Stellar Evolution at low Metallicity: Mass Loss, Eplosions, Cosmology
ASP Conference Series, Vol. 353, 2006
Henny J.G.L.M. Lamers, Norbert Langer, Tiit Nugis, Kalju Annuk

Carbon-enhanced metal-poor stars – effects of binary evolution at low metallicity

Onno R. Pols and Robert G. Izzard

Astronomical Institute, P.O. Box 80 000, NL-3508 TA Utrecht, The Netherlands

Abstract. Recent spectroscopic surveys have revealed a large number of extremely metal-poor stars in the Galactic halo. Many of these stars are being subjected to detailed spectroscopic analysis, and a surprisingly large fraction, about 25 %, turn out to be carbon-rich stars with enhancements of C by as much as a factor 100. The majority of these carbon-enhanced metal-poor (CEMP) stars also show enhancements of heavy s-process elements, in particular of lead. Many of these stars have been found to be spectroscopic binary systems. Their binarity and abundance patterns strongly suggest that most, possibly all, CEMP stars have been polluted by a companion star while in an advanced stage of evolution, which has long since faded away. They provide strong indications that (1) binary stars were as common among very low-metallicity populations as they are in the Galactic disk and (2) binaries may have played an important role in shaping the abundance patterns of the earliest generations of stars.

1. Introduction

Very metal-poor stars (with $[\mathrm{Fe/H}] < -2.0$)[1] in the Galactic halo are relics from the earliest stages in the formation and evolution of our Galaxy. Owing to spectroscopic surveys in the last 15 years (the HK survey, Beers et al. 1992, and the Hamburg/ESO survey, Christlieb et al. 2001), the number of known very metal-poor stars has increased enormously. In most cases the detected stars are luminous giants with a mass just above the turn-off mass of the Galactic halo ($\sim 0.8\,M_\odot$), though subgiants and turn-off main-sequence stars have also been found. Many of these stars are now being subjected to careful abundance analysis using high-resolution spectroscopy. They provide an important means of studying the nucleosynthesis output of the first generation of stars, and the initial chemical evolution of the Galaxy (see Beers & Christlieb 2005 for a recent review).

Perhaps the most remarkable finding of these surveys is the high proportion of carbon-rich objects among very metal-poor stars. The frequency of carbon-enhanced metal-poor (CEMP) stars, commonly defined as those having $[\mathrm{C/Fe}] > 1.0$, appears to rise with decreasing metallicity (Norris et al. 1997; Rossi et al. 1999), and could be as high as 25 % for $[\mathrm{Fe/H}] < -2.5$ and perhaps 40 % for $[\mathrm{Fe/H}] < -3.5$ (Beers & Christlieb 2005). The two most iron-deficient stars known to date, with $[\mathrm{Fe/H}] < -5$, are both strongly enriched in carbon. Just how common CEMP stars are is still subject to debate; Cohen et al. (2005) have

---

[1] Using the common notation $[\mathrm{A/B}] \equiv \log(N_\mathrm{A}/N_\mathrm{B}) - \log(N_\mathrm{A}/N_\mathrm{B})_\odot$

