Modelling the evolution and nucleosynthesis of carbon-enhanced metal-poor stars

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Abstract. We present the results of binary population simulations of carbon-enhanced metal-poor (CEMP) stars. We show that nitrogen and fluorine are useful tracers of the origin of CEMP stars, and conclude that the observed paucity of very nitrogen-rich stars puts strong constraints on possible modifications of the initial mass function at low metallicity. The large number fraction of CEMP stars may instead require much more efficient dredge-up from low-metallicity asymptotic giant branch stars.

Keywords. Stars: AGB and post-AGB, stars: evolution, stars: binaries, stars: abundances, stars: mass function

1. Introduction

One of the most striking results of recent large surveys for very metal-poor stars in the Galactic halo is the large proportion of highly carbon-enriched objects among them. These carbon-enhanced metal-poor (CEMP) stars, usually defined as metal-poor stars with $[C/Fe] > 1.0$, make up at least 10 per cent and probably as much as 20–25 per cent of very metal-poor stars with $[Fe/H] < -2$ (Frebel *et al.* 2006; Lucatello *et al.* 2006).

The majority (about 80 per cent, according to Aoki *et al.* 2007) of CEMP stars are also enriched in Ba and other heavy elements produced by slow neutron captures (the *s*-process) in asymptotic giant branch (AGB) stars. For these so-called CEMP-s stars a likely scenario is pollution by mass transfer from a more massive AGB companion in a binary system, which has since become a white dwarf. Supporting evidence for this scenario comes from radial velocity monitoring, which suggests that all CEMP-s stars could statistically be binaries (Lucatello *et al.* 2005a). The remaining fraction of CEMP stars that do not show s-process enrichments (the CEMP-no stars) are typically more metal-poor than the CEMP-s stars and so far have shown no evidence for binarity (Aoki *et al.* 2007). These stars exhibit a variety of abundance patterns, and may have formed instead from material ejected from rapidly rotating massive stars (Meynet *et al.* 2006) or from faint core-collapse supernovae (Umeda & Nomoto 2005). Confusing such a clear distinction are a surprisingly large number of CEMP stars enhanced in both *s*-process and *r*-process (rapid neutron-capture) elements, whose origin is still quite unclear (Jonsell *et al.* 2006).

Within the mass transfer scenario, the large proportion of CEMP-s stars requires the existence of a sufficient number of binary systems with primary components that have undergone AGB nucleosynthesis. In recent studies (Lucatello *et al.* 2005b; Komiya *et al.* 2007) it has been argued that this requires a different initial mass function (IMF) at low metallicity, weighted towards intermediate-mass stars. If true, this in turn has important consequences for the chemical evolution of the halo and, by implication, of other galaxies.

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However, the model calculations on which these estimates are based still contain many uncertainties regarding the evolution and nucleosynthesis of low-metallicity AGB stars, the efficiency of mass transfer, and the evolution of the surface abundances of the CEMP stars themselves.

In this contribution we explore the effect of some of these uncertainties on the number fraction of CEMP stars by means of a binary population synthesis study. Apart from carbon, we concentrate on nitrogen and fluorine enrichments as possible tracers of the origin of CEMP stars, the latter motivated by the recent discovery of fluorine in a CEMP star (see Sect. 2). In Sect. 3 we present the first results of our binary population synthesis simulations, and in Sect. 4 we give our conclusions.

