

THE BINARY FREQUENCY AMONG CARBON-ENHANCED, *s*-PROCESS-RICH, METAL-POOR STARS^{1,2}

SARA LUCATELLO,^{2,3} STELIOS TSANGARIDES,⁴ TIMOTHY C. BEERS,⁵ EUGENIO CARRETTA,^{2,6}
RAFFAELE G. GRATTON,² AND SEAN G. RYAN⁴

Received 2004 April 7; accepted 2004 December 14

ABSTRACT

We discuss radial velocities for a sample of carbon-enhanced, *s*-process-rich, very metal-poor (CEMP-*s*) stars, analyzed with high-resolution spectroscopy obtained over multiple epochs. We find that $\sim 68\%$ of the stars in the sample show evidence of radial velocity variations. The expected detection fraction for these stars, adopting the measured binary fraction in the field ($\sim 60\%$) and assuming that they share the same period and eccentricity distribution, is $\sim 22\%$. Even if one assumes that the true binary fraction of these stars is 100%, the expected detection percentage is $\sim 36\%$. These values indicate that the binary fraction among CEMP-*s* stars is higher than the field binary fraction, suggesting that *all* of these objects are in double (or multiple) systems. The fact that the observed frequency of velocity variation exceeds the expected detection fraction in the case of an assumed binary fraction of 100% is likely due to a more restricted distribution of orbital periods for these objects, as compared to normal field binaries. Our results indicate that CEMP-*s* stars are the metal-poor analogs of classical CH stars.

Subject headings: binaries: spectroscopic — stars: AGB and post-AGB — stars: carbon — stars: chemically peculiar

1. INTRODUCTION

The most extensive spectroscopic surveys undertaken to date to identify large samples of very metal-poor stars, the HK survey (Beers et al. 1992; Beers 1999) and the Hamburg/ESO survey (HES; Christlieb et al. 2001a, 2001b; Christlieb 2003), have shown that carbon-enhanced, metal-poor (CEMP) stars (here taken to mean $[C/Fe] > 1.0$) account for up to $\sim 25\%$ of stars with metallicities lower than $[Fe/H] \sim -2.5$.⁷ Despite extensive investigations of this class of objects by means of high-resolution spectroscopy (e.g., Norris et al. 1997a, 1997b; Aoki et al. 2001, 2002a, 2002c, 2002d), the origin of carbon in these stars still remains unclear. The carbon enhancement phenomenon appears in stars that exhibit (at least) five different abundance patterns. A handful of CEMP stars have been identified with *no* enhancements in their *n*-capture elements (CEMP-*no* stars; Norris et al. 1997b; Aoki et al. 2002a), at least two of which (CS 29498-043, Aoki et al. 2002b; CS 22949-037, Depagne et al. 2002) also appear to exhibit large enhancements in N, O, and the α -elements, while a single case of a highly *r*-process-enhanced CEMP star, CS 22892-052 (Snedden et al. 2003b and references therein), has been noted (CEMP-*r* star). There also exist several objects that, together with very pronounced *s*-process enrichment, exhibit an overabundance in Eu with respect to the *s*-process models' predictions, so that they have been claimed to have been enriched by both the *r*- and *s*-process (see, e.g., Cohen et al. 2003). By far the most nu-

merous class is represented by CEMP stars characterized by *s*-process element enrichments (CEMP-*s* stars). Several CEMP-*s* stars have been studied with high-resolution, high signal-to-noise ratio spectroscopy (e.g., Aoki et al. 2001, 2002a, 2002d; Johnson & Bolte 2002; Lucatello et al. 2003; Sivarani et al. 2004). Aoki et al. (2003) recently found, on the basis of a sample of 33 CEMP stars, that over 70% of their objects with $[Fe/H] < -2.5$ are characterized by *s*-process element enrichment.

The differences between these five classes suggest that the mechanisms responsible for the carbon enrichment in these objects might well be associated with different astrophysical scenarios. While the number of CEMP-*no* and CEMP-*r* stars is still small, making proposed enrichment scenarios difficult to explicitly test, the number of well-studied CEMP-*s* stars (~ 30 so far) provides a reasonable sample for a statistical analysis of their binary status, which we undertake in this paper.

One of the scenarios proposed to explain CEMP-*s* stars is that they are the formed by a mechanism that is analogous to that invoked for the origin of the Ba II, classical CH, and subgiant CH stars. The Ba II stars have low velocities and high metallicities (see, e.g., Jorissen et al. 1998), while the classical CH giants exhibit high velocities and are metal-poor (see, e.g., Bond 1974); these giants are not sufficiently luminous to be asymptotic giant branch (AGB) stars. Both classes exhibit enhancements in C and *s*-process elements. Subgiant CH stars, discovered by Bond (1974), are characterized by a similarly peculiar abundance pattern and are thought to be progenitors of moderately metal-deficient Ba II stars (Luck & Bond 1991). Systematic spectroscopic studies have shown that essentially all of these stars are members of binary systems (see, e.g., McClure & Woodsworth 1990). Hence, the scenario invoked to account for the observed chemical peculiarities in stars of these evolutionary states is that of accretion of material synthesized by a more massive intermediate-mass companion star during its AGB phase. Such mass transfer can take place via Roche lobe overflow (more likely in objects with shorter periods; see Han et al. 1995) or wind accretion (longer periods). The detection of the expected white dwarf companion stars (see, e.g., Böhm-Vitense 1980; Dominy & Lambert 1983;

¹ Based in part on observations collected at the European Southern Observatory, Paranal, Chile (ESO Programme 167.D-0173).

² INAF-Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio 5, I-35122 Padova, Italy.

³ Dipartimento di Astronomia, Università di Padova, Vicolo dell'Osservatorio 2, I-35122 Padova, Italy.

⁴ Open University, Milton Keynes, MK7 6AA, UK.

