/extremely low-metallicity stars such as studied in Paper I. On the other hand, we also need to take into account the fraction of turnoff stars, having T\(_{\text{eff}}\) \(\sim\) 5500 K, included in the Carney–Latham sample, which is estimated to be about half, according to Table 6 of Carney et al. (1994). Hence, if the sample is limited to turnoff stars, the fraction of double-lined spectroscopic binaries is also about 2%–3% in the Carney–Latham sample.

For the Carney–Latham sample, Latham et al. (2002) reported 181 single-lined spectroscopic binaries based on their long-term radial velocity monitoring survey and concluded that the binary fraction among halo stars was not lower than found for disk stars. The fraction of binaries with P < 1000 days is about 10%. While binaries with long periods (P > 10,000 days) are not well-sampled by their study, their survey should be close to complete for shorter periods. The fraction of short-period binaries in EMP stars is already as high or higher than that of the Carney–Latham sample, even though the searches for short-period binaries of EMP stars is still incomplete. This suggests that the high fraction of short-period binaries could be a unique property found for EMP stars.

One possible interpretation of the high fraction of short-period binaries among EMP stars is simply that the binary fraction for EMP stars is generally higher compared with metal-rich stars. This hypothesis can be examined only by future investigations of wider binaries. Another possibility is that the period distribution of binary systems among EMP stars is biased toward shorter periods, as has been suggested by Rastegaev (2010) for metal-poor stars (but not for EMP stars). Further long-term radial velocity monitoring or imaging studies with high spatial resolution to distinguish binary components for EMP stars are required to derive more definitive conclusions about the period distributions of EMP binaries.

Numerical simulations of low-mass star formation from gas clouds with various metallicities by Machida (2008) demonstrate that the fragmentation of clouds, which results in the formation of multiple stellar systems, tends to occur in the clouds that have larger initial rotational energy. The simulations indicate that the initial rotational energy required for fragmentation depends on the metallicity of the clouds. Fragmentation occurs in clouds with smaller rotational energy at lower metallicity because adiabatic cores form at later phases of evolution in the clouds with lower metallicity. As a result, binary (and multiple) systems with short periods are formed with higher frequency at low metallicity and the total fraction of binary systems becomes higher. The high fraction of binary systems with short periods among the EMP stars suggested by the present work might well be accounted for by this effect.

We note that although a metallicity dependence of the binary nature of stars has not been observed for more metal-rich populations (Latham et al. 2002), the metallicity range that has been previously inspected is [Fe/H] \(\gtrsim\) − 2, higher than our EMP stellar sample. Further exploration of the properties of binary systems in metal-poor stars, including the EMP population, is clearly desired.

This work is based on data collected at the Subaru Telescope, which is operated by the National Astronomical Observatory of Japan. The data obtained with Subaru/HDS are

---

\(^6\) CEMP-no stars are defined as CEMP stars without enhancements of neutron-capture elements; see Beers & Christlieb (2005). CEMP-no stars are not expected to be associated with mass-transfer events; see Norris et al. (2013); Hansen et al. (2014); Starkenburg et al. (2014), and Andersen et al. (2015, in preparation).
available on the Subaru Mitaka Okayama Kiso Archive system (SMOKA: http://smoka.nao.ac.jp). W.A. and T.S. are supported by the JSPS Grant-in-Aid for Scientific Research (S:23224004). S.H. is supported by the JSPS Grant-in-Aid for Young Scientists (B:26400231). T.C.B. acknowledges partial support from grant PHY 08-22648: Physics Frontiers Center/Joint Institute for Nuclear Astrophysics (JINA), and PHY 14–30152; Physics Frontier Center/JINA Center for the Evolution of the Elements (JINA-CEE), awarded by the US National Science Foundation.

