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On the binarity of carbon-enhanced, metal-poor stars

S. Tsangarides[1], S. G. Ryan[1], and T. C. Beers[2]

[1] Department of Physics and Astronomy, The Open University, Walton Hall, Milton Keynes, MK7 6AA, United Kingdom. e-mail: s.tsangarides@open.ac.uk, s.g.ryan@open.ac.uk

[2] Department of Physics and Astronomy and JINA: Joint Institute for Nuclear Astrophysics, Michigan State University, East Lansing, Michigan 48824, USA. e-mail: beers@pa.msu.edu

Abstract. We report on a programme to monitor the radial velocities of a sample of candidate and confirmed carbon-enhanced, metal-poor (CEMP) stars. We observed 45 targets using the Echelle Spectrographs of three 4-m class telescopes. Radial velocities for these objects were calculated by cross-correlation of their spectra with the spectrum of HD 140283, and have errors < 1 km s^{-1}. Sixteen of our programme's targets have reported carbon excess, and nine of these objects also exhibit s-process enhancements (CEMP-s). We combine these stars' radial velocities with other literature studies in search of binarity. The search reveals that four of our CEMP-s stars (~ 44%) are in binary systems. Using the analysis of Lucatello et al. (2004), we find that all the CEMP-s stars in our sample are binaries. This conclusion implies that CEMP-s stars may be the very metal-poor relatives of CH and Ba II stars, which are believed to have acquired their peculiar abundance patterns by mass transfer from a thermally-pulsing AGB companion.

Key words. binaries: spectroscopic – binaries: mass transfer – stars: Population II – stars: carbon

1. Introduction

Large-scale surveys of metal-poor stars, such as the HK and Hamburg-ESO surveys, find that a large portion of their metal-poor[1] sample exhibit considerable excess of carbon relative to iron. In fact, the numbers of these C-enhanced, metal-poor (CEMP) stars rise as [Fe/H] decreases (Rossi et al. 1999); CEMP stars may account for up to ~ 25% of stars with [Fe/H] $\lesssim$ -2.0.

The enhancement of C in these stars is accompanied by at least five different abundance patterns. Aoki et al. (2003c) report that ~ 70% of CEMP stars in their sample exhibit super-solar abundances of the s-process elements relative to iron (CEMP-s stars). In addition, some objects may possess excesses in both the s- and r-process elements (CEMP-r/s; e.g. Hill et al. 2000) and one star (CS 22892-052) has an r-process overabundance (CEMP-r). Finally, some objects show no excess of

[1] We will use the term 'metal-poor' to refer to objects with [Fe/H] $\lesssim$ -2.0. We adopt $[A/B] = \log(N_A/N_B)_{star} - \log(N_A/N_B)_{\odot}$, for elements A and B.

Table 1. A brief summary of our programme's six observing runs.

Telescope/Instrument	AAT/UCLES	WHT/UES	TNG/SARG
Dates	2000 Sep	2001 Aug, 2002 Apr, Jun, Jul	2002 May
$N_{objects}$	3	61	3
$\lambda\lambda$ (Å)	3750 – 4900	3550 – 5860	3900 – 5140
Resolution	40,000	52,000	57,000
Dispersion (km s^{-1} pix^{-1})	3.13	1.75	2.20

neutron-capture elements (CEMP-no), but a few are rich in the α-elements (CEMP-α).

As CEMP stars are not luminous enough to be AGB objects, it is frequently speculated that they acquired their peculiar abundance patterns by binary mass transfer from an AGB star. In particular, CEMP-s stars bear a surface abundance pattern similar to CH and Ba II stars (Keenan 1942; Warner 1965; see also the review by O. Pols in these Proceedings). McClure, Woodsworth (1990) show that all CH and Ba II stars are in binary systems with faint, degenerate companions. Jorissen et al. (1998) find that their periods vary from 100 days to 10 yr and their eccentricities are mostly small. These orbital properties suggest that CH and Ba II stars are produced by mass transfer from a former thermally-pulsing AGB companion which has subsequently evolved into a white dwarf (e.g. Han et al. 1995).

Are CEMP-s stars the metal-poor relatives of CH and Ba II stars? Although several CEMP-s stars are members of binaries, we do not yet possess the dynamical evidence to confirm this link. Also, we cannot yet verify that the carbon excess of the other four CEMP-star abundance patterns is produced by the same mass-transfer paradigm. This work will attempt to answer the simpler of the two questions: how many CEMP-s stars are binaries? We review our observations in §2, describe the calculation of radial velocities in §3, and present our search for binaries in §4. Finally, in §5, we focus our discussion to the confirmed CEMP-s stars, and ascertain the binary fraction among them.