⁵ Department of Physics and Astronomy and JINA: Joint Institute for Nuclear Astrophysics, Michigan State University, East Lansing, MI 48824-1116.

⁶ INAF-Osservatorio Astronomico di Bologna, via Ranzani 1, I-40127 Bologna, Italy.

⁷ Note that $[A/B] = \log(N_A/N_B) - \log(N_A/N_B)_\odot$.

Böhm-Vitense & Johnson 1985) has provided further support for this scenario.

While there has been speculation that CEMP-*s* stars might be the metal-poor equivalent of the classical CH stars (Preston & Sneden 2001; Sneden et al. 2003a), conclusive evidence in support of this hypothesis has not yet been presented. Recent theoretical results (e.g., Fujimoto et al. 2000; Schlattl et al. 2002) suggest that low-mass, extremely metal-poor stars evolve into carbon stars along paths that are quite different from those followed by more metal-rich stars of younger populations. Carbon may well be produced through an additional (different) mechanism at low metallicity, e.g., extra mixing at the onset of the He flash. Hence, in order to understand the formation mechanism of CEMP-*s* stars, it is crucial to first establish whether these objects are all members of binary systems.

2. SAMPLE DEFINITION AND OBSERVATIONS

We first set a few criteria for the selection of CEMP-*s* stars. The aim of these criteria is to clearly characterize the sample and differentiate it from the classical Ba II, CH, and subgiant CH stars. Thus, for our analysis we select stars with temperatures higher than 4800 K and surface gravities $\log g \geq 1.3$, in order to rule out likely cases of self-enrichment, which may apply to AGB stars (in any case, intermediate-mass, metal-poor AGB stars are not expected to be present in the Galactic halo, because of their comparatively rapid evolution). Moreover, we set a metallicity upper limit of $[\text{Fe}/\text{H}] = -1.8$, in order to distinguish CEMP-*s* stars from the classical CH stars, whose typical metallicities extend as low as -1.0 to -1.5 (see, e.g., Vanture 1992). Thus, our objects have a metallicity $[\text{Fe}/\text{H}]$ that is *at least* a factor of 2 less than that of classical CH stars. This separation is set to limit the sample to a metallicity range for which, as discussed, C production might possibly occur through different mechanisms. We also set a lower limit on C enhancement of 1 dex ($[\text{C}/\text{Fe}] \geq +1.0$). Among the stars that meet both criteria, we have selected those objects with clear evidence of *s*-process enrichment. The atmospheric parameters of the selected sample stars are listed in Table 1.

We have collected new observations for nine CEMP-*s* stars. The observations for two objects, CS 22956-028 and CS 29497-034, were obtained using UVES at the VLT Unit 2 (Kueyen). The resolving power of these spectra is $R = \lambda/\Delta\lambda \simeq 50,000$, and the spectral coverage ranges from 3600 to 4800 Å and from 5700 to 9500 Å, respectively, in the blue and red arms; the slit width was fixed at 1". The extraction and reduction was performed using the standard UVES pipeline.

The remaining seven objects, CS 22880-074, CS 22898-027, CS 29526-110, CS 30301-015, HD 196944, LP 625-44, and LP 706-7, were observed as part of a larger program to monitor the radial velocities of candidate and confirmed CEMP stars and to calculate abundance patterns for the former (S. Tsangarides 2005, in preparation). The observations are described in detail in that document and are only briefly summarized here. Three high-resolution echelle spectrographs were used in six observing runs for this program: the (now decommissioned) Utrecht Echelle Spectrograph (UES; Unger et al. 1993) of the William Herschel Telescope (WHT), Spettrografo ad Alta Risoluzione Galileo (SARG; Gratton et al. 2001) of Telescopio Nazionale Galileo (TNG), and the University College London (Coudé) Echelle Spectrograph (UCLES; Walker & Diego 1985) of the Anglo-Australian Telescope (AAT). The spectra taken with these telescopes had resolving powers of $R = \lambda/\Delta\lambda \simeq 52,000$, 57,000 and 40,000, respectively. We set the slit widths to 1".1 (UES), 0".8 (SARG), and 1".5 (UCLES). The raw frames for the seven

TABLE 1
ATMOSPHERIC PARAMETERS FOR SAMPLE STARS

Star Identification	T_{eff} (K)	$\log g$	$[\text{Fe}/\text{H}]$	Reference
CS 22880-074	5850	3.8	-1.93	1
CS 22881-036	6200	4.0	-2.10	2
CS 22898-027	6250	3.7	-2.25	1
CS 22942-019	5000	2.6	-2.64	1
CS 22948-027	4800	1.8	-2.47	3
CS 22956-028	7035	4.5	-1.90	4
CS 29497-030	7050	4.2	-2.16	4
CS 29497-034	4980	2.1	-2.60	3
CS 29509-027	7050	4.2	-2.02	4
CS 29526-110	6500	3.1	-2.38	1
CS 30301-015	5250	1.8	-2.25	1
HD 196944	5250	1.7	-2.40	5
HD 198269	4800	1.3	-2.20	5
HD 201626	5190	2.3	-2.10	5
HD 224959	5200	1.9	-2.20	5
HE 0024-2523	6625	4.3	-2.72	6
HE 2148-1247	6380	3.9	-2.50	7
LP 625-44	5500	2.8	-2.71	8
LP 706-7	6600	3.8	-2.74	8

REFERENCES.—(1) Aoki et al. 2002c; (2) Preston & Sneden 2001; (3) Hill et al. 2000; (4) Sneden et al. 2003a; (5) Van Eck et al. 2003; (6) Lucatello et al. 2003; (7) Cohen et al. 2003; (8) Aoki et al. 2001.

objects were reduced in IRAF,⁸ using standard data reduction procedures. The reduced spectra cover 3550–5860 Å (UES), 3900–5140 Å (SARG), and 3750–4900 Å (UCLES).

