THE IMPACT OF CARBON ENHANCEMENT ON EXTRA MIXING IN METAL-POOR STARS

PAVEL A. DENISSENKOV1,2 AND MARC PINSONNEAULT1

Received 2007 September 26; accepted 2008 February 19

ABSTRACT

We critically examine the constraints imposed by carbon-enhanced metal-poor (CEMP) stars on the mixing mechanisms that operate in red giants. CEMP stars are created when the surface layers of a metal-poor dwarf are enriched with He-burning products via mass transfer from an evolved donor. The difference between main-sequence (MS) and red giant CEMP abundances can be used as a diagnostic of the timescale for the mixing of the processed material into stellar interiors on the MS. Abundance trends with luminosity among red giant CEMP stars test theories of canonical extra mixing for low-mass giants with a high bulk metallicity. We find a significant dilution in CN enrichment in giant CEMP stars relative to their MS precursors, and take this as evidence that thermohaline mixing induced by mean molecular weight inversions is ineffective in CEMP stars. This contradicts models that rely on efficient thermohaline mixing induced by small $\mu$ gradients in red giants, because such models would predict that MS CEMP stars with large $\mu$ inversions would be homogenized on a very short timescale. The data do not rule out slower MS thermohaline mixing comparable to previously published estimates. We also find that canonical extra mixing is strongly suppressed in CEMP giants relative to stars with the same iron abundance. A likely cause is the shift in the location of non-equilibrium CN processing relative to the steep $\mu$ gradient in the hydrogen-burning shell, which also occurs in solar metallicity RGB stars. Implications for the mass accreted by CEMP stars and the mechanism for canonical extra mixing are discussed.

Subject headings: stars: abundances — stars: evolution — stars: interiors

1. INTRODUCTION

It has long been known that asymptotic giant branch (AGB) stars can have their surfaces enriched in helium, carbon, and slow neutron capture products, and such stars are known nucleosynthetic sources (e.g., Herwig 2005). If there is a nearby main-sequence (MS) companion, mass transfer from the giant can produce surface abundance anomalies that persist even after the AGB star is gone. Such a system would appear to be a chemically peculiar MS star. In recent years there have been large-scale surveys for metal-poor stars that have included substantial spectroscopic follow-up campaigns, such as the Hamburg/ESO r-process Enhanced Star Survey (HERES: Christlieb et al. 2004). A large population of carbon-enhanced metal-poor (CEMP) stars has been discovered (e.g., Beers & Christlieb 2005; Lucatello et al. 2006), and a majority of the CEMP stars have white dwarf companions (Lucatello et al. 2005). This is strong evidence that there is a significant population of low-mass metal-poor stars that have experienced mass transfer from a former AGB companion. Much of the interest in these stars has been driven by chemical evolution studies (e.g., Frebel et al. 2005; Tumlinson 2007). However, we wish to emphasize another important property of CEMP stars: they are unique astrophysical laboratories that can produce surface abundance anomalies that persist even after the AGB star is gone. Such a system would appear to be a chemically peculiar MS star. In recent years there have been large-scale surveys for metal-poor stars that have included substantial spectroscopic follow-up campaigns, such as the Hamburg/ESO r-process Enhanced Star Survey (HERES: Christlieb et al. 2004). A large population of carbon-enhanced metal-poor (CEMP) stars has been discovered (e.g., Beers & Christlieb 2005; Lucatello et al. 2006), and a majority of the CEMP stars have white dwarf companions (Lucatello et al. 2005). This is strong evidence that there is a significant population of low-mass metal-poor stars that have experienced mass transfer from a former AGB companion. Much of the interest in these stars has been driven by chemical evolution studies (e.g., Frebel et al. 2005; Tumlinson 2007). However, we wish to emphasize another important property of CEMP stars: they are unique astrophysical laboratories that can be used to test theories of mixing in low-mass stars. A comparison of MS and evolved CEMP stars can test the timescale for mixing on the MS, and abundance trends within evolved stars can be used to test mixing on the red giant branch (RGB). In this paper we demonstrate that CEMP stars are not fully homogenized on the MS, and that they do not experience the same RGB mixing pattern as other stars with the same iron abundance; we explore the theoretical explanations for and consequences of both results. There are sound theoretical reasons to expect internal mixing in stars that accrete mass from an evolved companion. Metal-poor turnoff stars have thin surface convection zones, and as a result their surface abundances after mass transfer will reflect the composition of the accreted material. The He and C rich ejecta of an evolved AGB star has a higher mean molecular weight $\mu$ than a normal stellar envelope. Although the strong density gradients in a star prevent a classical Rayleigh-Taylor instability when such ejecta is accreted, Stancliffe et al. (2007) pointed out that this structure is unstable against thermohaline convection.3 The precise timescale, however, depends critically on assumptions about the fluid geometry. Under the assumption of a simple spherical geometry (following Kippenhahn et al. 1980), Stancliffe et al. derived a characteristic timescale of order 1 Gyr for homogenizing a CEMP star. In this theoretical model the surface abundances are diluted through 90% of the mass of the star within this timescale for typical companion masses and ages, with only the nuclear processed core escaping full mixing. As supporting evidence, the authors cite both the absence of extremely high ([C/Fe] > 2.5)4 enrichment in MS stars and the apparent lack of a difference between MS and RGB surface abundances.