2. Observations

Details of the sample selection, observations and data reduction are discussed in Tsangarides (2004). For the purposes of this work, suffice it to say that we have observed 31 candidate CEMP stars from the HK survey (Beers et al. 1992, and subsequent unpublished work), and 14 stars with prior observations, as part of a programme to increase the sample of known CEMP stars and monitor their radial velocities. Most candidate stars had no prior observations at the time our programme started; thus, we had no knowledge of their kinematics when constructing our target list. In addition, we selected pre-observed stars only based on our runs' right-ascension and declination windows. Thus, we expect not to have biased the sample towards or against the inclusion of binaries.

Our targets were observed using the Echelle Spectrographs of three 4-m class telescopes during six runs. Table 1 briefly summarises these runs. We obtained more than 77 spectra, observing most stars in two or more different runs. We had signal-to-noise $\gtrsim$ 10 in the spectra used for the calculation of radial velocities, and $\sim$ 40 for those objects whose abundances were additionally to be calculated. Our wavelength coverage contains the G band of CH around 4320 Å, the CN band near 3883 Å and features from several n-capture elements.

3. Calculation of heliocentric radial velocities

The heliocentric radial velocities (HRVs) of our programme targets were calculated by cross-correlation of their reduced, skysubtracted spectra with the spectrum of HD 140283. This star was observed in all our runs, and was used to set the zero-point of our velocities. Instead of adopting a literature velocity for it, we compared the observed and rest wavelengths of 200-400 clean metallic lines (typically Fe I and Ti II) to calculate its geocentric velocity.

From six runs, our mean velocity for HD 140283 is -170.98 ± 0.22 km s^{-1}. Given this standard deviation, we adopt a systematic error of 0.30 km s^{-1} in our HRVs, in order to compare them with literature velocities at different zero-points (§4). Our mean HRV is identical to the velocity calculated by Latham et al. (2002) for this object (-170.981 ± 0.29 km s^{-1}), from 19 observations spanning 8.5 yr.

Our HRV calculations are also susceptible to two internal errors. These include the deviation of individual pairs of lines from the mean geocentric velocity of HD 140283, and the deviation of individual pairs of echelle orders from the mean cross-correlation velocity of the target.

The quadrature-sum 1σ error of internal and systematic sources is taken to be the total error in each HRV. Total errors are always considerably less than 1 km s^{-1}.

4. The search for binaries

We combined our HRVs with literature velocities which also had errors < 1 km s^{-1}, and used them to search for HRV variation. The combined velocities were subjected to two tests: a χ^2-test (e.g. Carney et al. 2003) and plots of velocity against Julian date of observation. In total, we tested 41 objects, excluding two stars with only a single HRV and two objects which are potential white dwarfs contaminating our sample of candidate CEMP stars.

In the χ^2-test, we assumed the mean of all HRVs weighed by their total error to be the target's true velocity ($\langle$HRV$\rangle$). Thus, we calculated the χ^2-statistic using:

$$\chi^2 = \sum_{i=1}^{n} \frac{HRV_i - \langle HRV \rangle}{\sigma_i}.$$

In addition, we adopted the degrees of freedom (f) to be the number of observations less 1, and used the χ^2 distribution to evaluate the probability (p) of observing the χ^2-statistic given f. Clearly, p is equivalent to the probability that individual HRVs are all measures of the object's true velocity within the observational errors.

The χ^2-test becomes sensitive to even minor HRV variations for $f \leq 4$. That is, even small differences between velocities at this f, cause the χ^2 statistic to become unrealistically large, underestimating the p-value and biasing the test towards the detection of possibly non-real binarity. As most of our targets have only a few observations, however, they lie in this range of f. Thus, for the χ^2 test, we consider that a target exhibits HRV variation if $p < 1\%$ at $f > 4$, and is only potentially variable for $p \lesssim 10\%$ if $f \leq 4$.

Further to the χ^2-test, we plotted each star's HRVs against their Julian date of observation (HJD). Since HRV variation does not necessarily imply binarity, we classified an object as binary only if the amplitude of HRV variation was large enough to be discerned visually from these plots.