3. OBSERVED BINARY FREQUENCY AMONG CEMP-*s* STARS

The radial velocities V_r for the UVES spectra were measured using a scheme based on the cross-correlation technique (Tonry & Davis 1979), which was developed to measure radial and rotational velocities for globular cluster dwarfs and subgiant stars; the typical error for these measurements is $\sim 0.2 \text{ km s}^{-1}$ for well-exposed spectra (Lucatello & Gratton 2003).

A detailed description of the procedure to measure the V_r values of the remaining seven sample stars is given in S. Tsangarides (2005, in preparation). Here we provide a brief outline. A cross-correlation technique was adopted for these objects as well; this uses the metal-poor ($-2.60 \leq [\text{Fe}/\text{H}] \leq -2.40$; Lambert & Allende Prieto 2002; Nissen et al. 2002; Aoki et al. 2002d), mildly carbon-enhanced ($0.22 \leq [\text{C}/\text{Fe}] \leq 0.6$; Tomkin et al. 1992; Norris et al. 1997a) subgiant HD 140283 as the template. A spectrum of this object with a signal-to-noise ratio greater than 80/1 was obtained for each of the runs during which the program stars were observed and was reduced according to the same data reduction procedures as the target spectra.

The geocentric radial velocity of HD 140283 provided the zero point for the heliocentric radial velocities we obtained for the seven objects. It was calculated from the observed spectra, as opposed to being adopted from the literature, by measuring the shift of several hundred metallic lines, which were carefully selected, discarding possible blends, clearly asymmetric lines, and very strong lines. The internal error of this calculation is

⁸ IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the United States National Science Foundation.

TABLE 2
OBSERVATION LOG AND MEASURED RADIAL VELOCITIES

Star Identification	MJD	Exposure Time (s)	Instrument	V_r (km s ⁻¹)
CS 22956-028	52,470.29	1800	UVES	24.60 ± 0.20
CS 29497-034	52,471.31	2700	UVES	-52.10 ± 0.40
CS 22880-074	52,391.72	1200	UES	59.29 ± 0.14
	52,419.65	1800	SARG	58.83 ± 0.22
	52,487.51	2100	UES	58.71 ± 0.26
CS 22898-027	52,151.49	2700	UES	-48.41 ± 0.11
	52,417.67	1200	SARG	-49.54 ± 0.25
	52,487.47	1200	UES	-48.78 ± 0.28
CS 29526-110	51,804.40	12600	UCLES	186.16 ± 0.19
	52,152.73	900	UES	201.83 ± 0.26
CS 30301-015	52,152.35	1200	UES	85.66 ± 0.12
	52,390.55	1800	UES	85.28 ± 0.14
HD 196944	52,419.72	300	SARG	-169.29 ± 0.08
	52,487.46	300	UES	-168.49 ± 0.11
LP 625-44	52,150.35	300	UES	28.06 ± 0.12
	52,390.68	450	UES	26.66 ± 0.10
	52,417.74	480	SARG	26.34 ± 0.30
	52,487.39	600	UES	27.48 ± 0.22
LP 706-7	52,150.75	300	UES	79.48 ± 0.15
	52,487.70	1200	UES	79.53 ± 0.17

given by dividing the standard deviation of individual lines by the number of lines used.

Finally, the heliocentric radial velocities of the spectra of the seven program stars were measured by cross-correlating them with the spectrum of HD 140283 using the IRAF task *fxcor* and then adding the appropriate heliocentric correction. This procedure produces a second internal error for each object's heliocentric radial velocity: the deviation of individual pairs of cross-correlated echelle orders. The errors reported in Table 2 are equivalent to the quadrature sum of the internal errors but do not take into account any systematic effects in the calculated velocity of HD 140283.

The heliocentric radial velocities measured for HD 140283 from each run range between -171.33 ± 0.08 and -170.63 ± 0.04 km s⁻¹. Latham et al. (2002) monitored HD 140283 for 3114 days with 19 observations and reported a mean radial velocity of -171.12 ± 0.29 km s⁻¹ for this object. The mean of our determinations, -170.98 ± 0.22 km s⁻¹, is in close agreement with the radial velocity reported by Latham et al. Thus, we estimate the systematic error affecting the radial velocity of the template to be 0.30 km s⁻¹.

Table 2 lists the observation log, the measured V_r values, and their estimated errors. Adding published data in the literature to our sample, we obtain a total of 19 CEMP-*s* stars with high-resolution, high signal-to-noise ratio spectroscopic analysis and multiepoch observations, with a minimum baseline of ~ 200 days. The sources of the literature data used in our sample are listed in column (7) of Table 3. Orbital solutions have been derived for several objects in our sample (see cols. [8] and [9] of Table 3). On the basis of these data, we calculate the χ^2 value for the radial velocity distribution,

$$\chi^2 = \sum_{i=1}^n \left(\frac{v_i - \bar{v}}{\sigma_{v_i}} \right)^2, \quad (1)$$

for each of the stars in the sample. Then, we compute the probability $P(\chi^2|f)$ that the V_r values obtained for the same stars

are compatible with different measurements of the same values, i.e., the probability that the observed scatter is due to observational errors, not the intrinsic variation of the measured physical quantity.

Preston & Sneden (2001) found that velocity errors derived from multiple observations of constant radial velocity giant stars are larger than the standard deviations for individual spectra by a factor of $\sim 2-3$. Some red giants are known to exhibit velocity “jitter” (Carney et al. 2003); however, this phenomenon appears to affect only stars within ~ 1 mag of the red giant tip, which, adopting an isochrone of metallicity of -2.3 and an age of 12 Gyr (Yi et al. 2003), corresponds approximately to $\log g \sim 1.1$. Our adopted limit on surface gravity of $\log g \geq 1.3$ should exclude such objects. We choose to multiply the σ values derived from our measurements (as well as those from the literature) by a factor of 3 to allow for systematic errors when comparing radial velocities from different sources. The factor of 3 is arbitrary and acts to reduce the number of binary detections; therefore, it is a conservative choice. It should be kept in mind that multiplying the measurement errors by this value distorts the χ^2 statistics toward higher values of P for constant radial velocity stars.