There has also been considerable interest in thermohaline mixing as an explanation for deep mixing in the envelopes of red giants. There is clear evidence that ordinary low-mass giants experience in situ mixing of CN-processed material as they become more luminous (e.g., Gratton et al. 2000; Smith & Martell 2006). The precise timescale, however, depends critically on assumptions about the fluid geometry. Under the assumption of a simple spherical geometry (following Kippenhahn et al. 1980), Stancliffe et al. derived a characteristic timescale of order 1 Gyr for homogenizing a CEMP star. In this theoretical model the surface abundances are diluted through 90% of the mass of the star within this timescale for typical companion masses and ages, with only the nuclear processed core escaping full mixing. As supporting evidence, the authors cite both the absence of extremely high ([C/Fe] > 2.5) enrichment in MS stars and the apparent lack of a difference between MS and RGB surface abundances.

There has also been considerable interest in thermohaline mixing as an explanation for deep mixing in the envelopes of red giants. There is clear evidence that ordinary low-mass giants experience in situ mixing of CN-processed material as they become more luminous (e.g., Gratton et al. 2000; Smith & Martell 2006). The precise timescale, however, depends critically on assumptions about the fluid geometry. Under the assumption of a simple spherical geometry (following Kippenhahn et al. 1980), Stancliffe et al. derived a characteristic timescale of order 1 Gyr for homogenizing a CEMP star. In this theoretical model the surface abundances are diluted through 90% of the mass of the star within this timescale for typical companion masses and ages, with only the nuclear processed core escaping full mixing. As supporting evidence, the authors cite both the absence of extremely high ([C/Fe] > 2.5) enrichment in MS stars and the apparent lack of a difference between MS and RGB surface abundances.

3 Thermohaline convection is driven by a density difference between a fluid element and its surrounding medium, provided that the latter has a higher mean molecular weight and the heat exchange keeps the temperature difference sufficiently small.

4 We use the standard spectroscopic notation: $[A/B] = \log [N(A)/N(B)] - \log [N(A)/N(B)]_\odot$, where $N(A)$ and $N(B)$ are number densities of the nuclides A and B.
Because of its universality, Denissenkov & VandenBerg (2003) proposed to call it canonical extra mixing. Rotational mixing has long been a popular explanation (e.g., Sweigart & Mengel 1979; Charbonnel et al. 1998; Denissenkov & Tout 2000; Denissenkov & VandenBerg 2003; Denissenkov et al. 2006), but viable models have proven to be difficult to construct (Chanamé et al. 2005; Palacios et al. 2006). Attention has therefore recently shifted toward other physical mechanisms.

When performing hydrodynamic simulations using the three-dimensional stellar evolution code Djehuty, Eggleton et al. (2006) found unexpected convective-like motions in the radiative envelope of an upper RGB model. They attributed this to a Rayleigh-Taylor instability (RTI) driven by a mild ($\Delta \mu / \mu \approx -10^{-4}$) $\mu$ inversion generated by $^3$He burning. $^3$He is produced by non-equilibrium $p-p$ burning on the MS and dredged up on the lower RGB. On the upper RGB, material enriched in $^3$He falls onto the hydrogen burning shell and the $^3$He($^3$He, $2p$)$^4$He reaction lowers $\mu$, while equilibrium H burning raises $\mu$ in still deeper layers; the net effect is a well-defined local minimum above the hydrogen-burning shell.

We note that the RTI would not be expected in compressible, and hence stratified, stellar material. Instead, thermohaline convection (for the same reasons as in the CEMP case) would be a natural consequence. This phenomenon would be an attractive candidate to drive canonical extra mixing if it could provide mixing depths and rates consistent with their empirically constrained values. As regards its mixing rate, Charbonnel & Zahn (2007) as well as Denissenkov & Pinsonneault (2007) have demonstrated that the $^3$He-driven thermohaline convection will be fast enough to explain the RGB abundance patterns only if fluid elements have finger-like structures with a length to diameter ratio $l/d \gtrsim 10$. This produces a much shorter mixing timescale than proposed by Kippenhahn et al. (1980).

