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Mixing processes in carbon–enhanced metal–poor stars

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Abstract. Carbon-enhanced metal-poor (CEMP) stars that are rich in *s*-process elements are believed to have formed in binary systems that once contained an asymptotic giant branch (AGB) star. The relatively unevolved object that we see today is thought to have accreted some of the AGB star's ejecta via a stellar wind. This simple picture is complicated by the occurrence of mixing of the accreted material in the secondary star, where there are many processes that can potentially alter the surface abundances. We review some of these and discuss their effects on the abundances that we may expect to observe in CEMP stars, assuming our predictions for the AGB stars themselves are correct.

Key words. Stars: carbon – Stars: evolution – Stars: AGB and Post-AGB – Stars: Population II – Binaries: General

1. Introduction

Carbon-enhanced metal-poor (CEMP) stars are defined as stars with [C/Fe][1]>+1.0 (Beers & Christlieb 2005), with [Fe/H] < −2 in most cases. These objects appear with increasing frequency at low metallicity, with the fraction of carbon-rich to carbon-normal stars being around 20% (Lucatello et al. 2006), although the current generation of theoretical models struggles to reproduce this high a fraction (Izzard et al. 2009). The study of CEMP stars is being used to probe conditions in the early Universe. For example, CEMP stars have been used to infer the initial mass function in the early Galaxy (e.g. Lucatello et al. 2005a). Chemical abundance studies have revealed that the majority of the CEMP stars are rich in *s*-process elements like barium (Aoki et al. 2003), forming the so-called CEMP-*s* group. Recent survey work has detected radial velocity variations in around 68% of these CEMP-*s* stars and this is consistent with them all being in binary systems (Lucatello et al. 2005b).

Binary systems provide a natural explanation for the se objects, which are of too low a luminosity to have been able to produce their own carbon. The primary[2] of the system was an asymptotic giant branch (AGB) star which became carbon-rich through the action of third dredge-up (the deepening of the convective envelope into regions of the star where material has undergone nuclear burning, see e.g. Iben & Renzini 1983) and transferred material on to the low-mass secondary (most likely via a stel-

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[1] [A/B] = $\log(N_A/N_B) - \log(N_A/N_B)_\odot$, where N_i is the number abundance of species i.

[2] This is the initially more massive star in the system; the secondary is the initially less massive star.

lar wind). The primary became a white dwarf and has long since faded from view, with the carbon-rich secondary now being the only visible component of the system.

It has commonly been assumed that accreted material remains unmixed on the surface of the recipient star during the main-sequence evolution and only becomes mixed with the stellar interior during first dredge-up. However, there are many processes that can modify the surface composition of the secondary once it has received this material. Here we review some of the work that has been done on the subject to date.

2. Thermohaline mixing

Material ejected from the AGB star has undergone nuclear burning. As such, this processed material has a higher mean molecular weight than the pristine material of the secondary on to which it is accreted. This is a secularly unstable situation. A blob of material, if displaced from this accreted layer and allowed to come into thermal equilibrium with its surroundings is denser than those surroundings, on account of its higher mean molecular weight. Thus the blob continues to sink, eventually dissipating and mixing with its surroundings. This process is called thermohaline mixing. It is a double-diffusive process, relying first on the diffusion of heat and subsequently on the diffusion of chemical species.

Thermohaline mixing has received much attention in recent years. It has long been recognised as being important in scenarios involving accretion, both in binary star systems (Marks & Sarna 1998) and in the accretion of planets on to stars (Vauclair 2004). In the context of carbon-enhanced metal-poor stars, thermohaline mixing has historically been ignored. Material accreted from the AGB primary was assumed to remain on the surface of the secondary (which has an extremely shallow convective envelope while on the main sequence so that there would be little mixing due to convection) and would only become mixed in when the star ascended the giant branch and developed a deep convective envelope. One would thus expect the surface abundances to be constant across the main sequence and then show a sharp drop at first dredge-up. After this, the abundance would remain constant for the rest of the giant branch.

The effect of thermohaline mixing in carbon-enhanced metal-poor stars was first studied by Stancliffe et al. (2007). Using a somewhat extreme case of a $2\,M_\odot$ star that had produced a large quantity of carbon (but more importantly helium, on account of its impact on the mean molecular weight), these authors showed that thermohaline mixing could lead to the accreted material being mixed throughout nearly 90% of a star. They showed that mixing would reach equilibrium after about a tenth of the main-sequence lifetime. In this case, no change in the carbon abundance is seen at first dredge-up, because the accreted material has already been thoroughly mixed into the secondary.