The typical errors quoted in the literature for the adopted V_r values are ~ 1 km s⁻¹. Table 3 lists the calculated values of χ^2 , degrees of freedom f (i.e., $f = n - 1$, where n is the number of observations), and $P(\chi^2|f)$ for each of the 19 CEMP-*s* stars. The quantity $Q(\chi^2|f) = 1 - P(\chi^2|f)$, i.e., the probability of the measurement scatter arising from intrinsic variation of radial velocity, is also listed.

Inspection of Table 3 shows that most of the stars in this sample have a very high probability of being radial velocity variables. The stars with derived orbital solutions are consistently found to have very low values of P (high values of Q), supporting the validity of our test. For such stars we list the derived orbital elements, along with their source, in Table 4. We consider the stars with positive identification of radial velocity variability to be those with $P < 0.01$ ($Q \geq 0.99$). Adopting this definition, the fraction of stars showing V_r variation in our sample is $68\% \pm 11\%$. The error has been computed using a binomial distribution. This value

TABLE 3
PROBABILITY OF RADIAL VELOCITY VARIATIONS

Star Identification (1)	Baseline (days) (2)	f (3)	χ^2 (4)	$P(\chi^2 f)$ (5)	$Q(\chi^2 f)$ (6)	References (7)	Orbital Solution? (8)	Reference (9)
CS 22880-074.....	3662	17	1.698	1.000	0.000	1, 2, 3	No	...
CS 22881-036.....	2561	13	1.645	1.000	0.006	4	No	...
CS 22898-027.....	4737	15	4.553	0.995	0.008	1, 2, 3	No	...
CS 22942-019.....	3665	15	118.234	0.000	1.000	1, 3	Yes	3
CS 22948-027.....	2560	23	42.733	0.007	0.993	4, 5, 6	Yes	3
CS 22956-028.....	3636	24	499.586	0.000	1.000	2, 4, 7	Yes	7
CS 29497-030.....	3313	16	69.791	0.000	1.000	4, 7	Yes	7
CS 29497-034.....	3020	9	48.512	0.000	1.000	2, 8, 9	Yes	9
CS 29509-027.....	351	2	40.914	0.000	1.000	7	Yes	7
CS 29526-110.....	348	2	314.863	0.000	0.994	1, 2	No	...
CS 30301-015.....	275	5	1.003	0.606	0.431	1, 2	No	...
HD 196944.....	683	4	47.579	0.000	1.000	1, 2, 10	No	...
HD 198269.....	2351	17	96.683	0.000	1.000	10, 11	Yes	11
HD 201626.....	3352	26	85.147	0.000	1.000	10, 11	Yes	11
HD 224959.....	2934	15	156.755	0.000	1.000	10, 11	Yes	11
HE 0024–2523.....	399	17	4955.382	0.000	1.000	12	Yes	12
HE 2148–1247.....	364	3	8.720	0.033	0.967	13	No	...
LP 625-44.....	5183	12	1088.632	0.000	1.000	2, 5, 14	No	...
LP 706-7.....	4433	7	8.428	0.296	0.704	2, 14	No	...

REFERENCES.—(1) Aoki et al. 2002c; (2) this work; (3) Preston & Sneden 2001; (4) Preston & Sneden 2000; (5) Aoki et al. 2001; (6) Aoki et al. 2002a; (7) Sneden et al. 2003a; (8) Hill et al. 2000; (9) Barbuy et al. 2005; (10) Van Eck et al. 2003; (11) McClure & Woodsworth 1990; (12) Lucatello et al. 2003; (13) Cohen et al. 2003; (14) Norris et al. 1997a.

is *not* compatible with the most recent estimates of the spectroscopic binary frequency among normal field stars, such as that found by Carney et al. (2003) for local metal-poor dwarfs and giants. In fact, these authors performed an analysis very similar to that used in this work, relying on the χ^2 statistic to discriminate V_r -variable stars from those with constant V_r , and found that a fraction of $\sim 17\%$ of stars exhibited detectable V_r variations. We stress that the comparison with the results obtained by Carney et al. is meaningful with the underlying assumption that the binary fraction among field stars is not dependent on metallicity. Strictly speaking, the observed CEMP-*s* binary frequency should be compared to that of C and *s*-process *normal* stars of similarly low metallicity. The binary fraction among stars at such a metallicity is still not well known. However, for the high-metallicity end of our sample ($[\text{Fe}/\text{H}] \sim -2.0$), it is quite similar to that found for stars of solar metal abundance (see, e.g., Carney et al. 2003; Zapatero Osorio & Martín 2004). We henceforth as-

sume that the binary fraction is independent of metallicity and thus adopt for the present discussion a value of $\sim 60\%$ (Jahreiss & Wielen 2000).

We must warn the reader of a potential bias that might affect our sample. When a star is suspected to be a V_r variable, the data might be published faster than those of an analogous star that does not exhibit variation. This would introduce a bias in favor of short-period objects and, in principle, in favor of binaries versus nonbinaries. This effect cannot be estimated quantitatively. However, in most cases the binarity of the objects in our sample could not be established on the basis of the data from a single author. Moreover, recently published results constitute only a small fraction of the data set. Therefore, this bias is expected to have a negligible impact on the final results of the present work.