If canonical extra mixing is to be explained by thermohaline convection, the inferred mixing timescale in MS CEMP stars should be extremely short (of order 1–10 Myr). If an MS CEMP star is mixed through 90% of its mass after a mass-transfer episode, this implies that its surface N abundance will not show a decrease (dilution) during the classical first dredge-up (FDU). Instead, $[N/Fe]$ is expected to be noticeably increased by the dredge-up of N produced at the expense of the abundant C that was brought into the core of the MS CEMP star by thermohaline convection (see Fig. 5 of Stancliffe et al. 2007). By contrast, if mixing is inefficient on the MS, one might expect that large abundance anomalies, including the observed excess of N (e.g., Aoki et al. 2007), confined to the outer layers will be diluted when the star goes to the RGB and develops a deep surface convection zone. We therefore propose using the relative abundances in MS and RGB CEMP stars as a diagnostic of the mixing timescale on the MS, and by extension as a test of the timescale for thermohaline convection in a very favorable environment.

Canonical extra mixing might also be expected to set in for CEMP stars when they reach the upper RGB, and a distinctive manifestation of canonical extra mixing at low metallicities is a decline of $[C/Fe]$ with increased luminosity (e.g., Smith & Martel 2003). There have been published claims (Lucatello et al. 2006; Aoki et al. 2007) that the abundances of CEMP stars decline with increased luminosity. However, these studies did not separate out the MS/RGB transition (which tests the depth of accreted material) from the RGB trends. We therefore both examine the data for trends with luminosity and compare to theoretical expectations for empirical models based on normal metal-poor giant data. Again, in addition to the direct implications, our test can be used to study the metallicity dependence of RGB mixing. It is known that solar abundance open-cluster RGB stars have weaker extra mixing than globular cluster giants (e.g., Chanamé et al. 2005). However, the open cluster giants are both more metal-rich and more massive; both properties could influence the mixing pattern. CEMP stars permit a direct comparison of low-mass stars with different metal abundances.

2. OBSERVATIONAL DATA

Ideally, our goal would be to select a sample of binary mass transfer systems where we can look for abundance trends both between MS and RGB stars and with luminosity on the RGB. There are now large samples of CEMP stars, but there are obvious potential biases associated with examining abundance patterns in samples defined by abundance measurements. As a result, some discussion of the selection of the observational sample is essential.

One important clue is that the amount of carbon in CEMP stars is very high relative to halo non-C-enhanced stars. This is most clearly seen in the anticorrelation between $[C/Fe]$ and $[Fe/H]$ (Fig. 3 in Aoki et al. 2007). This is the pattern that one would expect if mass transfer from an evolved companion gave the recipient star so much C that the initial inventory was negligible. However, especially at the iron-poor end, some chemical evolution models might be able to produce exotic abundance patterns for the primordial composition (e.g., Ryan et al. 2005; Frebel et al. 2005; Komiya et al. 2007). Fortunately, the binary mass-transfer model makes other predictions: there should still be a white dwarf companion and there should be associated $s$-process anomalies. A majority of CEMP stars exhibit radial velocity variations consistent with a white dwarf companion; the observed fraction of 68% is consistent with all CEMP stars being in binaries (Lucatello et al. 2005). Extensive surveys have also shown $s$-process enrichment (e.g., Barklem et al. 2005; Aoki et al. 2007).

We have therefore used two samples of CEMP stars: a smaller sample from Aoki et al. (2007) in which only stars with $s$-process enhancement ($[Ba/Fe] > +0.5$) were included (Fig. 1a), and a larger one (Lucatello et al. 2006) where the standard definition
The CEMP stars appears to be the standard first dredge-up at 0
sample of stars from the HERES survey (Barklem et al. 2005)
used in that paper to infer
from Barklem et al.’s original paper. The automated procedure
field halo stars (Fig. 1)
L
log
the error bars) stars. The latter are seen to experience canonical extra mixing at
No. 2, 2008
CARBON ENHANCEMENT AND EXTRA MIXING 1543

((C/Fe) > 1) was used to distinguish between CEMP and normal
field halo stars (Fig. 1b). Lucatello et al.’s sample is in fact a sub-
ample of stars from the HERES survey (Barklem et al. 2005)
that were reanalyzed. We did not use the stars with [C/Fe] > 1
from Barklem et al.’s original paper. The automated procedure
used in that paper to infer \(T_{\text{eff}}\) values from colors became unre-
liable for CEMP stars with strong CH, C2, and CN molecular bands
(S. Lucatello 2007, private communication). The luminosities
were inferred from the surface gravity and \(T_{\text{eff}}\) with an assumed
mass of \(M = 0.8-0.85\ M_\odot\). The values of \(\log L/L_\odot\) ≤ 0.8
\(\log L/L_\odot\) ≥ 1.4 were defined as the divisions between unevolved
MS and subgiant stars that have not yet experienced the FDU and
evolved RGB stars in which the FDU has already ended. We
have found that 10 out of 14 unevolved stars in the second sample
have [Ba/Fe] > +1 according to Barklem et al.’s data, which is a
distinctive feature of accretion of AGB material.