2. Nitrogen and fluorine in CEMP stars

Apart from carbon, substantial enhancements of nitrogen with respect to iron are common among CEMP stars, typically with [C/N] > 0. Detailed AGB nucleosynthesis models of low initial mass ($< 2.5\,M_\odot$) produce carbon (by the 3α reaction during thermal pulses and subsequent convective dredge-up), but do not produce nitrogen because it is burned during the same helium shell flashes. On the other hand, AGB models of higher mass convert the dredged-up carbon effectively into nitrogen by CN-cycling at the bottom of the convective envelope (hot bottom burning, HBB). The surface abundances of these more massive AGB stars approach the CN-equilibrium ratio of [C/N] ≈ -2. Detailed evolution models of AGB stars (Karakas & Lattanzio 2007) indicate that HBB sets in at significantly lower mass at low metallicity (between 2.5 and $3\,M_\odot$ at [Fe/H] = -2.3) than at solar metallicity (around $5\,M_\odot$). One may thus expect a population of so-called nitrogen-enhanced metal-poor (NEMP) stars, with [C/N] < -0.5. Although a few examples of such stars are known, mostly at [Fe/H] < -2.9, they appear to be very rare (Johnson *et al.* 2007). As we show in Sect. 3 the number of NEMP stars sets an additional constraint on possible changes to to IMF at low metallicity.

Recently, Schuler *et al.* (2007) derived a super-solar fluorine abundance of [F/Fe] = $+2.9$ in the halo CEMP star HE 1305+0132. This is the most iron-deficient star, [Fe/H] = -2.5, for which the fluorine abundance has been measured. Enhancements of carbon and nitrogen are also measured ([C/Fe] = $+2.7$; [N/Fe] = $+1.6$), and Ba and Sr lines are seen in its spectrum (Goswami 2005), placing HE 1305+0132 in the group of CEMP-s stars.

Fluorine can be made in AGB stars as a by-product of the $^{14}N +^4 He$ reaction under neutron-rich conditions during thermal pulses (Lugaro *et al.* 2004). Fluorine enhancements of up to 30 times solar have been measured among Galactic AGB stars (Jorissen *et al.* 1992), demonstrating that these stars can indeed produce fluorine efficiently. Detailed AGB nucleosynthesis models (Karakas & Lattanzio 2007) show that fluorine is produced and dredged to the surface alongside carbon in low-metallicity AGB stars with masses $< 3\,M_\odot$. At larger masses fluorine is destroyed by proton captures as a result of HBB.

In Fig. 1 we show the enhancements of F and C+N relative to hydrogen as observed in HE 1305+0132 and compare these to the abundance ratios in the material lost by AGB stars at [Fe/H] = -2.3 according to the Karakas & Lattanzio (2007) models. The figure shows that AGB stars with masses between 1.7 and $2.3\,M_\odot$ produce fluorine and carbon in the right amounts to account for the observed abundances, after accretion of the material by a low-mass companion and subsequent dilution in its envelope by a factor 6 to 9 (Lugaro *et al.* 2008). Assuming a mass of $0.8\,M_\odot$ and a convective envelope mass fraction of 60 %, this implies that the star should have accreted 0.05–$0.12\,M_\odot$ from its companion, corresponding to 3–11 % of the mass lost by the AGB star. These constraints
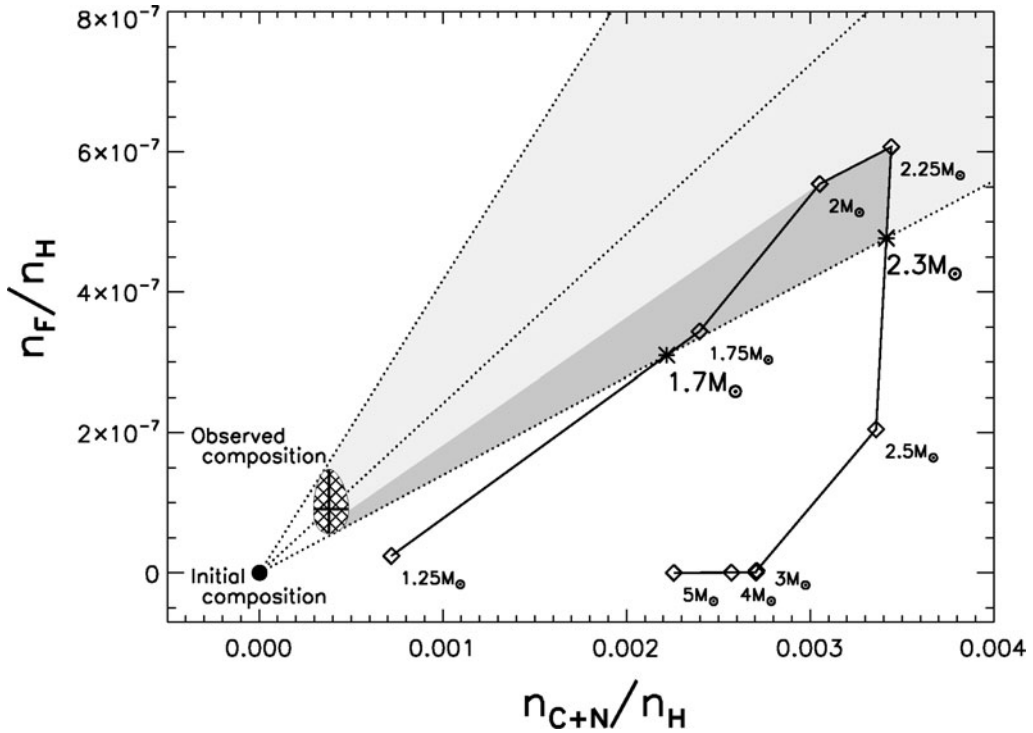
Figure 1. Abundances by number of F and C+N with respect to H as observed in HE 1305+0132 from Schuler *et al.* (2007; hatched ellipsoid showing 1σ errors) compared to those computed in the material lost in AGB star winds at $[\text{Fe/H}] = -2.3$, with labels indicating the initial masses. The light gray area is the region of the plot where the F and C+N abundances from the AGB companion should lie in order to match the observed abundances, after dilution. The darker gray area represents the region covered by the models with masses in the range 1.7–$2.3\,M_\odot$ indicated by the asterisks.