We emphasize that the sample for this analysis was selected *exclusively* on the basis of metallicity, C enhancement, evolutionary status, and observational baseline without any a priori knowledge

TABLE 4
ORBITAL ELEMENTS FOR SAMPLE STARS

Star Identification	P (days)	K_1 (km s^{-1})	ω (deg)	JD_0	V_γ (km s^{-1})	e	Reference
CS 22942-019.....	2800	5.0	280	2,439,390	-237.7	0.10	1
CS 22948-027.....	505	4.0	78	2,448,110	-66.2	0.30	1
CS 22956-028.....	1290	8.5	266	2,448,831.0	34.0	0.22	2
CS 29497-030.....	342	4.1	120	2,448,500.0	45.0	0.00	2
CS 29497-034.....	4130	5.2	13	2,449,800	-47.5	0.02	3
CS 29509-027.....	194	3.8	194	2,448,624.0	74.2	0.15	2
HD 189269.....	1295	9.3	352	2,446,358	-203.39	0.094	4
HD 201626.....	407	12.1	...	2,445,858.3	-378.77	0	4
HD 224959.....	1273	9.0	10	2,446,064	-127.85	0.179	4
HE 0024–2523.....	3.41	51.9	...	2,452,059.596	-178.3	0	5

REFERENCES.—(1) Preston & Sneden 2001; (2) Sneden et al. 2003a; (3) Barbuy et al. 2005; (4) McClure & Woodsworth 1990; (5) Lucatello et al. 2003.

of their showing radial velocity variations and/or being known binaries.

4. SIMULATIONS

It is interesting to compare our reported results with the percentage of expected detectable binary stars for a given binary fraction that could be identified as such by our observational scheme. This is accomplished using a Monte Carlo simulation. We extract 10,000 data sets, each of which is randomly assigned to be either a V_r -constant or a V_r -variable star according to the input binary fraction.

For each of the binary stars, the orbital parameters are assigned randomly according to appropriate distributions. The orbital inclination i , the longitude at the ascending node ω , and the initial phase ν_0 have no preferred values; hence for each we assume a uniform distribution over the physically meaningful range of values, i.e., $[0, \pi/2]$, $[0, 2\pi]$, and $[0, 2\pi]$, respectively.

McClure & Woodsworth (1990) pointed out that the orbital solutions obtained for Ba II and classical CH stars indicate that their orbital eccentricity e is typically lower than those for systems containing C- and *s*-process element-*normal* stars, likely because of the mass transfer that has taken place in such objects. The adoption of an eccentricity distribution peaked at low values only marginally affects the simulations, slightly *decreasing* the detection probability. Our choice of a uniform distribution for e within the permitted range $[0, 1)$ is thus a *conservative* one.

For the orbital periods P we adopted the distribution observed by Duquennoy & Mayor (1991), which has been measured for field stars and has been adopted in order to compare them to CEMP-*s* stars. This distribution is characterized by $\log P = 4.8$ and $\sigma_{\log P} = 2.3$, where P is expressed in days. Given the fact that the longest observation baseline for our sample stars is only ~ 12 yr, allowing very long periods, such as could arise from the use of the full distribution (which peaks at ~ 120 yr), would only contribute to the noise. Therefore, we set an upper limit to the period distribution by discarding those values of P for which the expected orbital amplitude falls to one-third of the adopted velocity error ($\sim 0.3 \text{ km s}^{-1}$).

The value of the orbital semimajor axis a is fixed by the extracted period and the values set for the masses. We assume for the stars under analysis $M_1 = 1.0 M_\odot$ for the mass of the already evolved member of the pair, now likely to be a white dwarf, and $M_2 = 0.8 M_\odot$ for the mass of the observed (surviving) star. The choice of such a large value for M_1 provides conservative estimates of the likely detectable fraction of binaries. In fact, the use of such a mass, instead of $\sim 0.6 M_\odot$, which is probably more likely, results in a higher probability of radial velocity variation detection. Moreover, it must be kept in mind that while the choices for the values of the masses are reasonable, they are somewhat arbitrary. Fortunately, they do not considerably affect the value of a . The semimajor axis is proportional to the cube root of the sum of the masses; therefore, any choice of a pair of values within reasonable limits for the stars under analysis would have a small effect on the derived parameters.

For each of the simulated stars, either binary or single, we randomly select one of the observation patterns k ($1 \leq k \leq 19$), i.e., one of the 19 combinations of the j_k time intervals and measurement errors that was actually used for the k th star. For each of the simulated stars, on the basis of the orbital parameters and for each one of the time intervals in the selected observational pattern we calculate the expected values of V_r , to which we added an ‘‘observational error.’’ The latter is determined as a value randomly extracted on the basis of a normal distribution whose σ is the observational error attributed to the actual observation. Then,

TABLE 5
EXPECTED FRACTION OF V_r -VARIABLE STARS AS A FUNCTION
OF ADOPTED BINARY FRACTION

Binary Fraction	Detection Fraction
0.0.....	0.001
0.1.....	0.036
0.2.....	0.070
0.3.....	0.108
0.4.....	0.144
0.5.....	0.176
0.6.....	0.217
0.7.....	0.256
0.8.....	0.286
0.9.....	0.322
1.0.....	0.356

the values of χ^2 , $P(\chi^2|f)$, and $Q(\chi^2|f)$ for these simulated observations are calculated. For consideration of these simulations, we also take $P < 0.01$ as a positive detection of V_r variation, the same criterion used for our sample of real stars. Table 5 shows the result of this procedure, listing the percentage of the total number of stars detected as V_r variables with the described algorithm on the basis of the set criterion as a function of the input binary fraction.

As seen in Table 5, the percentage of V_r variables expected to be detected by our observational scheme, adopting, as discussed, the measured binary fraction in the field ($\sim 60\%$; Jahreiss & Wielen 2000), is $\sim 22\%$. This value is somewhat larger than the spectroscopic binary frequency measured by Carney et al. (2003), $\sim 17\%$ for metal-poor field stars. Nevertheless, the agreement is reasonable. The small difference with the Carney et al. value could be due to our assumption about the masses, as noted above. Moreover, it should be kept in mind that the simulations were performed on the basis of the observation patterns for our specific sample, which are different from the observational patterns of Carney et al. (2003).