We compare the trends in our small and large CEMP samples
in Figure 1, and find that they are very similar. In fact, the [C/H]
abundances in the two samples have the same linear fit (black
lines in our Fig. 1 reproduce those from the respective figures of
Lucatello et al. 2006 and Aoki et al. 2007). We also note that
there is a small, but real, difference between the MS and RGB
abundances. To be more precise, Lucatello et al. (2006) have
obtained very similar slopes of
\(-0.18 \pm 0.05, -0.21 \pm 0.05,\)
\(-0.19 \pm 0.04\) for [C/H], [N/H], and [C+\ N]/H,
respectively. We argue that this is evidence for dilution of enriched
material in the MS stars by the classical FDU in the RGB stars. Both
effects are quantified below.

Under the binary mass-transfer hypothesis, the initial carbon
inventory is dwarfed by the transferred carbon, so the physical
quantities of interest are [C/H] and [N/H] rather than [C/Fe]
and [N/Fe]. As a result, we work in the former plane. There is a
striking difference in carbon as a function of luminosity between
CEMP stars (blue open circles in Fig. 2 representing the data
from Lucatello et al. 2006) and normal halo stars (black filled
circles in Fig. 2 showing the data from Barklem et al. 2005),
with canonical extra mixing being clearly seen in the non-C-
enhanced stars above \(\log L/L_\odot \approx 2.2\), but not in the CEMP stars.
The black curve reproduces the evolutionary decline of [C/H]
in the non-C-enhanced stars by our stellar models with can-
nical extra mixing (for details, see next section). The red curve
is a model constructed under the assumption that neither the
MS thermohaline convection nor RGB extra mixing have taken
place. The only mixing event experienced by this model is the
standard FDU. It seems to adequately describe the [C/H] abun-
dances in the CEMP stars.

3. REDUCED EFFICIENCY OF CANONICAL EXTRA
MIXING IN RGB CEMP STARS

In this section, we show that the efficiency of canonical extra
mixing in CEMP stars is strongly reduced. This is most likely
due to shallower mixing which does not penetrate deep enough
to dredge up carbon-deficient material. The most plausible in-
terpretation of the shallower mixing depth is that it is limited by a
steeper \(\mu\)-gradient built up by H burning on the abundant \(^{12}\)C
nuclei. Denissenkov et al. (2006) came to a similar conclusion
for solar metallicity red giants. Given that RGB mixing is ineff-
cient in CEMP stars, we can use the C and N abundance distribu-
tions for unevolved (the MS and subgiant branch) and evolved
(upper RGB) CEMP stars to test the FDU and draw conclusions
about the efficiency of thermohaline convection in MS CEMP
stars. This will be done in the next section.

The slope of [C/H] as a function of \(\log L/L_\odot\) produced by
canonical extra mixing depends on the mixing depth and diffusion
coefficient \(D_{\text{mix}}\). We model canonical extra mixing by setting \(D_{\text{mix}}\)
equal to a fixed fraction of the thermal diffusivity \(K\). This param-
terization takes into account that large-scale mixing instabilities
in a stably stratified radiative zone may only develop on a time-
scale longer than the thermal one, in which case one would ex-
pect \(D_{\text{mix}} < K\). The known examples of such instabilities that
have been proposed as possible driving mechanisms for canonical
extra mixing are rotational shear instability (Denissenkov &
Tout 2000; Denissenkov & VandenBerg 2003; Denissenkov et al.
2006) and thermohaline convection (Charbonnel & Zahn 2007;
Denissenkov & Pinsonneault 2007). In the latter case, the diffusion
efficient can be estimated using the following heuristic expression:

\[
D_{\text{mix}} \approx \left(\frac{l}{d}\right)^2 \frac{\nabla_\mu}{\nabla_{\text{ad}} - \nabla_{\text{rad}}} K, \tag{1}
\]

where \(\nabla_\mu < 0, \nabla_{\text{ad}}, \) and \(\nabla_{\text{rad}}\) are the \(\mu\)- and temperature (adiabatic
and radiative) gradients (logarithmic and with respect to pressure).
Note that \(D_{\text{mix}}\) should formally vanish wherever \(\nabla_\mu \geq 0\).
Equation (1) adequately represents both the diffusion coefficient
for thermohaline convection derived by Kippenhahn et al. (1980)

\[
D_{\text{Kipp}} = \frac{3K}{\nabla_{\text{ad}} - \nabla_{\text{rad}}} |\nabla_\mu|, \tag{2}
\]

who argued that the length (or the mean free path) \(l\) of a con-
vective element should be of the order of its diameter \(d,\) and the
rate of mixing by elongated narrow “fingers” \((l > d)\) advocated
by Ulrich (1972),