Figure 1 illustrates the four classes of HRV variability we were able to identify. The filled triangles are literature HRVs (Table 2) and the open circles are velocities measured in §3. The dashed line through the data is *not* a systemic velocity; even for the confirmed binaries, we usually lack enough observations to calculate a unique orbital solution. Instead, the line represents the mean HRV and is only meant to aid the eye in detecting velocity variation.

Plotted in panel (a) is CS 29526-110, an object reported to be CEMP-s (Table 2). Even with $f = 3$, this object clearly is binary since the amplitude of HRV variation is ~ 10 km s^{-1}, or > 25σ away from the mean line. Of the 41 tested objects, we found 13 binaries, all as visibly clear as CS 29526-110. Note that these objects exhibit $p = 7 \times 10^{-6}$ to 10^{-210}.

In panel (b) we show the potential HRV-variable CEMP-s star CS 30301-015. This object has $p = 0.001$, but with $f = 3$, the variation is still not large enough (within 3σ) to confirm variability. This object requires further HRV monitoring. In total, 10 objects were classified as potential variables.

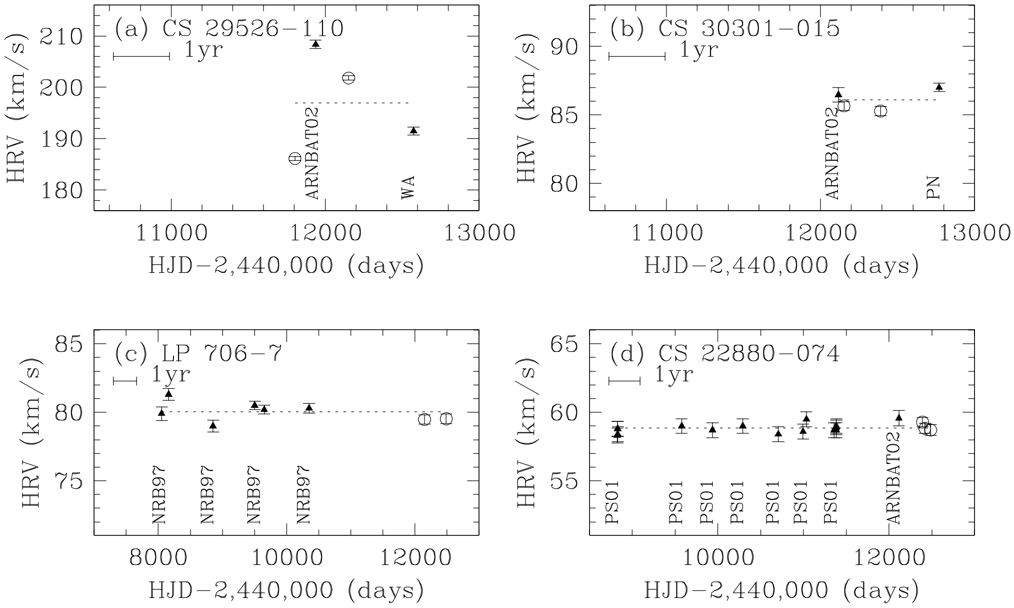

Fig. 1. Plots of heliocentric radial velocity (HRV) in km s^{-1} versus Julian date of observation (HJD) in days, for 4 stars in our sample. The line through the data is simply the arithmetic mean HRV of all the observations. The filled triangles represent literature velocities and the open circles are velocities calculated in §3. Error bars are quadrature-sum errors of each velocity's internal errors and our adopted systematic error.

The seemingly HRV-variable, CEMP-s star LP 706-7 is shown in panel (c). HRV variation is detected in the χ^2-test (p = 0.002; f = 7), but its amplitude is not large enough to classify this object as binary from inspection of the plot, since the reported HRVs lie within 3σ of the mean velocity[2]. More likely, an underestimation of our errors could have resulted in a larger χ^2-statistic, thereby leading the χ^2 test to detect non-existent variation. We identified 3 such objects, the other two being BS 16090-048 and CS 22892-052. The latter was also studied by Preston, Sneden (2001), who comment that any periodicity in this object's HRV variation requires confirmation.

[2] *If* the observed variation is real, its small amplitude may be caused by stellar pulsation, spots or planetary companions, instead of a stellar companion. Discussion on these topics is deferred to Tsangarides (2004), as the present work only focuses on the large-amplitude, confirmed binaries.

Finally, panel (d) shows the CEMP-s star CS 22880-074, which exhibits no HRV variation over a period of ∼ 4000 days. This object is either single or, if in a binary, the orbital axis of the system is inclined at 0^o. 15 stars exhibit no apparent variation, but most have only a few observations.