fit well within the binary mass transfer scenario. Furthermore this result indicates the potential of using fluorine as a tracer for the origin of CEMP stars.

3. Binary population nucleosynthesis of CEMP stars

We have simulated populations of metal-poor halo stars in binary systems using the rapid synthetic binary nucleosynthesis code of Izzard *et al.* (2004) and Izzard *et al.* (2006). The code uses fits to detailed single-star evolution and nucleosynthesis models, in particular the AGB models of Karakas & Lattanzio (2007), and follows the surface abundances as a star evolves through dredge-up episodes. A prescription for hot bottom burning in massive AGB stars is included, calibrated against the same detailed AGB models. Binary evolution is followed according to the prescriptions of Hurley *et al.* (2002). We model mass transfer by stellar wind accretion, according to the Bondi & Hoyle (1944) prescription, and by Roche-lobe overflow (RLOF). In binaries with AGB primaries, RLOF is usually unstable and leads to the ejection of a common envelope without any further accretion onto the companion. In our default model we assume efficient thermohaline mixing, in accordance with the findings of Stancliffe *et al.* (2007).

In all models we use solar-scaled initial abundances according to Anders & Grevesse (1989) with $Z = 10^{-4}$, corresponding to $[\text{Fe/H}] = -2.3$, which is the lowest metallicity for which we have detailed AGB models. We select stars with ages between 10 and 13.7 Gyr

Table 1. Number fractions of CEMP and NEMP stars among halo stars at [Fe/H] $= -2.3$ and $\log g < 4.0$ resulting from binary population synthesis, for different sets of physical ingredients in the evolution models. The last two columns give the fraction of CEMP-s stars and of fluorine-rich FEMP stars, relative to the number of CEMP stars.

model		$f(CEMP)$	$f(NEMP)$	$\frac{NEMP}{CEMP}$	$\frac{CEMP-s}{CEMP}$	$\frac{FEMP}{CEMP}$
1A	default physics	2.30 %	0.35 %	0.15	0.29	0.85
2A	no thermohaline mixing	4.20 %	0.52 %	0.12	...	...
3A	calibrated 3DUP	9.43 %	0.34 %	0.036	0.99	0.82
4A	no therm. mix. + calibr. 3DUP	14.96 %	0.47 %	0.031	0.75	0.87

(roughly corresponding to the age of the halo) and $\log g < 4.0$ (thus including turnoff stars and (sub)giants but excluding unevolved main-sequence stars). Among this sample we designate as CEMP stars those with [C/Fe] > 1.0 and as NEMP stars those with [N/Fe] > 0.5 and [C/N] < -0.5, following the definition of Johnson *et al.* (2007). Note that these definitions partly overlap.