That thermohaline mixing could be as efficient as suggested by Stancliffe et al. (2007) was called into question by several authors. Denissenkov & Pinsonneault (2008) used a set of carbon-rich stars from the HERES survey (Lucatello et al. 2006) to show that the population of C-rich stars on the giant branch was consistent with coming from the same population as observed at the main-sequence turn-off, provided that the stars underwent some dilution during first dredge-up. They concluded that the average C-rich star has an accreted layer that has been mixed to a depth of $0.2\,M_\odot$ from the solar surface (or alternatively that $0.2\,M_\odot$ of material has been accreted and remains unmixed). Similar conclusions were reached by Aoki et al. (2008) using a sample of barium-rich stars.

Thompson et al. (2008) also questioned the efficiency of thermohaline mixing. Their observations of CS 22964-161 – a double-lined spectroscopic binary, consisting of two unevolved carbon-enhanced metal-poor stars – showed the presence of a high level of lithium in the system. Lithium is a highly fragile element and is destroyed at temperatures around 3.5×10^6 K. In an unevolved star, such temperatures are reached close to the stellar surface. Any amount of thermohaline mixing (or indeed, mixing of material by *any* mechanism) would lead to a depletion of lithium.

3. Gravitational settling

Thermohaline mixing is a physical process and one cannot simply ignore physics! If thermohaline mixing is inefficient in these stars, there must be something to inhibit it. Thompson et al. (2008) suggested that gravitational settling could be responsible. Helium settles from the surface, reducing the mean molecular weight at the surface but leading to an increase in the layers beneath. This produces a small region in which the mean molecular weight, μ, decreases outwards toward the stellar surface – a situation which is stable to thermohaline mixing. This stabilising composition gradient (a so-called 'μ-barrier') can inhibit the process of thermohaline mixing.

To investigate this process, Stancliffe & Glebbeek (2008) incorporated the physics of gravitational settling into their stellar evolution code. Using the prescription of Pelletier et al. (1986), with atomic and thermal diffusion coefficients taken from Paquette et al. (1986), they evolved a set of carbon-enhanced metal-poor stars taking into account both thermohaline mixing and gravitational settling. The depth to which the accreted material from their 1, 1.5 and 2-$M_\odot$ models was mixed into the secondary is shown in Figure 1.

In summary, Stancliffe & Glebbeek (2008) showed that gravitational settling was only effective in the cases where small quantities of material were accreted and where that accretion was from a low-mass companion. This is readily understandable if one considers the nature of the μ-barrier. Settling is a slow process that takes place over gigayear timescales. If the primary of the system is massive then it reaches the TP-AGB before the secondary has time to form a substantial barrier. Settling is efficient only in the outermost layers of the star. If a substantial quantity of material is accreted, this completely overwhelms any μ-barrier that might have formed.

One potential problem with gravitational settling is that it does not cease once material is accreted. As the star evolves post-accretion, the

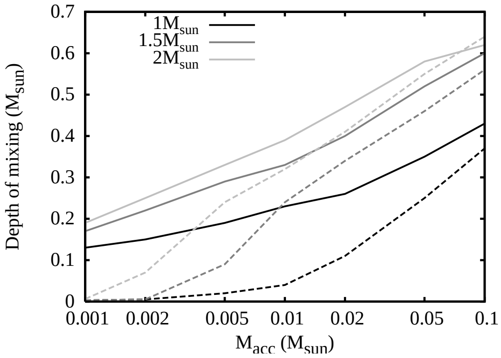

Fig. 1. Depth of mixing as a function of mass accreted by the secondary. Solid lines indicate models evolved with only thermohaline mixing taken into account. Dashed lines indicate models that have both thermohaline mixing and gravitational settling included.

heavy elements continue to settle away from the surface, lowering the [C/Fe] value. While models with settling do help to reproduce the lower envelope of the observations (see the upper panel of figure 9 in Stancliffe & Glebbeek 2008), the upper envelope fits less well because of this surface depletion due to settling. We must still be missing some important piece of physics!

4. The light elements

Carbon and nitrogen are not the only light elements that may be able to tell us about the efficiency of thermohaline mixing. Many CEMP stars also have determinations for sodium and magnesium. Fluorine has also been detected in one star, HE 1305+0132 (Schuler et al. 2007), and further determinations for other stars may become available in the near future (Lucatello et al. 2009). Lithium can also serve as a potentially useful indicator of the efficiency of mixing.