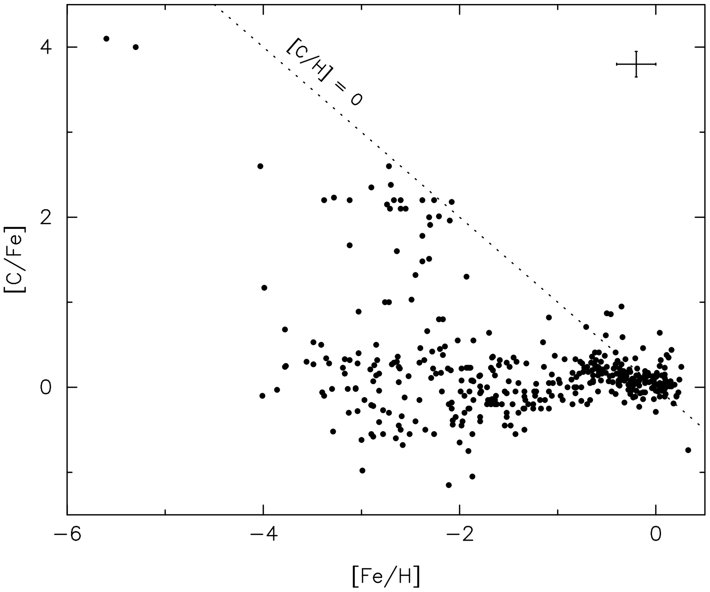

Figure 1. Distribution of [C/Fe] versus [Fe/H] for Galactic disk and halo stars from the recent literature, as collected by T. Masseron (2005, private communication). A typical error bar is shown in the top right corner. The dotted line indicates the solar carbon abundance.

argued that the fraction of CEMP stars has been overestimated in previous studies and their analysis puts it at $14 \pm 4\,\%$, which is in any case still very substantial.

Despite extensive investigation, the origin of carbon in these stars remains unclear. As many as five different abundance patterns have been identified among CEMP stars, indicating that several different carbon-production mechanisms may play a role. As we shall see, there are strong indications that mass transfer in binary systems plays an important part in their formation. A proper understanding of the origin of CEMP stars is required in order to assess the implications of their high frequency, and their effect on the early chemical evolution of the Galaxy.

2. Abundance patterns

The carbon enhancements relative to iron in CEMP stars can be as large as [C/Fe] $\sim$ 2.5, and increase with decreasing [Fe/H], see Fig. 1. In the two most iron-deficient stars found so far (HE 0107-5240, Christlieb et al. 2004 and HE 1327-2326, Frebel et al. 2005) [C/Fe] $\sim +4$. Often the absolute carbon abundance is within 10 % of the solar value. Apart from carbon, nitrogen and in some cases oxygen also tend to be enhanced with respect to iron in many of these stars. As regards heavier elements, various abundance patterns can be discerned.

A number of objects have only mild C and N enhancements without an excess of heavier elements (Aoki et al. 2002b), while several others show strong enhancements of the α elements (e.g. CS 29498-043, Aoki et al. 2002a, 2004). The neutron-capture elements are not enhanced relative to iron in either of these subclasses. Another object, CS 22892-052, shows large enhancements of heavy elements following a pattern like the solar r-process component, including elements like Th and U that can only be produced by rapid neutron captures (Sneden et al. 2003a). This star belongs to a rather rare class of highly r-process enriched metal-poor stars which are, however, not carbon-enhanced in general.

By far the most common variety are CEMP stars in which also the s-process elements are enhanced, such as CS 29497-030 (Sivarani et al. 2004). Aoki et al. (2003) estimate that about 70 % of all CEMP stars belong to this class of 'CEMP-s' stars. The abundance pattern of the s-enhanced CEMP stars seems to find a natural explanation from nucleosynthesis in intermediate-mass asymptotic giant branch (AGB) stars, which are known to produce both carbon and s-process elements through dredge-up of material processed by helium burning in thermal pulses. The CEMP-s stars often show a very strong enhancement of lead (Pb), which is the endpoint of the slow neutron-capture process. Indeed, the s-process in very metal-poor AGB stars is expected to produce an abundance pattern that is strongly biased towards the heaviest s isotopes and in particular Pb, because of the large neutron to iron-seed ratio (Busso et al. 1999; Goriely & Mowlavi 2000). Several such 'lead stars' have been discovered recently (Van Eck et al. 2001, 2003), and their existence among very metal-poor stars indicates that the s-process can be very effective even in AGB stars of very low metallicity (Sneden et al. 2003b; Sivarani et al. 2004). To add to the confusion, however, some of these CEMP-s stars seem to require an additional r-process component to explain their abundance pattern.