REFERENCES

Aoki, W., Barklem, P. S., Beers, T. C., et al. 2009, ApJ, 698, 1803
Aoki, W., Beers, T. C., Lee, Y. S., et al. 2013, AJ, 145, 13
Aoki, W., Beers, T. C., Christlieb, N., et al. 2007, ApJ, 655, 492
Aoki, W., Beers, T. C., Sivarani, T., et al. 2008, ApJ, 678, 1351
Aoki, W., Ito, H., & Tajitsu, A. 2012, ApJL, 751, L6
Beers, T. C., & Christlieb, N. 2005, ARA&A, 43, 531
Behara, N. T., Bonifacio, P., Ludwig, H.-G., et al. 2010, A&A, 513, A72
Busso, M., Gallino, R., & Wasserburg, G. J. 1999, ARA&A, 37, 239
Carney, B. W., Latham, D. W., Laird, J. B., & Aguilar, L. A. 1994, AJ, 107, 2240
Cohen, J. G., McWilliam, A., Shectman, S., et al. 2006, AJ, 132, 137
Depagne, E., Hill, V., Christlieb, N., & Primas, F. 2000, A&A, 364, L6
Duquennoy, A., & Mayor, M. 1991, A&A, 248, 485
Frebel, A., & Norris, J. E. 2013, in Planets, Stars and Stellar System, Vol. 5, ed. T. D. Oswalt, & G. Gilmore (Dordrecht: Springer Science+Business Media), 55
Goldberg, D., Mazeh, T., Latham, D. W., et al. 2002, AJ, 124, 1132
González Hernández, J. I., Bonifacio, P., Ludwig, H.-G., et al. 2008, A&A, 480, 233
Hansen, T., Hansen, C. J., Christlieb, N., et al. 2014, ApJ, 787, 162
Hirano, S., Hosokawa, T., Yoshida, N., et al. 2014, ApJ, 781, 60
Jorissen, A., van Eck, S., Mayor, M., & Udry, S. 1998, A&A, 332, 877
Keller, S. C., Bessell, M. S., Frebel, A., et al. 2014, Natur, 506, 463
Kim, Y.-C., Demarque, P., Yi, S. K., & Alexander, D. R. 2002, ApJS, 143, 499
Komiyama, Y., Suda, T., Minaguchi, H., et al. 2007, ApJ, 658, 367
Lai, D. K., Bolte, M., Johnson, J. A., et al. 2008, ApJ, 681, 1524
Latham, D. W., Stefanik, R. P., Torres, G., et al. 2002, AJ, 124, 1144
Lugaro, M., Karakas, A. I., Stancliffe, R. J., & Rijs, C. 2012, ApJ, 747, 28
Machida, M. N. 2008, ApJL, 682, L1
Nakamura, F., & Umemura, M. 2002, ApJ, 569, 549
Norris, J. E., Beers, T. C., & Ryan, S. G. 2000, ApJ, 540, 456
Norris, J. E., Bessell, M. S., Yong, D., et al. 2013, ApJ, 762, 28
Planck Collaboration, Ade, P. A. R., Aghanim, N., et al. 2014, A&A, 571, A1
Rastegaev, D. A. 2010, AJ, 140, 2013
Sbordone, L., Bonifacio, P., Caffau, E., et al. 2010, A&A, 522, A26
Sivarani, T., Beers, T. C., Bonifacio, P., et al. 2006, A&A, 459, 125
Spite, M., Depagne, E., Nordström, B., et al. 2000, A&A, 360, 1077
Starkenburg, E., Shetrone, M. D., McConnachie, A. W., & Venn, K. A. 2014, MNRAS, 441, 1217
Suda, T., Aikawa, M., Machida, M. N., Fujimoto, M. Y., & Iben, I., Jr. 2004, ApJ, 611, 476
Suda, T., Katsuta, Y., Yamada, S., et al. 2008, PASJ, 60, 1159
Susa, H., Hasegawa, K., & Tomiaga, N. 2014, ApJ, 792, 32
Trimble, V. 1990, MNRAS, 242, 79
Yanny, B., Rockosi, C. M., Newberg, H. J., et al. 2009, AJ, 137, 4377
York, D. G., Adelman, J., Anderson, J. E., et al. 2008, AJ, 120, 1579