Each of these elements was investigated by Stancliffe (2009) in the hope that they would help to constrain the mixing efficiency. The fluorine rich star HE 1305+0132 was determined to be at the limit of what can be produced with the current generation of stellar models, a conclusion that had been previously reached by

Lugaro et al. (2008). Because this star is a giant, it cannot tell us much about the extent of mixing during the main sequence. Magnesium also turns out to be rather unhelpful. CEMP stars tend to be enriched in α-elements to the level of $[\alpha/\mathrm{Fe}] \approx 0.4$. As shown by figure 6 in Stancliffe (2009), [Mg/Fe] as a function of luminosity is mostly flat for barium-rich CEMP stars – there is no evidence for any change in the surface abundances at first dredge-up. The reason for this is that the ^{24}Mg already present in the star dominates the ^{25}Mg and ^{26}Mg that can be produced on the AGB.

Lithium and sodium turned out to be more useful. Stancliffe's models confirmed the expected result that lithium is strongly depleted if thermohaline mixing occurs. Even if as little as $0.001\,\mathrm{M}_\odot$ of material is accreted, thermohaline mixing efficiently depletes the surface of lithium. The inclusion of gravitational settling can reduce the effect but, again, this is only effective when small quantities of material are accreted. The downside of including gravitational settling is that it leads to the Li abundances falling over the main sequence. To counter this, Stancliffe also included the *ad hoc* mixing prescription of Richard et al. (2005). This applies turbulent mixing (of unknown physical origin!) throughout a portion of the stellar envelope. Richard et al. (2005) developed this prescription to explain the existence of the Spite Plateau and it seems reasonable that a similar mechanism may be at work in CEMP stars. The mixing prescription does prevent the drop of the surface Li abundance during the main sequence, but it also reduces the height of the μ-barrier so that the surface value reached is slightly lower than in the case of gravitational settling alone.

Stancliffe (2009) concluded that sodium showed evidence for the occurrence of thermohaline mixing. Figure 2 shows the evolution of [Na/Fe] as a function of luminosity for CEMP stars accreting $0.01\,\mathrm{M}_\odot$ from a $1.5\,\mathrm{M}_\odot$ companion. Three models are shown: one includes only convective mixing, one includes thermohaline mixing and one includes thermohaline mixing and gravitational settling. The observed abundances in CEMP stars do not support the sharp drop in the sodium abundance that one would expect in a model without thermohaline mixing. We are forced to conclude that some mixing of accreted material must take place during the main sequence[3].

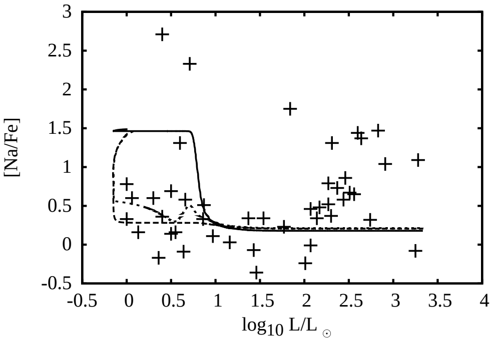

Fig. 2. The evolution of the surface [Na/Fe] with luminosity of a model in which $0.01\,\mathrm{M}_\odot$ of material has been accreted from a $1.5\,\mathrm{M}_\odot$ companion, so that the total stellar mass is $0.8\,\mathrm{M}_\odot$. The solid line is for a model with only convective mixing included. The dashed line is for a model including thermohaline mixing and the dotted line is for a model that includes both gravitational settling and thermohaline mixing. Pluses indicate sodium measurements from Ba-rich CEMP stars taken from Aoki et al. (2007) and Aoki et al. (2008).

The sodium data may also show evidence for the occurrence of yet more mixing on the giant branch. Stancliffe (2009) tentatively identified a rise in the sodium abundances above $\log_{10} L/\mathrm{L}_\odot \approx 2$. It is well known that extra mixing takes place on the giant branch in low-mass stars. Stancliffe showed that it would be possible for such a rise to take place on account of the preponderance of ^{22}Ne in the material accreted from the AGB star. A slight activation of the $^{22}\mathrm{Ne}(\mathrm{p},\gamma)^{23}\mathrm{Na}$ reaction could then produce the necessary sodium, which could then be mixed to the surface (by thermohaline mixing in the case of Stancliffe's model).