3. The origin of CEMP stars

Several different processes may lie at the origin of the abundance patterns observed in CEMP stars. Some objects may have formed out of pre-enriched and poorly mixed ejecta from one or a few early supernovae, possibly of very massive population III stars in the case of the most metal-deficient stars (Chieffi & Limongi 2002; Umeda & Nomoto 2002). This may provide an explanation for the observed enhancements of α-elements, as well the r-process enrichments.

Internal nucleosynthesis and mixing processes may explain some of the peculiarities. During the core helium flash of the lowest-mass stars at very low metallicity ($[\mathrm{Fe/H}] < -4$) the flash-driven convection zone can penetrate into the hydrogen-rich layers above. As a result both carbon and nitrogen can be mixed to the surface (Fujimoto et al. 2000; Schlattl et al. 2002) and a C- and N-rich giant can be formed. This behaviour is inhibited in more metal-rich stars but it might explain the most metal-poor CEMP giants without heavy-element enrichment. In somewhat less metal-poor stars ($-4 \lesssim [\mathrm{Fe/H}] \lesssim -2.5$), a similar behaviour of He-shell flashes during the first few thermal pulses on the AGB can produce both C- and N-enhancements (Fujimoto et al. 2000).

The abundance pattern of the most common subclass, the s-enhanced CEMP stars, can be explained by nucleosynthesis in AGB stars, as indicated above. This suggests that they are low-metallicity analogues of the CH stars among the mainstream population II, and the barium stars among population I, which are also both C- and s-enriched (Jorissen 1999). Both the Ba stars and the CH stars have been confirmed to be binary systems by radial velocity studies (McClure & Woodsworth 1990). Mass transfer in a binary system is the accepted mechanism for the formation of these objects, in which a companion AGB star has polluted the star we see today as a chemically peculiar giant. The distribution of periods and eccentricities of both types show that some degree of orbital circularization has occurred, and there is an upper period limit consistent with mass transfer from a companion star. Main sequence and sub-giant Ba and CH stars have also been found and observed to be binaries (North et al. 2000), confirming the AGB mass transfer hypothesis.

If the CEMP stars are produced by the same mechanism as the Ba and CH stars, then we should expect them all to be binary systems. Indeed, there are strong indications that binarity is related to the CEMP phenomenon, at least in the case of the s-enhanced CEMP stars (Preston & Sneden 2001). Sneden et al. (2003b) performed an abundance analysis of six blue metal-poor stars with $[\mathrm{Fe/H}] < -2$, three of which are single and three are binaries. They found that the three single stars have a normal halo abundance pattern, while the three binary systems show strong carbon and s-process enhancements. Lucatello et al. (2005b) analysed radial velocity data for a sample of 19 CEMP-s stars and find evidence for binarity in $\approx \frac{2}{3}$ of the stars, which is consistent with a true binary fraction of 100 %. The orbital periods of detected binaries are between 195 and 4100 days, similar to the CH stars, except for one system (HE 0024-2523) with a very short period of 3.4 d.

The stars analysed by Sneden et al. (2003b) belong to the population of so-called blue metal-poor (BMP) stars, which are main-sequence stars characterized by their blue colour compared to the generally old halo population. Preston & Sneden (2000) performed a radial-velocity survey of 62 BMP stars, and found that a large fraction (2/3) are binaries with orbital periods are between 2 and 4000 days. Their binary mass functions are small indicating that the companion masses are generally low. The large binary fraction and low companion masses among BMP stars indicates that they are most likely blue stragglers, formed by mass transfer between the companions, rather than interlopers from an intermediate-age population as has also been suggested. Those with $[\mathrm{Fe/H}] > -2$ have normal halo abundances, while those with $[\mathrm{Fe/H}] < -2$ display a wide range of neutron-capture abundances. Some of these BMP binaries belong to the class of CEMP-s stars, as in the case of CS 29497-030 (Sivarani et al. 2004).