We can compare our model results with the statistics of the SAGA database of metal-poor stars (Suda *et al.* 2008). We selected 375 stars from the database in a metallicity range [Fe/H] $= -2.3 \pm 0.5$ and $\log g < 4.0$. Of these, 296 have a C abundance measurement and 69 classify as CEMP stars, yielding a CEMP fraction of 18–23 %. Only one star classifies as a NEMP star, giving a very small nominal NEMP fraction of <0.3 %. If we consider an extended metallicity range $-4 <$ [Fe/H] < -2 in order to improve the number statistics, we find 6 NEMP stars and a NEMP fraction of about 1.5 %. We conclude that CEMP stars outnumber NEMP stars by at least a factor 10.

In our default model (1A) we assume that the initial primary masses M_1 are distributed according to the solar neighbourhood IMF as derived by Kroupa *et al.* (1993), the initial periods come from a flat distribution in $\log P$ and the initial mass ratios from a flat distribution in $q = M_2/M_1$. In Table 1 we present the resulting number fractions of CEMP and NEMP stars (first row). This model clearly fails to account for the large observed CEMP fraction, although the small NEMP fraction is consistent with the observations. The last two columns give the number ratio of CEMP-s stars (defined as those CEMP stars with [Ba/Fe] > 0.5) to CEMP stars and the ratio of FEMP stars (defined as stars with [F/Fe] > 1.0) to CEMP stars. Although all our CEMP stars are also enriched in Ba, in this model the majority have [Ba/Fe] < 0.5.

In the next rows of Table 1 we vary some of the uncertain physical ingredients in our models, while keeping the input distributions the same. In model 2A we switch off thermohaline mixing, which has the effect of increasing the surface abundances of C, N and Ba in turnoff stars with shallow convection zones relative to our default model. The numbers of CEMP stars and NEMP stars correspondingly increase, although the CEMP fraction remains too low to be compatible with observations. In model 3A we vary some of the parameters relating to third dredge-up (3DUP), in particular we assume a smaller value (by up to $0.1\,M_\odot$) of the minimum core mass at which 3DUP occurs, and after dredge-up has started we assume efficient 3DUP (with $\lambda \geqslant 0.8$) regardless of how small the envelope mass is. In practice this means that almost all AGB stars with initial masses $> 0.8\,M_\odot$ undergo efficient dredge-up. These modifications are motivated by similar changes needed to reproduce the carbon-star luminosity function of the Magellanic Clouds (Izzard & Tout 2004) and the abundances of Galactic post-AGB stars (Bonačić Marinović *et al.* 2007). This leads to an increase of the CEMP fraction to almost 10 %, much closer to but still short of the observed value. Model 4A is a combination of 2A and 3A and results in a CEMP fraction of 15 %. We note that in these latter two models

Table 2. Number fractions of CEMP and NEMP stars among halo stars at [Fe/H] = −2.3 and log g < 4.0 as in Table 1, for the default physical ingredients while varying the input distributions.

model		f(CEMP)	f(NEMP)	$\frac{\text{NEMP}}{\text{CEMP}}$
1A	default $N(M_1, q, P)$	2.30 %	0.35 %	0.15
1B	$N(q, P)$ from Duquennoy & Mayor (1991)	3.50 %	0.71 %	0.20
1C	$N(M_1)$ from Miller & Scalo (1979)	3.15 %	0.62 %	0.20
1D	$N(M_1)$ from Lucatello *et al.* (2005b)	4.81 %	1.35 %	0.28
1E	$N(M_1)$ from Komiya *et al.* (2007)	13.47 %	26.61 %	1.98

nearly all CEMP stars are CEMP-s stars, in accordance with observations. We also note that in all models the majority (> 80 %) of CEMP stars are expected to be fluorine-rich, with [F/Fe] > 1.0.