5. Mixing in AGB stars

Let us return to the issue of lithium in CEMP stars. A handful of CEMP stars have lithium

[3] Alternatively, the models could be overabundant in sodium.

abundances at the level of $\log_{10}\epsilon(\mathrm{Li}) \approx 2$. This is difficult to reconcile with the AGB mass transfer scenario because low-mass AGB stars are expected to deplete lithium. Lithium is not the only element that causes problem for the AGB mass transfer scenario. Most CEMP stars show significant enhancements of nitrogen and this is not predicted by the low-mass stellar models that we think provide the *s*-process elements. In addition, CEMP stars display $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratios no higher than around 40 *regardless* of their evolutionary state. I.e. one cannot invoke first dredge-up or mixing on the giant branch in the CEMP star as a means of producing the necessary CN-cycling. AGB models predict $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratios in excess of 10^4 (Stancliffe et al. 2009).

One solution to these problems would be to include some form of extra mixing during the AGB phase in the primary. If some process were to circulate material from the base of the convective envelope down to the hydrogen burning shell CN-cycling could take place, allowing some of the dredged up carbon-12 to be converted into carbon-13 and nitrogen-14. In addition, mixing would allow beryllium and lithium to be brought up from the hydrogen burning shell.

Parametric studies of extra mixing have shown great promise in explaining the C and N compositions of AGB stars (e.g. Boothroyd & Sackmann 1999; Nollett et al. 2003), but the physical cause of this mixing remains elusive. Following on from recent success of modelling mixing on the first giant branch using thermohaline mixing (Eggleton et al. 2006; Charbonnel & Zahn 2007; Stancliffe et al. 2009), Stancliffe (2010) investigated the effects of thermohaline mixing on low-mass, low-metallicity AGB stars. His models computed using the latest version of the STARS code (Stancliffe & Eldridge 2009) showed that thermohaline mixing could lead to significant lithium *production* during the AGB phase. In particular, his $1.5\,\mathrm{M}_\odot$ model was able to reach a final lithium abundance of $\log_{10}\epsilon(\mathrm{Li}) = 2.5$. Figure 3 shows the results of accreting this material on to a companion in which thermohaline mixing, gravitational settling and an extra turbulent process are at work. With this model, we

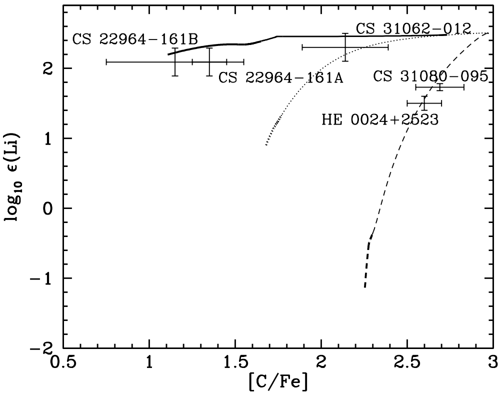

Fig. 3. The evolution of $\log_{10}\epsilon(\mathrm{Li})$ with [C/Fe] when accreting material from a $1.5\,\mathrm{M}_\odot$ companion. The cases displayed are for when $0.001\,\mathrm{M}_\odot$ (solid line), $0.01\,\mathrm{M}_\odot$ (dotted line) and $0.1\,\mathrm{M}_\odot$ (dashed line) is accreted. In each case, the secondary is left with a total mass of $0.8\,\mathrm{M}_\odot$. Bold lines indicate where $\log_1 0(g/\mathrm{cm\,s}^{-2})$ passes from 4.5 to 3.5 as the object evolves off the main sequence. The errorbars denote the locations of specific observed systems. The secondary is modelled with thermohaline mixing, gravitational settling and an extra turbulent process.

can reproduce the abundances of CS 22964-161.

Thermohaline mixing cannot be the whole answer to the abundance problems in CEMP stars. While thermohaline mixing is able to produce Li during the AGB, it is unable to substantially reduce the $^{12}\mathrm{C}/^{13}\mathrm{C}$ nor is it able to elevate the nitrogen abundance. Some other mixing mechanism must also be at work or indeed the abundance changes may be caused by a different mechanism entirely. This mechanism, or mechanisms may include rotational mixing (Charbonnel et al. 1998), gravity waves (Denissenkov & Tout 2003) or magnetic fields (Palmerini et al. 2009).

6. What now?

Many problems still remain with the carbon-enhanced metal-poor stars. Establishing which (if any) mixing processes may modify the surface compositions of these stars and how efficient are these processes is a priority. The obvious next step is to examine the heavy element abundances in these stars to see what information they can provide. In addition, modelling of mixing mechanisms acting during the AGB lifetime of the primary is also necessary to try and resolve the existing light element abundance problems.

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