Binary Populations of Carbon-Enhanced Metal-Poor Stars

Robert G. Izzard[A,B], *Evert Glebbeek*[B,C], *Richard J. Stancliffe*[D,E], *and*
Onno Pols[B]

[A] Institut d'Astronomie et d'Astrophysique, Université Libre de Bruxelles, Boulevard du Triomphe, B-1050 Brussels, Belgium. Email: Robert.Izzard@ulb.ac.be
[B] Sterrenkundig Instituut, Universiteit Utrecht, P.O. Box 80000, NL-3508 TA Utrecht, The Netherlands.
[C] Department of Physics and Astronomy, McMaster University, Hamilton, Ontario, L8S 4M1, Canada.
[D] School of Mathematical Sciences, PO Box 28M, Monash University, Victoria 3800, Australia.
[E] Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge, CB3 0HA, United Kingdom.

Abstract: We construct binary-star population nucleosynthesis models of carbon-enhanced metal poor (CEMP) stars. We compare the CEMP to EMP (extremely metal poor) ratio of our models to the observed ratio and find it is an order of magnitude too small. Through an increase in the efficiency of third dredge-up in low-mass, low-metallicity thermally-pulsing asymptotic-giant branch (TPAGB) stars our models better match the observations.

Keywords: Binary stars — mass transfer — Galactic halo — metal-poor stars

1 Introduction

The carbon-enhanced metal-poor stars (CEMPs) are Galactic halo objects which are observed to be iron poor ([Fe/H] $\lesssim -2$), relatively carbon rich ([C/Fe] ≥ 1) and mostly giant and turn-off stars ($\log g \lesssim 4$). Their mass is around $0.85\,\mathrm{M}_{\odot}$, as dictated by the age of the halo. Canonical models of $\sim 0.85\,\mathrm{M}_{\odot}$ single stars do not predict such a large carbon enhancement at any phase of their evolution. Instead, it seems likely that most CEMPs form in binary systems as a result of mass transfer from a carbon-rich thermally-pulsing asymptotic giant branch (TPAGB) star which is now an unseen white dwarf. Radial velocity surveys concur, at least for those CEMPs which are also rich in *s*-process elements (Tsangarides et al. 2004; Lucatello et al. 2005b). According to detailed TPAGB models the primary star should have had a mass in the range 1.2 to $3\,\mathrm{M}_{\odot}$, in order to undergo efficient third dredge-up of carbon without hot-bottom burning (which converts carbon to nitrogen, e.g. Karakas and Lattanzio 2007). For a review of the properties of carbon stars see e.g. Wallerstein and Knapp (1998) or Abia et al. (2003).

The CH stars are thought to be the higher metallicity ([Fe/H] ~ -1) equivalents of the CEMPs because they form by a similar binary-accretion mechanism. They make up about 1% of the giant population (Luck and Bond 1991), in rough agreement with our theoretical estimates based on binary population synthesis (see Section 2). By contrast 9–30% of the EMP (extremely metal poor) giant population are CEMPs (Frebel et al. 2006; Lucatello et al. 2006; Suda et al. 2008), in disagreement with our standard binary population models.

Recent studies suggest that an initial-mass function (IMF) quite different to that of the solar neighbourhood is responsible for the large CEMP to EMP (extremely metal poor) number ratio (e.g. Lucatello et al. 2005a; Komiya et al. 2007). We attempt to explain the CEMP to EMP number ratio without a change in the initial distributions of stellar masses and initial periods from those found in the solar neighbourhood.

Many of the physical parameters in our binary-star model are quite uncertain, but we show that most are not important in calculation of the CEMP to EMP number ratio. The parameters which matter most are those that affect the efficiency of third dredge-up in low-mass stars.

2 Binary Population Models

We base our population synthesis models on the rapid binary-star evolution and nucleosynthesis models of Hurley et al. (2002); Izzard et al. (2004) and Izzard et al. (2006). Our nucleosynthesis algorithm has been updated to better model first dredge-up in low-metallicity stars which have accreted carbon-rich material from a companion. Third dredge-up is modelled as in Karakas et al. (2002) using the parameters $M_{\mathrm{c,min}}$, the minimum core mass for third dredge-up, and λ, , the ratio of the mass of material which is dredged up at a given pulse to the mass by which the core grew during the preceding interpulse period.

We also include the correction factors $\Delta M_{\mathrm{c,min}}$ and λ_{min} which were introduced in Izzard et al. (2004) in order to match our synthetic TPAGB models to observed carbon-star luminosity functions in the Magellanic Clouds. These alter the prescription of Karakas et al. (2002) such that $M_{\mathrm{c,min}} = M_{\mathrm{c,min}}^{\mathrm{Karakas}} + \Delta M_{\mathrm{c,min}}$ and $\lambda = \max\left(\lambda^{\mathrm{Karakas}}, \lambda_{\mathrm{min}}\right)$.

A new parameter in our model is $M_{\mathrm{env,min}}$, the minimum envelope mass a star must have in order for third dredge-up to occur. This was set to $0.5\,\mathrm{M}_{\odot}$ in previous models, following Straniero et al. (1997), but will be treated as a free parameter for our purposes. Note that while our models include canonical third dredge-up and hot-bottom burning, they do not contain prescriptions for dual-core flashes or dual-shell flashes (e.g. Campbell and Lattanzio 2008, Cristallo et al. this volume) which are expected to occur at low metallicity ([Fe/H] $\lesssim -3$). Our standard choice

of physical parameters is described in some detail in Izzard et al. (2006) and the metallicity is, in most of our models, $Z = 10^{-4}$ (such that [Fe/H] $= -2.3$). We distribute initial primary masses according to the IMF of Kroupa et al. (1993), the binary mass ratio is distributed evenly between 0 and 1 and the separation distribution is flat in log–separation between 3 and $10^5\,\mathrm{R}_{\odot}$ (the upper limit is chosen to include all CEMPs formed by wind accretion). We assume a binary fraction of 100%.