\[
D_{\text{Ulrich}} = \frac{8}{3} \pi^2 \frac{K}{\nabla_{\text{ad}} - \nabla_{\text{rad}}} |\nabla_\mu| \left(\frac{l}{d}\right)^2. \tag{3}
\]
Unfortunately, the ratio \( l/d \) cannot be estimated from first principles. Semiempirical models require \( l/d > 10 \) to generate sufficient mixing to explain the data (Charbonnel & Zahn 2007; Denissenkov & Pinsonneault 2007). The maximum depth of the \(^3\)He-driven thermohaline convection is uncertain also. Indeed, the simple assumption that it coincides with the location of the minimum on the \( \mu \)-profile produces mixing that is too shallow (Denissenkov & Pinsonneault 2007). Therefore, we have to admit that thermohaline convection overshoots beneath the point at which \( \nabla \mu \) crosses the zero line in the absence of mixing (Fig. 3c). Hence, thermohaline convection has to penetrate a region with a positive \( \nabla \mu \), where it is strongly decelerated. VandenBerg & Stetson (2004) have estimated the average extent of overshooting beyond the convective core border in massive MS stars, which turns out to be a \( \sim 0.20-0.25 \) fraction of a pressure scale height \( H_P \). If thermohaline convection overshoots the same distance, it would still be too shallow to reproduce the evolutionary decrease of \([C/Fe]\) in upper RGB stars (e.g., Gratton et al. 2000; Smith & Martell 2003). This conclusion is based on results of computations presented by Denissenkov & Pinsonneault (2007). It can also be anticipated by comparing Figures 3a and 3c, given that we find \( H_P/r \approx 0.3 \) at \( r \approx 0.05 \, R_\odot \). Therefore, we have chosen to specify the mixing depth using a radius \( r_{\text{mix}} \) (in units of \( R_\odot \)) down to which mixing is allowed to penetrate from the bottom of the convective envelope, and adjust it appropriately. This choice is motivated by our finding that the \( \mu(r) \) does not change much with time. In the absence of any information on how the mixing depth should vary with time, keeping \( r_{\text{mix}} \) constant is a reasonable parameterization.

To allow an interpolation in the abundances of He and C as the AGB material gets redistributed inside an accreting star by convection and extra mixing, we have modified our stellar evolution code (Denissenkov et al. 2006) to include the 2005 version of the OPAL equation of state (Rogers et al. 1996).\(^5\) Taking into account that the average metallicity of the non-C-enhanced stars from the spectroscopic study of Barklem et al. (2005) is \( \langle [Fe/H] \rangle \approx -2.7 \), we have represented them with a stellar model having the heavy-element mass fraction \( Z = 4 \times 10^{-5} \). For the initial helium mass fraction, stellar mass, and mixing length parameter, we have used the values \( Y = 0.24, M = 0.85 \, M_\odot \), and \( \alpha_{\text{MLT}} = 1.58 \), respectively (Lucatello et al. 2006).

We begin with the normal halo star sample, and we use them to constrain our model of canonical extra mixing. The sharp decline of \([C/H]\) at log\( L/L_\odot \geq 2.2 \) in the non-C-enhanced very metal-poor (VMP) stars (Fig. 2) has been reproduced by us with \( r_{\text{mix}} = 0.05 \, R_\odot \) and \( D_{\text{mix}} = 0.1 \). The chosen depth is shown with the vertical black line in Figure 3a. It guarantees that material deficient in C is dredged up to the bottom of convective envelope, as indicated by observations. A similar result can be obtained for a slightly smaller \( r_{\text{mix}} \) with an appropriately reduced value of \( D_{\text{mix}} \), e.g., for \( r_{\text{mix}} = 0.045 \, R_\odot \) and \( D_{\text{mix}} = 0.04 \). At the adjusted mixing depths \( T(r_{\text{mix}}) \) is lower than the temperature at the base of the H shell by \( \Delta \log T \approx 0.24 \) and 0.19, respectively, which agrees very well with the estimates obtained by Denissenkov & VandenBerg (2003) based on globular cluster data.

Our results for the CEMP stars are plotted in Figure 4. The short-dashed red and solid blue curves have been computed for a stellar model with \( Y = 0.24 \) and \( Z = 10^{-4} \) (the CEMP stars have \( \langle [Fe/H] \rangle \approx -2.1 \) whose initial mass and CN abundances were \( M = 0.7 \, M_\odot, [C/Fe] = +0.3 \), and \( [N/Fe] = -0.5 \). Following Stanciliffe et al. (2007), we have assumed that at the age of 0.86 Gyr the star began accreting material with the rate \( 10^{-6} \, M_\odot \, \text{yr}^{-1} \) from its AGB binary companion. The total mass accreted and its He and CN abundances were chosen to be \( M_{\text{accr}} = 0.15 \, M_\odot, Y = 0.34, [C/Fe]_{\text{accr}} = +2.1 \), and \( [N/Fe]_{\text{accr}} = +1.6 \).