5. Discussion

If we assume all 41 tested objects to be CEMP stars, we find a binary frequency of ∼ 32%. However, only 16 objects in our sample have *reported* C overabundances in the literature, and 9 of these possess s-process enhancements. Table 2 summarises abundances and binary status for these 16 confirmed CEMP objects. The first column gives the star name, and the second through fifth columns [Fe/H], [C/Fe], [Ba/Fe] and [Pb/Fe] abundances, respectively. The sixth column shows the result of our two binarity tests: SB1 is used to label the binaries,

Table 2. Abundances and binary status for 16 confirmed CEMP stars.

Star	[Fe/H]	[C/Fe]	[Ba/Fe]	[Pb/Fe]	Binarity test	Refs
BS 16080-175	-1.86	+1.75	...	...	vbl?	1
BS 16929-005	-3.09	+0.92	-0.59	...	non-vbl	1,10,13
BS 17436-058	-1.78	+1.50	...	...	non-vbl	1,13
CS 22183-015	-2.85	+2.34	+2.09	+3.17	vbl?	1,11
CS 22877-001	-2.72	+1.00	-0.49	...	vbl?	1,4,13
CS 22880-074	-1.76	+1.51	+1.34	...	non-vbl	1,6,14
CS 22887-048	-1.70	+1.84	...	...	SB1	1,13
CS 22892-052	-2.92	+0.91	+0.92	...	vbl	1,8,10,11,12,13,14
CS 22898-027	-2.25	+2.20	+2.23	+2.84	non-vbl	1,6,13,14
CS 29502-092	-2.76	+1.00	-0.82	...	non-vbl	1,4,7,13
CS 29526-110	-2.38	+2.20	+2.11	+3.30	SB1	1,6,7
CS 30301-015	-2.64	+1.60	+1.45	+1.70	vbl?	1,6,13
CS 31062-050	-2.32	+2.00	+2.30	+2.90	SB1	1,6,9
HD 196944	-2.26	+1.20	+1.10	+1.90	SB1	1,6,7,15
LP 625-44	-2.71	+2.10	+2.74	+2.55	SB1	1,2,3,5,9,12
LP 706-7	-2.74	+2.15	+2.01	+2.28	vbl	1,3,12

1: This work; Tsangarides (2004).
2: Aoki et al. (2000).
3: Aoki et al. (2001).
4: Aoki et al. (2002a).
5: Aoki et al. (2002b).
6: Aoki et al. (2002c ARNBAT02).
7: W. Aoki (2003, private communication; WA).
8: Aoki et al. (2003a).
9: Aoki et al. (2003b).
10: Honda et al. (2004a,b).
11: Johnson, Bolte (2002).
12: Norris et al. (1997 NRB97).
13: P. North (2003, private communication; PN).
14: Preston, Sneden (2001 PS01).
15: Van Eck et al. (2003).

vbl for objects seeming to exhibit HRV variation but not confirmed binarity, vbl? for potential HRV variables, and non-vbl to identify objects with no apparent HRV variation. The final column gives references from which we obtained abundances and HRVs.

From Table 2, 4 CEMP-s stars (~ 44%) are members of binary systems. Most of the s-process-rich stars reported here are a subset of Lucatello et al.'s (2004) sample. These authors calculate expected detection rates for binary CEMP-s stars assuming different true binary fractions. Using their analysis, we find that our detection rate of 44% implies that all CEMP-s stars in our sample are likely binaries. Although this result does not constitute enough dynamical evidence to verify that the CEMP-s abundance pattern is produced by mass transfer from a former AGB star, it strengthens the relation between CEMP-s, CH and Ba II stars. Further HRV monitoring will enable the derivation of orbital solutions, which may help establish the evolutionary status of the companion during mass transfer.

We are still calculating abundances for three of the remaining seven CEMP stars in Table 2, including the only other confirmed binary (CS 22887-048). Thus, we defer discussion on these objects to a later publication (e.g. Tsangarides 2004).

The final four objects include the CEMP-r star, CS 22892-052, which was briefly discussed in §4, and three stars from Honda et al. (2004b) with no apparent n-capture or α-element overabundances. Although all three CEMP-no stars exhibit no HRV variability, this sample is too small and the considered observations too few for meaningful statistics. Thus, it is important to continue monitoring the velocities of all CEMP objects and find more objects of the less populous abundance patterns. Observations for both aims are planned for the future.

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