The observed fraction of radial velocity variables, $68\% \pm 11\%$, is much larger than the value expected on the basis of our simulations for a binary fraction of 60%, as measured in the solar neighborhood. This indicates that the binary fraction among the CEMP-*s* stars in the sample under consideration is likely to be larger than that found among a randomly selected sample of metal-poor field stars.

Another possibility for explaining our finding is that the binary fraction among CEMP-*s* stars is similar to that found for normal halo field stars, $\sim 60\%$, but that the orbital period distribution for CEMP-*s* stars in double systems is different from that measured for binary field stars, peaking at much shorter values. For a detected binary fraction of $68\% \pm 11\%$, this would require a success rate in identifying binaries of $\geq 95\%$. To achieve such a high success rate with our observing pattern, the maximum period would have to be ~ 6 yr ($\log P = 3.4$), as Table 4 shows. We cannot, in principle, rule out a maximum period this short, which might be consistent with the enrichment scenario via wind accretion (Han et al. 1995). However, the fact that a couple of the periods determined for CEMP-*s* stars are considerably longer than this value argues against it. Moreover, under this scenario $\sim 40\%$ of the CEMP-*s* population must be nonbinary, and no plausible explanation exists for the chemical enrichment of the *s*-process elements in these systems, which would appear to be completely analogous to that due to binaries.

When the input binary fraction is set to 100%, the expected detection of V_r variables from our observational pattern rises to

TABLE 6
 EXPECTED FRACTION OF V_r -VARIABLE STARS FOR DIFFERENT PERIOD CUTOFFS

$\log(P)_{\max}$	$\log(P)_{\min}$						
	-1.0	-0.5	0.0	0.5	1.0	1.5	2.0
2.6.....	0.970	0.969	0.967	0.966	0.963	0.957	0.948
3.0.....	0.965	0.960	0.959	0.957	0.954	0.949	0.945
3.4.....	0.950	0.947	0.949	0.946	0.941	0.937	0.929
3.8.....	0.920	0.919	0.916	0.914	0.914	0.906	0.894
4.2.....	0.856	0.855	0.854	0.851	0.844	0.830	0.813
4.6.....	0.764	0.763	0.757	0.756	0.741	0.726	0.704
5.0.....	0.674	0.672	0.667	0.662	0.645	0.626	0.596
5.4.....	0.596	0.593	0.588	0.579	0.564	0.543	0.508
5.8.....	0.534	0.528	0.526	0.518	0.502	0.478	0.445
6.2.....	0.490	0.448	0.486	0.478	0.456	0.439	0.407
6.6.....	0.458	0.455	0.451	0.440	0.424	0.404	0.374

NOTES.—Results assuming that all CEMP-*s* stars are binaries. Period cutoffs are in days.

about 36% of the total. This arises because the observations collected so far for the sample under analysis have a baseline of *at most* ~ 12 yr (and in many cases much less), which is quite short, considering that the period distribution peaks at $\log P = 4.8$, i.e., ~ 120 yr. A considerable fraction of actual binaries have periods that are too long to result in detectable V_r variations using the available instruments over the time intervals explored.

5. ORBITAL PERIOD LIMITATIONS

The observational result of $68\% \pm 11\%$ radial velocity variables obtained from our sample exceeds the detection fraction even when all the stars in the simulation are assumed to be binaries. This is a further argument in favor of a binary scenario for the formation of CEMP-*s* stars.

This result leads to speculation about the period distribution of the stars under consideration. Most likely, *all* CEMP-*s* stars are in binary systems and owe their chemical peculiarities to the accretion of processed material from a post-AGB evolved companion. If this scenario is correct, the semimajor axis of their orbits (and therefore their orbital periods) must lie within the useful range of values in which such accretion processes are thought to take place. The separation *must* exceed the stellar radius of the presumed donating companion during its previous evolutionary phases. In fact, if the separation were smaller than the red giant branch (RGB) radius of the evolved companion, mass transfer would take place during that phase and affect subsequent evolution, preventing the donor star from undergoing its normal AGB phase. This phenomenon indeed exists and is referred to as the McCrea transfer mechanism (McCrea 1964); its outcome would likely be to convert the close pair of stars into a blue straggler. In fact, as shown by Carney et al. (2001), field blue stragglers share similar properties with Ba II stars, classical CH stars, and subgiant CH stars, i.e., they are members of long-period, low-eccentricity binaries, suggesting that mass transfer has been involved in their formation. Ryan et al. (2001, 2002) were led to a similar conclusion concerning field blue stragglers by considering the depletion of Li during a mass transfer episode and spin-up of the surviving star. However, in the present case it is necessary for the donor star to pass through its AGB phase in order for the *s*-process elements to be synthesized.⁹

On the other hand, the value of the orbital separation must be small enough to allow for capture of a sufficient amount of processed material to create the observed chemical enhancements in carbon and the *s*-process elements. A reasonable value for the lower limit can be set by adopting the RGB tip radius. Using the Y^2 (Yi et al. 2003) database and an α -enhanced isochrone, $[\alpha/\text{Fe}] = 0.3$ with $[\text{Fe}/\text{H}] = -2.5$, we obtain a value of ~ 0.5 AU, which in turn leads to a limit on $\log P$ of about -0.65 . The upper limit to the useful interval requires detailed modeling of the enrichment mechanism (see, e.g., Han et al. 1995) and depends on the evolutionary state of the accreting star. An approximate estimate for the most extreme value predicted by S. Cristallo (2005, in preparation) is $\log P \sim 5.4$; however, given the complexity of the assumptions involved, such a value must be considered as only a very rough estimate.