Canonical extra mixing in our CEMP model has been modeled using the same mixing parameters that we have adjusted for the non-C-enhanced VMP stars. Comparing the \([C/H]\) data at
The average abundance yields predicted by Herwig (2004) for metal-poor squares, respectively, are lower than those for the CEMP stars with \( \log g > 3.5 \) and \( \log g < 3.5 \). Magenta asterisks represent the average abundance yields predicted by Herwig (2004) for metal-poor AGB models whose masses (in \( M_\odot \)) are given below the data points. Black curve shows changes of the surface C and N abundances produced by canonical extra mixing with the depth \( r_{\text{mix}} = 0.045 \, R_\odot \) and rate \( \dot{r}_{\text{mix}} = 0.04 \, \text{K} \) in an RGB model with \( M = 0.83 \, M_\odot \) and \( Z = 0.0001 \). Note that most of the CEMP stars are located in the gap between the predicted AGB yields.

\[
\log L/L_\odot \approx 2.4 \quad \text{with the short-dashed red and solid blue curves in Figure 4a, we infer that the efficiency of canonical extra mixing appears to be strongly reduced in the CEMP stars compared to their non-C-enhanced VMP counterparts.}
\]

The reduced efficiency of canonical extra mixing in the CEMP stars becomes even more evident when we consider their [N/H] values as a function of luminosity (Fig. 4b). CN processing for a high initial carbon should result in a sharp increase of [N/H] on the upper RGB (the short-dashed red and solid blue curves at \( \log L/L_\odot \approx 2.4 \)). Contrary to this, the observed trend of [N/H], as well as those of [C/H] and the sum \([C+N]/H\), with luminosity were characterized by Lucatello et al. (2006) as gradual declines (long-dashed black lines in Fig. 4). They have ascribed them to a dilution “by mixing with a much larger H content.” We concur in part, and interpret the decline from the MS to the RGB as a dilution effect produced by the FDU alone. However, we also believe that representing this dilution as a continuing process occurring on the RGB is not supported. The FDU is effectively complete at \( \log L/L_\odot \approx 1.4 \). At 1.4 \( \leq \log L/L_\odot \leq 1.8 \), the convective envelope mass is still increasing, but only by another 3–4%. So, no noticeable changes of the surface chemical composition due to the FDU dilution would be expected above \( \log L/L_\odot \approx 1.4 \), and we contend that no trend is seen.

Canonical extra mixing begins to operate only at \( \log L/L_\odot \approx 2.4 \) but it must increase the surface N abundance, as in fact it does in non-C-enhanced VMP stars (the open blue circles in Fig. 5), and not decrease it. Hence, a dilution of the accreted He-, C-, and N-rich material can only occur either on the MS, as a result of thermohaline convection, or on the lower RGB at 0.8 \( \leq \log L/L_\odot \leq 1.4 \), as a result of the FDU. We will return to this problem in the next section. Here, we have to conclude that, as revealed by the non-increase of [N/H] in the upper RGB CEMP stars, canonical extra mixing does not manifest itself in them. This conclusion agrees with the different behavior of [C/H] at high luminosities in the CEMP and non-C-enhanced VMP stars (Fig. 2).

Interestingly, there is another group of stars in which canonical extra mixing is observed to have a low efficiency. These are low-mass RGB stars of nearly solar metallicity. Only modest depletions of the carbon isotopic ratio \( ^{12}\text{C}/^{13}\text{C} \approx 10–15 \) are reported in them, while the variations of [C/H] and [N/H] are close to their FDU limits (e.g., Gilroy & Brown 1991; Origlia et al. 2006). This contrasts with metal-poor red giants in which canonical extra mixing often reduces the \( ^{12}\text{C}/^{13}\text{C} \) ratio down to its equilibrium value \(~4\), which is accompanied by the well-marked evolutionary decline of [C/H]. Charbonnel et al. (1998) have shown that such a dependence of the efficiency of canonical extra mixing on metallicity is expected if the mixing cannot penetrate below some universal critical \( \mu \)-gradient (\( \nabla _\mu \)) in the core. Recently, Denissenkov et al. (2006) have proposed that this mixing is driven by a contribution to the \( \mu \)-gradient from the H depletion that accompanies the C to N transformation. This contribution increases with the metallicity because \( N(C) \propto Z \). At a metallicity close to the solar one, the H burning on the \(^{12}\text{C}\) nuclei builds up an additional hump in the \( \mu \)-gradient profile that prevents mixing from approaching the H-burning shell as close as in metal-poor giants. If this interpretation is correct, then the reduced efficiency of canonical extra mixing in RGB CEMP stars is almost definitely caused by their much higher C abundances compared to their non-C-enhanced counterparts.