In Table 2 we present CEMP and NEMP fractions of the default physical model while varying the initial distributions of binary parameters. In model 1B we assume mass ratios and periods drawn from the distributions derived by Duquennoy & Mayor (1991) for the local population of G dwarfs (i.e. a log-normal period distribution with a broad peak at 170 years and a q distribution with a broad peak at $M_2/M_1 = 0.23$). This leads to an increase by a factor of 1.5–2 in the number of CEMP and NEMP stars as the peak in the period distribution coincides with the period range in which mass transfer is effective.

Models 1C, 1D and 1E explore the effect of varying the initial mass function, by assuming the default q and P distributions in combination with a log-normal form of the IMF. The Miller & Scalo (1979) IMF also represents the solar neighbourhood but gives somewhat higher CEMP and NEMP fractions than the Kroupa *et al.* (1993) IMF. Model 1D assumes the IMF suggested by Lucatello *et al.* (2005b) as required to reproduce the large CEMP fraction (it has a median mass of $0.79\,M_\odot$, compared to $0.10\,M_\odot$ for the Miller & Scalo IMF). It results in a larger CEMP fraction but still falls short of the observed value. The discrepancy between our and Lucatello's results arises mainly because in our (default) models the initial primary mass and period range contributing to CEMP stars are smaller than they assumed. Model 1D also shows an increased NEMP fraction, the result of a larger weight of intermediate-mass stars (with $M > 2.7\,M_\odot$ undergoing HBB) in this IMF. This effect is much more extreme when we assume the IMF suggested by Komiya *et al.* (2007) which has a median mass of $10\,M_\odot$. Although it gives rise to a substantial CEMP fraction, the CEMP stars are outnumbered by NEMP stars by a factor of two. This is not compatible with the observed limits on the number fraction of NEMP stars.

4. Conclusions

The detection of a large fluorine overabundance in the CEMP star HE 1305+0132 is well explained within the AGB binary mass transfer scenario (Lugaro *et al.* 2008). On the other hand, models of rapidly rotating massive stars do not produce fluorine (Meynet *et al.* 2006). Therefore fluorine appears to be a useful discriminant between different scenarios proposed for the origin of CEMP stars. Our population synthesis results indicate that (rather independent of model assumptions) at least 80 % of CEMP stars formed by AGB mass transfer should be enriched in fluorine ([F/Fe] > 1.0), i.e. most CEMP-s stars should also be FEMP stars.

Our binary population synthesis models show that the paucity of NEMP stars among metal-poor halo stars is incompatible with a strongly modified IMF at low metallicity,

heavily weighted towards intermediate-mass stars, as has been suggested by Komiya *et al.* (2007) in order to explain the high proportion of CEMP stars. Another possible explanation for the ubiquity of CEMP-s stars is that low-metallicity AGB stars undergo much more efficient dredge-up than shown by the detailed evolution models available to date.