4. Nucleosynthesis in binary stars

The ubiquity of carbon- and s-process enhancements among very metal-poor stars, and the evidence for their binarity, indicates that a combination of (AGB) nucleosynthesis and binary evolution is required to explain their properties. Detailed nucleosynthesis models of intermediate-mass AGB stars at $Z = 10^{-4}$ (corresponding to $[\mathrm{Fe/H}] \approx -2.3$) have recently been computed e.g. by Herwig (2004). Carbon production in AGB stars is a primary process, which to first order does not depend on Z. Efficient dredge-up in these models therefore leads to carbon enhancements by factors approaching 1000 at moderately low mass

($< 4\,M_\odot$), and nitrogen enhancements up to a factor 500 in more massive stars. Only a tiny fraction ($1 - 2\,\%$) of such AGB ejecta need to be accreted by the companion star in a binary to raise its carbon abundance to the level observed in CEMP stars.

Mass transfer from a low-metallicity AGB star in a binary is therefore much more effective at producing a carbon-enhanced star than at solar metallicity. Thus an increasing incidence of carbon-rich stars with decreasing Z appears to be a natural consequence of the mass transfer scenario, provided that the binary fraction at low metallicity is similar to that observed in the solar neighbourhood, i.e. $> 50\,\%$. A combination of detailed AGB nucleosynthesis and binary evolution models is required to confirm if the high frequency and the abundance patterns of CEMP-s stars can be explained in this way. Until such models are available one should take with some caution the recent claim by Lucatello et al. (2005a) that the ubiquity of CEMP stars provides evidence for a different initial mass function at low metallicity, weighted towards intermediate-mass stars.

We are currently making efforts to model CEMP stars by means of a combination of detailed stellar evolution and nucleosynthesis models and a binary population synthesis technique (Izzard et al. 2004, 2006 [in preparation]), which will be extended with models at very low metallicity. The binary interaction processes that are particularly relevant for binary systems containing an AGB star, and the associated uncertainties, have been reviewed by Pols (2004). Here we would like to stress a few points.

(1) Mass transfer can occur by a combination of wind accretion and Roche-lobe overflow. Because AGB winds are slow and dense, wind accretion is an effective mechanism even in very wide-orbit binaries. In the commonly used Bondi-Hoyle approximation the efficiency of wind accretion scales inversely with a high power of the wind velocity (Boffin & Jorissen 1988). Not much is known at present about AGB winds at very low metallicity, but Van Loon (these proceedings) provides evidence that at least down to the metallicity of the SMC the mass-loss rate is independent of Z, while the wind velocity increases with Z. If this trend continues to very low Z then wind accretion could be very effective at low metallicity, which would help to explain the high frequency of CEMP-s stars.

(2) Tidal interaction becomes effective when the size of the AGB star is a considerable fraction of the orbital separation, i.e. for orbital periods less than a few years. As a consequence the orbit will tend to circularize and the AGB star will be spun up to synchronization with the orbit. This spin-up could have interesting consequences for nucleosynthesis in the AGB star, in particular for extra-mixing processes that may depend on the (differential) rotation rate in the intershell region, such as the formation of the ^{13}C-pocket (Herwig et al. 2003) that provides neutrons for the s-process and perhaps the simultaneous C and N enrichment which is seen in many CEMP stars (and which is not predicted by canonical AGB models). The effects of a relatively fast-spinning envelope on AGB nucleosynthesis are still unexplored.

Acknowledgments. This work has made use of the *Stellardb* stellar abundance database, `http://www.phys.uu.nl/~izzard/cgi-bin/stellardb.cgi` (Ödman & Izzard 2004).