Table 6 shows the results of the same simulations described in § 4, but applying an orbital period cutoff. In other words, the Duquennoy & Mayor (1991) orbital period distribution was adopted, but the permitted values of $\log P$ are limited to ranges whose lower cutoffs range between $\log(P)_{\min} = -1.0$ and 2.0, while the upper ones are between $\log(P)_{\max} = 2.6$ and 6.6. It is important to keep in mind that the application of sharp cutoffs is only a very rough approximation. In fact, a more accurate approach would require the convolution of the period distribution function for binary field stars with theoretical Roche lobe overflow (for short periods) and wind (for long periods) accretion efficiencies, which would reflect the C and *s*-process enhancements as a function of the period. Thus, the period distribution for these objects would taper off, rather than truncate, at high values of $\log P$. However, we are not aware of the existence of any systematic accretion efficiency calculation, and therefore we adopt simple cutoffs for our simulations, which, although not strictly accurate, provides an interesting comparison with the observations.

According to our simulations, the fraction of binaries expected to be detected with the observational schemes used to observe the sample stars, assuming the period cutoffs discussed in the text ($-0.65 < \log P < 5.4$) along with the Duquennoy & Mayor (1991) distribution, is about 60%, compatible with the observed value. If the upper limit is shortened to 5.0 ($-0.65 < \log P < 5.0$), the expected binary detection fraction is 67%, very similar to our observational finding. This result does indeed partially depend on the fact that about half of the sample is made up of objects with derived orbital parameters and periods much shorter than typical values in the field population, as provided by the

⁹ C-enhanced, *s*-process-enhanced blue stragglers are known (Snedden et al. 2003a); Luck & Bond (1991) proposed that some of them evolve into subgiant CH stars.

Duquennoy & Mayor (1991) distribution. However, it should be noted that this is not a bias for the sample, as the objects were selected *only* on the basis of their chemical and evolutionary characteristics, with no previous knowledge of their binary status.

It should be noted that the predicted detection fraction values are much more sensitive to the adopted upper limit on the period than to the lower limit. In fact, a change of a factor of 100 in the upper cutoff, bringing it from $\log P = 6.2$ to 4.2, would increase the expected detection rate by over 40%, while moving the lower limit from 2.0 to 0.0 increases the fraction by less than 10%. This is not surprising, given that the adopted period distribution tails off to very small values for low values of $\log P$, while the upper cutoffs lie around the maximum of the distribution. Hence, the large observed binary fraction reflects (and constrains) the period distribution of CEMP-*s* stars primarily at the high end of the distribution of possible values. It is noteworthy that models predict that one of the effects of mass transfer is a lengthening of the orbital period. Therefore, it is expected that the original period distribution (i.e., before mass transfer took place) for these objects was likely shifted toward shorter values.

6. FORMATION SCENARIO FOR CEMP-*s* STARS

Analysis of a well-defined sample of CEMP-*s* stars has led to the identification of a binary fraction that exceeds that expected if the actual proportion of binaries in the sample were consistent with the measured binary fraction for field stars (Jahreiss & Wielen 2000). Our extensive simulations show that with our observational patterns, we should identify only $\sim 22\%$ (i.e., ~ 4 stars out of 19) as radial velocity variables, while we find that 14 stars out of 19 in our sample, $68\% \pm 11\%$, exhibit clear V_r variations. This value is larger than that expected even for the case in which the binary fraction of the population is 100%. This provides very strong evidence that the binary fraction among CEMP-*s* stars is higher than that found in the field, suggesting that in fact *all* of these objects are members of binary systems. We conclude that CEMP-*s* stars are indeed the metal-poor equivalents of the classical CH stars (McClure & Woodsworth 1990). Thus, the source of their chemical peculiarities is likely to be the accretion of material processed by the now evolved, more massive companion, which during or after its AGB phase transfers mass either via Roche lobe overflow or wind to the star we now observe as a CEMP-*s* object.

The discrepancy between the number of binaries identified in our sample and the expected numbers computed from simulations that assume a binary fraction of 100% and adopt the observed orbital period distribution of normal field stars (Duquennoy & Mayor 1991) may be of significance. Adopting the period range of $\log P$ between -0.65 and 5.0, we find that the expected number of identified binaries is much closer to that which is observed. While we make no claim that the true orbital period limits can be obtained using this method, the available data suggest that the measured period distribution of Duquennoy & Mayor (1991) is not appropriate for this class of stars; the true orbital distribution is likely peaked at shorter periods. This result is consistent with chemical enrichment via a mass transfer scenario. The orbital separation needs to be large enough to allow the donor star to undergo its AGB phase but small enough to allow the accretion to take place with sufficient efficiency to create the observed abundance patterns.

Long-term radial velocity monitoring will allow for a further test of our results, possibly leading to the determination of orbital elements for a wider sample of CEMP-*s* stars. With a sufficiently large sample, a statistical analysis of the orbital elements (see McClure 1983) could provide indications of the masses of the companions of the observed stars and test whether they are consistent with those typical of white dwarfs.

We are very grateful to our referee, Bruce Carney, for his comments and suggestions, which greatly improved this paper. The authors thank Norbert Christlieb, Judy Cohen, Sergio Cristallo, John Norris, and Oscar Straniero for useful discussion. S. L., R. G., and E. C. acknowledge partial support from the MURST COFIN 2001 and MURST COFIN 2002. S. T. gratefully acknowledges partial support from a UK Universities Overseas Research Student Award (ORS/2001031002) for his large Ph.D. program and a travel grant to the TNG provided by the European Commission through the “Access to Research Infrastructure Action” of the “Improving Human Potential Programme” awarded to the Instituto de Astrofísica de Canarias. T. C. B. acknowledges partial funding for this work from grants AST 00-98508, AST 00-98549, and AST 04-06784, as well as from grant PHY 02-16783, Physics Frontier Centers, JINA: Joint Institute for Nuclear Astrophysics, awarded by the US National Science Foundation.