To test this hypothesis, we confront the CN-abundance and \( \nabla _\mu \) profiles in the vicinity of the H-burning shell in our two upper RGB models in which the H shell has just erased the discontinuity in the H-abundance profile left behind by the bottom of the convective envelope at the end of the FDU (it is not until this moment when canonical extra mixing begins to manifest itself). The first model represents the non-C-enhanced VMP stars: it has \( M = 0.85 \, M_\odot , Z = 4 \times 10^{-5} , [\text{C/Fe}] = +0.3 , \) and \([\text{N/Fe}] = -0.5 \) (Figs. 3a and 3c). The second had the initial mass \( M = 0.7 \, M_\odot \) and abundances \( Z = 10^{-4} \), \([\text{C/Fe}] = +0.3 , \) and \([\text{N/Fe}] = -0.5 \); but it had accreted 0.15 \( M_\odot \) of material with \([\text{C/Fe}] = +2.1 \) and \([\text{N/Fe}] = +1.6 \) (Figs. 3b and 3d). The vertical line crossing Figures 3a and 3c shows the mixing depth \( r_{\text{mix}} = 0.05 \) that has been used to model the evolutionary decline of [C/H] in the non-C-enhanced VMP stars. The horizontal line crossing Figures 3c and 3d reads the value of \( \nabla _\mu \text{crit} \approx 3.6 \times 10^{-3} \) corresponding to this mixing depth. When applied to the C-enhanced model this \( \nabla _\mu \text{crit} \) determines a shallower mixing depth \( r_{\text{mix}} \approx 0.061 \), Figs. 3b and 3d) with which extra mixing will only be able to diminish the surface \(^{12}\text{C}/^{13}\text{C} \) ratio without changing [C/H] and [N/H] (Fig. 3b). For comparison, dotted curves in Figures 3b and 3d show the C-abundance and \( \nabla _\mu \) profiles in a solar metallicity 1 \( M_\odot \), RGB model. It is seen that in terms of the depth of canonical extra mixing the CEMP model is equivalent to the solar metallicity model. Hence, it is most likely the mixing depth that is affected by the variation of the star’s C content in the first place.

For our CEMP model, we have intentionally chosen the large positive value of [N/Fe]_{accr}, because it resembles the observed N abundance anomaly in unevolved CEMP stars. It is thought that \(^{12}\text{C}\) dredged up from the He-burning shell in AGB stars might have partially been converted into N in the hot-bottom burning (in more massive AGB stars) or by extra mixing similar to the canonical one (Nollett et al. 2003; Masseron et al. 2006; Sivarani et al. 2006; Johnson et al. 2007). To illustrate this point, we have reproduced in a slightly modified form Figure 4 from the paper of Sivarani et al. (2006) in our Figure 5. For non-C-enhanced

![Fig. 5.—C and N abundances for the unmixed and mixed VMP stars (filled and open blue circles, respectively) obtained by Spite et al. (2005), as well as those for the CEMP stars with \( \log g > 3.5 \) and \( \log g < 3.5 \) (filled and open red squares, respectively) compiled by Sivarani et al. (2006). Magenta asterisks represent the average abundance yields predicted by Herwig (2004) for metal-poor AGB models whose masses (in \( M_\odot \)) are given below the data points. Black curve shows changes of the surface C and N abundances produced by canonical extra mixing with the depth \( r_{\text{mix}} = 0.045 \, R_\odot \) and rate \( \dot{r}_{\text{mix}} = 0.04 \, \text{K} \) in an RGB model with \( M = 0.83 \, M_\odot \) and \( Z = 0.0001 \). Note that most of the CEMP stars are located in the gap between the predicted AGB yields.](image-url)
VMP stars, we have used the data obtained by Spite et al. (2005; filled and open blue circles denote unmixed and mixed RG stars in their terminology). For CEMP stars, we have used the data compiled by Sivarani et al. (2006; filled and open red squares represent stars with $\log g > 3.5$ and $\log g < 3.5$, respectively). We have also plotted the C and N average abundances returned to the ISM by metal-poor AGB stars, as predicted by Herwig (2004; magenta asterisks with numbers below them giving the AGB model’s mass). The black curve in Figure 5 shows changes of the surface C and N abundances in an RGB model with $M = 0.83 M_\odot$ and $Z = 0.0001$ produced by canonical extra mixing with the depth $r_{\text{mix}} = 0.045 R_\odot$ and rate $D_{\text{mix}} = 0.04 K$. It is important to note that open blue circles (mixed stars) are located on the upper RGB (Spite et al. 2005). This observational fact and a comparison of our black curve with the blue data points support the conclusion made by Spite et al. (2005) that they had revealed the abundance patterns produced by canonical extra mixing in VMP stars.