We constructed dozens of binary-star populations with a wide variety of physical parameter choices, as shown in Figure 1. These include alternative TPAGB wind prescriptions, enhanced wind accretion efficiency, tidally-enhanced mass loss, alternative common-envelope evolution prescriptions, accretion of material in a common envelope phase, lower initial metallicity and various combinations of $\Delta M_{\mathrm{c,min}}$, λ_{min} and $M_{\mathrm{env,min}}$. Figure 1 shows that most combinations of parameters do not lead to a CEMP/EMP ratio which is anywhere near the observed values – instead most results cluster around a ratio of 2% (similar to the CH-to-giant ratio mentioned above). We conclude that most of the free parameters in our model are not important for CEMP formation.

This conclusion is untrue for the parameters which affect third dredge-up in low-mass stars: $\Delta M_{\mathrm{c,min}}$, λ_{min} and $M_{\mathrm{env,min}}$. A choice of $\Delta M_{\mathrm{c,min}} \sim -0.1\,\mathrm{M}_{\odot}$ reduces the minimum core mass for third dredge-up so that it can occur in low-mass stars right down to the lower-mass limit of $0.85\,\mathrm{M}_{\odot}$. A positive λ_{min} forces third dredge-up to be efficient in low-mass stars (we chose values of 0.5 and greater). Also important is $M_{\mathrm{env,min}}$: the default value of $0.5\,\mathrm{M}_{\odot}$ prevents third dredge-up in low-mass stars because they have a small envelope mass that is too small. When we set $M_{\mathrm{env,min}}$ to zero, together with $\Delta M_{\mathrm{c,min}} \sim -0.1\,\mathrm{M}_{\odot}$ and $\lambda_{\mathrm{min}} \sim 0.5$, we find CEMP/EMP ratios of up to 15%. These ratios are far more compatible with the observations.

We must point out that we have artificially increased the amount of third dredge-up in low-mass TPAGB stars without any physical justification. However, new detailed stellar evolution models by Stancliffe and Glebbeek (2008) show third dredge-up in a $0.9\,\mathrm{M}_{\odot}$ star, albeit with an efficiency of only $\lambda = 0.16$. Alternatively, Cristallo et al. (this volume) show that proton ingestion at a first "huge pulse" may occur at higher metallicities than previously thought, perhaps up to [Fe/H] $= -2$, in stars of mass around $0.85\,\mathrm{M}_{\odot}$. This mechanism also leads to an efficient third dredge-up and carbon enrichment of the stellar envelope, as our models suggest is required. Work to simulate populations of binaries which include this mechanism is underway.

3 Tentative Conclusions

If TPAGB stars with masses as low as $0.85\,\mathrm{M}_{\odot}$ and metallicity around [Fe/H] ≈ -2.3 undergo efficient third dredge-up they may be responsible for the formation of the majority of the CEMP stars. Canonical detailed TPAGB models do not tend to support this conclusion, as only stars with masses above about $1.2\,\mathrm{M}_{\odot}$ show third dredge-up.

New detailed models suggest that third dredge-up may occur in low-mass, low-metallicity stars, possibly due to a "huge first pulse". Even if we include this very efficient third dredge-up in low-mass stars in our binary population models, we cannot increase the CEMP to EMP number ratio beyond 15% even with a binary fraction of 100%. Perhaps a combination of efficient third dredge-up with alternative binary distributions (the IMF, mass-ratio and period distributions) is responsible (Pols et al., this volume).

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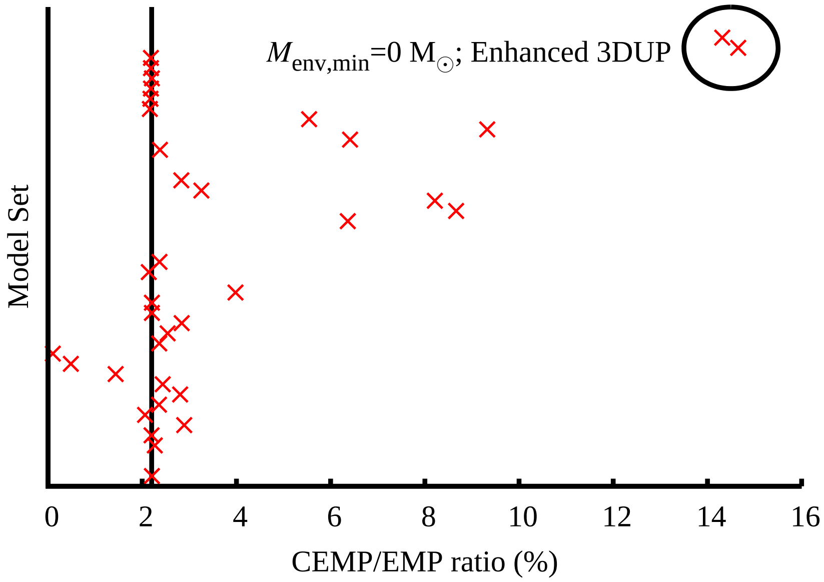

Figure 1: The CEMP/EMP ratio for our simulated binary populations. The abscissa is the CEMP/EMP ratio while the ordinate is chosen arbitrarily to separate the models with different physical parameters. The black vertical line at 2.2% shows the CEMP/EMP ratio of our default model set.

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