REFERENCES

- Aoki, W., Norris, J. E., Ryan, S. G., Beers, T. C., & Ando, H. 2002a, *ApJ*, 567, 1166
 ———. 2002b, *ApJ*, 576, L141
 Aoki, W., Ryan, S. G., Norris, J. E., Beers, T. C., Ando, H., & Tsangarides, S. 2002c, *ApJ*, 580, 1149
 Aoki, W., Ryan, S. G., Tsangarides, S., Norris, J. E., Beers, T. C., & Ando, H. 2003, in IAU Gen. Assem. 25, Joint Discussion 15, Elemental Abundances in Old Stars and Damped Lyman- α Systems (San Francisco: ASP), 19
 Aoki, W., et al. 2001, *ApJ*, 561, 346
 ———. 2002d, *PASJ*, 54, 427
 Barbay, B., Spite, M., Spite, F., Hill, V., Cayrel, R., Plez, B., & Petitjean, P. 2005, *A&A*, 429, 1031
 Beers, T. C. 1999, in ASP Conf. Ser. 165, The Third Stromlo Symposium: The Galactic Halo, ed. B. Gibson, T. Axelrod, & M. Putman (San Francisco: ASP), 202
 Beers, T. C., Preston, G. W., & Shectman, S. A. 1992, *AJ*, 103, 1987
 Böhm-Vitense, E. 1980, *ApJ*, 239, L79
 Böhm-Vitense, E., & Johnson, H. R. 1985, *ApJ*, 293, 288
 Bond, H. E. 1974, *ApJ*, 194, 95
 Carney, B. W., Latham, D. W., Laird, J. B., Grant, C. E., & Morse, J. A. 2001, *AJ*, 122, 3419
 Carney, B. W., Latham, D. W., Stefanik, R. P., Laird, J. B., & Morse, J. A. 2003, *AJ*, 125, 293
 Christlieb, N. 2003, *Rev. Mod. Astron.*, 16, 191
 Christlieb, N., Green, P. J., Wisotzki, L., & Reimers, D. 2001a, *A&A*, 375, 366
 Christlieb, N., Wisotzki, L., Reimers, D., Homeier, D., Koester, D., & Heber, U. 2001b, *A&A*, 366, 898
 Cohen, J. G., Christlieb, N., Qian, Y.-Z., & Wasserburg, G. J. 2003, *ApJ*, 588, 1082
 Depagne, E., et al. 2002, *A&A*, 390, 187
 Dominy, J. F., & Lambert, D. L. 1983, *ApJ*, 270, 180
 Duquennoy, A., & Mayor, M. 1991, *A&A*, 248, 485
 Fujimoto, M. Y., Ikeda, Y., & Iben, I. J. 2000, *ApJ*, 529, L25
 Gratton, R. G., et al. 2001, *Exp. Astron.*, 12, 107
 Han, Z., Eggleton, P. P., Podsiadlowski, P., & Tout, C. A. 1995, *MNRAS*, 277, 1443
 Hill, V., et al. 2000, *A&A*, 353, 557
 Jahreiss, H., & Wielen, R. 2000, in Poster Papers, IAU Symp. 200: The Formation of Binary Stars, ed. B. Reipurth & H. Zinnecker (San Francisco: ASP), 129
 Johnson, J. A., & Bolte, M. 2002, *ApJ*, 579, L87
 Jorissen, A., Van Eck, S., Mayor, M., & Udry, S. 1998, *A&A*, 332, 877
 Lambert, D. L., & Allende Prieto, C. 2002, *MNRAS*, 335, 325
 Latham, D. W., Stefanik, R. P., Torres, G., Davis, R. J., Mazeh, T., Carney, B. W., Laird, J. B., & Morse, J. A. 2002, *AJ*, 124, 1144
 Lucatello, S., & Gratton, R. G. 2003, *A&A*, 406, 691

- Lucatello, S., Gratton, R., Cohen, J. G., Beers, T. C., Christlieb, N., Carretta, E., & Ramírez, S. 2003, *AJ*, 125, 875
- Luck, R. E., & Bond, H. E. 1991, *ApJS*, 77, 515
- McClure, R. D. 1983, *ApJ*, 268, 264
- McClure, R. D., & Woodsworth, A. W. 1990, *ApJ*, 352, 709
- McCrea, W. H. 1964, *MNRAS*, 128, 147
- Nissen, P. E., Primas, F., Asplund, M., & Lambert, D. L. 2002, *A&A*, 390, 235
- Norris, J. E., Ryan, S. G., & Beers, T. C. 1997a, *ApJ*, 488, 350
- . 1997b, *ApJ*, 489, L169
- Preston, G. W., & Sneden, C. 2000, *AJ*, 120, 1014
- . 2001, *AJ*, 122, 1545
- Ryan, S. G., Beers, T. C., Kajino, T., & Rosolankova, K. 2001, *ApJ*, 547, 231
- Ryan, S. G., Gregory, S. G., Kolb, U., Beers, T. C., & Kajino, T. 2002, *ApJ*, 571, 501
- Schlattl, H., Salaris, M., Cassisi, S., & Weiss, A. 2002, *A&A*, 395, 77
- Sivarani, T., et al. 2004, *A&A*, 413, 1073
- Sneden, C., Preston, G. W., & Cowan, J. J. 2003a, *ApJ*, 592, 504
- Sneden, C., et al. 2003b, *ApJ*, 591, 936
- Tomkin, J., Lemke, M., Lambert, D. L., & Sneden, C. 1992, *AJ*, 104, 1568
- Tonry, J., & Davis, M. 1979, *AJ*, 84, 1511
- Unger, S., Walton, N., Pettini, M., & Tinbergen, J. 1993, *UES Users' Manual*, http://www.ing.iac.es/Astronomy/observing/manuals/html_manuals/wht_instr/ues/ues_manual.html
- Van Eck, S., Goriely, S., Jorissen, A., & Plez, B. 2003, *A&A*, 404, 291
- Vanture, A. 1992, *AJ*, 104, 1997
- Walker, D. D., & Diego, F. 1985, *MNRAS*, 217, 355
- Yi, S. K., Kim, Y., & Demarque, P. 2003, *ApJS*, 144, 259
- Zapatero Osorio, M. R., & Martín, E. L. 2004, *A&A*, 419, 167