References

Aoki, W., Norris, J. E., Ryan, S. G., Beers, T. C., & Ando, H., 2002a, ApJ, 576, L141

—, 2002b, ApJ, 567, 1166

Aoki, W., Norris, J. E., Ryan, S. G., et al., 2004, ApJ, 608, 971

Aoki, W., Ryan, S. G., Tsangarides, S., et al., 2003, in IAU GA 25, Joint Discussion 15, Elemental Abundances in Old Stars and Damped Lyman-α Systems, (San Francisco: ASP), 19

Beers, T. C. & Christlieb, N., 2005, ARA&A, 43, 531

Beers, T. C., Preston, G. W., & Shectman, S. A., 1992, AJ, 103, 1987

Boffin, H. M. J. & Jorissen, A., 1988, A&A, 205, 155

Busso, M., Gallino, R., & Wasserburg, G. J., 1999, ARA&A, 37, 239

Chieffi, A. & Limongi, M., 2002, ApJ, 577, 281

Christlieb, N., Green, P. J., Wisotzki, L., & Reimers, D., 2001, A&A, 375, 366

Christlieb, N., Gustafsson, B., Korn, A. J., et al., 2004, ApJ, 603, 708

Cohen, J. G., Shectman, S., Thompson, I., et al., 2005, ApJ, 633, L109

Frebel, A., Aoki, W., Christlieb, N., et al., 2005, Nat, 434, 871

Fujimoto, M., Ikeda, Y., & Iben, I., 2000, ApJ, 529, 25

Goriely, S. & Mowlavi, N., 2000, A&A, 362, 599

Herwig, F., 2004, ApJ, 605, 425

Herwig, F., Langer, N., & Lugaro, M., 2003, ApJ, 593, 1056

Izzard, R. G., Tout, C. A., Karakas, A. I., & Pols, O. R., 2004, MNRAS, 350, 407

Jorissen, A., 1999, in IAU Symp. 191: Asymptotic Giant Branch Stars, eds. T. Le Bertre, A. Lebre, and C. Waelkens, 437

Lucatello, S., Gratton, R. G., Beers, T. C., & Carretta, E., 2005a, ApJ, 625, 833

Lucatello, S., Tsangarides, S., Beers, T. C., et al., 2005b, ApJ, 625, 825

McClure, R. D. & Woodsworth, A. W., 1990, ApJ, 352, 709

Norris, J. E., Ryan, S. G., & Beers, T. C., 1997, ApJ, 488, 350

North, P., Jorissen, A., & Mayor, M., 2000, in IAU Symp. 177: The Carbon Star Phenomenon, ed. R. F. Wing, 269

Ödman, C. J. & Izzard, R. G., 2004, Mem. Soc. Astron. It., 75, 631

Pols, O. R., 2004, Mem. Soc. Astron. It., 75, 749

Preston, G. W. & Sneden, C., 2000, AJ, 120, 1014

—, 2001, AJ, 122, 1545

Rossi, S., Beers, T. C., & Sneden, C., 1999, in ASP Conf. Ser. 165: The Third Stromlo Symposium: The Galactic Halo, eds. B.K. Gibson and M.E. Putman, 264

Schlattl, H., Salaris, M., Cassisi, S., & Weiss, A., 2002, A&A, 395, 77

Sivarani, T., Bonifacio, P., Molaro, P., et al., 2004, A&A, 413, 1073

Sneden, C., Cowan, J. J., Lawler, J. E., et al., 2003a, ApJ, 591, 936

Sneden, C., Preston, G. W., & Cowan, J. J., 2003b, ApJ, 592, 504

Umeda, H. & Nomoto, K., 2002, ApJ, 565, 385

Van Eck, S., Goriely, S., Jorissen, A., & Plez, B., 2001, Nat, 412, 793

—, 2003, A&A, 404, 291

Discussion

Gustafsson: Comment: A possible explanation for the high frequency of EMP C stars might also be a ”cosmic selection effect”, in the sense that metal-poor gas with a carbon excess may cool more easily to form low mass stars. There is a check that is difficult but should be contemplated to check the formation scenario, to see whether the frequency distribution of various C and s-element enrichments for the dwarfs are compatible with that of the giants. Since the convection zone deepens when proceeding from dwarfs to giants one would expect a shift of the distribution.