Acknowledgements

References

Anders, E. & Grevesse, N. 1989, *Geochim. Cosmochim. Acta* 53, 197
Aoki, W., Beers, T. C., Christlieb, N., Norris, J. E., Ryan, S. G., & Tsangarides, S. 2007, *ApJ* 655, 492
Bonačić Marinović, A., Izzard, R. G., Lugaro, M., & Pols, O. R. 2007, *A&A* 469, 1013
Bondi, H., & Hoyle, F. 1944, *MNRAS* 104, 273
Duquennoy, A., & Mayor, M. 1991, *A&A* 248, 485
Frebel, A., Christlieb, N., Norris, J. E., *et al.* 2006, *ApJ* 652, 1585
Goswami, A. 2005, *MNRAS* 359, 531
Hurley, J. R., Tout, C. A., & Pols, O. R. 2002, *MNRAS* 329, 897
Izzard, R. G., & Tout, C. A. 2004, *MNRAS* 350, L1
Izzard, R. G., Tout, C. A., Karakas, A. I., & Pols, O. R. 2004, *MNRAS* 350, 407
Izzard, R. G., Dray, L. M., Karakas, A. I., & Lugaro, M., & Tout, C. A. 2006, *A&A* 460, 565
Johnson, J. A., Herwig, F., Beers, T. C., & Christlieb, N. 2006, *ApJ* 658, 1203
Jonsell, K., Barklem, P. S., Gustafsson, B., Christlieb, N., Hill, V., Beers, T. C., & Holmberg, J. 2006, *ApJ* 451, 651
Jorissen, A., Smith, V. V., & Lambert, D.L. 1992, *A&A* 261, 164
Karakas, A. & Lattanzio, J. C. 2007, *PASA* 24, 103
Komiya, Y., Suda, T., Minaguchi, H., Shigeyama, T., Aoki, W., & Fujimoto, M. Y. 2007, *ApJ* 658, 367
Kroupa, P., Tout, C. A., & Gilmore, G. 1993, *MNRAS* 262, 545
Lucatello, S., Tsangarides, S., Beers, T. C., Carretta, E., Gratton, R. G., & Ryan, S. G. 2005, *ApJ* 625, 825
Lucatello, S., Gratton, R. G., Beers, T. C., & Carretta, E. 2005, *ApJ* 625, 833
Lucatello, S., Beers, T. C., Christlieb, N., Barklem, P. S., Rossi, S., Marsteller, B., Sivarani, T., & Lee, Y. S. 2006, *ApJ* 652, L37
Lugaro, M., Ugalde, C., Karakas, A. I., Görres, J., Wiescher, M., Lattanzio, J. C., & Cannon, R. C. 2004, *ApJ*, 615, 934
Lugaro, M., de Mink, S. E., Izzard, R. G., *et al.* 2008, *A&A* 484, L27
Meynet, G., Ekström, S., & Maeder, A. 2006, *A&A* 447, 623
Miller, G. E., & Scalo, J. M. 1979, *ApJS* 41, 513
Schuler, S. C., Cunha, K., Smith, V. V., Sivarani, T., Beers, T. C., & Lee, Y. S. 2007, *ApJ* 667, L81
Stancliffe, R. J., Glebbeek, E., Izzard, R. G., & Pols, O. R. 2007, *A&A* 464, L57
Suda, T., Katsuta, Y., Yamada, S., *et al.* 2008, *PASJ* 60, in press, arXiv:0806.3697
Umeda, H. & Nomoto, K. 2005, *ApJ* 619, 427

Discussion

C. CHARBONNEL: You spoke about observations of s-process elements in CEMP in general. Are there some precise data, regarding the low- and high-mass s-elements, that may help discriminate the progenitor (e.g., AGB vs massive stars)?

O. Pols: There are certainly many detailed abundance determinations of heavy elements in CEMP stars, and these have been tested against s-process models by several groups. In general, these observations agree with AGB models, although different assumptions must be made for different stars regarding the free parameters in these models (such as the $^{1}3C$ pocket size), and there are still many open questions in this respect. Some CEMP stars show both an s-process and r-process signature, for these one may need pre-enrichment by massive stars and AGB mass transfer...

N. Langer: Could the fluorine in CEMP stars also come from neutrino-induced nucleosynthesis from supernovae?

O. Pols: Indeed, supernovae can also be sources of fluorine although this has not been confirmed observationally to my knowledge. However, SNe typically produce more Oxygen than Carbon, contrary to what is seen in CEMP stars. One would need to get rid of the Oxygen, or suppose a different source for the carbon. AGB stars naturally explain both C and F enhancements simultaneously.