It is interesting that most of the CEMP stars in Figure 5 fill the gap between the C and N abundance yields predicted for the low- and intermediate-mass AGB stars. The latter are well separated from the former because in the intermediate-mass AGB models C is efficiently transformed into N at the bottoms of their convective envelopes (the hot-bottom burning). The mysterious location of the CEMP stars in the gap probably indicates that in their low-mass AGB donors’ C was also transported down to a high-temperature region where it was partially transformed into N. The rather low carbon isotopic ratios (12C/13C < 40) in low-luminosity s-element-rich CEMP stars (Ryan et al. 2005) support this hypothesis, because without such extra mixing the low-mass AGB stars would produce $12C/13C > 1000$ (Herwig 2004).

4. LOW EFFICIENCY OF THERMOHALINE CONVECTION IN MS CEMP STARS

In the previous section, we have presented observational and theoretical arguments for the shallower depth of canonical extra mixing in RGB CEMP stars. The depth seems to be shallow enough for extra mixing to leave the post-FDU C and N abundances unchanged. As we noted, the FDU starts at $\log L/L_\odot = 0.8$ and it effectively ends at $\log L/L_\odot \approx 1.4$ (solid blue curve in Fig. 4c). Hence, we can compare the C and N abundance distributions for the CEMP stars with $\log L/L_\odot < 0.8$ and for those with $\log L/L_\odot > 1.4$ to estimate the degree of dilution of the CN-rich material by the FDU. These are plotted in Figures 6a and 6b (for our larger sample) and 6c (for the smaller sample). We see that the distributions for the stars that have not experienced the FDU yet (shaded histograms) are shifted toward higher abundances with respect to the distributions for the stars in which the FDU has already ended (thick solid histograms). This holds

---

**Fig. 6.** (a, c) C and (b) N abundance distributions for the CEMP stars that have not experienced the FDU yet (shaded histograms) and for those in which the FDU has already ended (thick solid curves). The data are from Lucatello et al. (2006; panels a and b) and from Aoki et al. (2007; panel c). (d) Kolmogorov-Smirnov probabilities that the shaded histograms in panels a and b do not differ from their thick solid counterparts after being shifted to the left by $\Delta [X/H]$. 
lower than in the radiative zone of the RGB model. As a result, the MS thermohaline diffusion coefficient can be less than 10% of $D_{\text{mix}}$ in the RGB model. However, this rate is still fast enough to mix the MS CEMP star on a timescale shorter than 10 Myr, i.e., almost instantaneously compared to the star’s MS lifetime. The evidence that this does not happen casts doubt on thermohaline convection as the mechanism for canonical extra mixing.

5. CONCLUSIONS

In this paper, we have put forward the hypothesis that the anomalously high C abundances in the material accreted by MS CEMP stars result in shallower depths of canonical extra mixing in these stars during their subsequent RGB evolution. The shallower mixing depths are limited by steeper $\mu$-gradients produced by the H burning on abundant $^{12}$C nuclei. A similar phenomenon occurs in open cluster RGB stars, which are of comparable total metal abundance. Until now, it was not clear whether the reduced efficiency of mixing in open cluster giants was caused by their higher metallicity or their higher mass relative to globular cluster giants. We now see the same trend in low-mass CEMP giants, and can therefore conclude that metallicity is the primary determinant of the depth of mixing. Mixing would still be expected in the outer envelopes of these giants, and could impact other diagnostics, such as the $^{12}$C/$^{13}$C ratio. Observational data on abundance trends with luminosity of tracers of shallower mixing, such as the carbon isotopic ratio, would be a useful further test of this theoretical prediction.

For thermohaline mixing to be effective on the RGB, the timescale must be 100–1000 times shorter than thekippenhahn et al. (1980) estimates. A comparable increase in efficiency on the MS relative to the Stancliffe et al. (2007) estimates would imply a mixing timescale far shorter than the MS lifetime. As a result, we would expect to see no dilution effect in the abundances, which contradicts the data. We therefore conclude that thermohaline mixing is inefficient in MS CEMP stars, contrary to the natural prediction of models where it is the dominant mechanism for RGB mixing. In light of the potential importance of this conclusion, we now discuss the limits that we can place on the timescale of MS mixing, potential observational and theoretical issues, and future observational tests.

We cannot make a similarly strong claim for thermohaline convection operating over Gyr timescales, as advocated by Stancliffe et al. (2007). Our globally averaged result is a 0.2 $M_\odot$ average amount of the accreted material; this could be an unmixed 0.2 $M_\odot$ accreted layer, or an initially lower mass accreted layer that has diffused to an average depth of 0.5 $M_\odot$. To estimate the ratio, and hence ($M_{\text{acc}}$, we shifted the shaded histograms to the left by small steps in $[X/H]$, where $X$ stands for C and N (the shifts were applied to each star in the group), and, after each step, we calculated the Kolmogorov-Smirnov probability $P_{\text{KS}}$ that the shifted shaded and thick solid histograms were drawn from the same (real) parent distribution. Results of this statistical test are plotted in Figure 6d. They show that the same shift $\Delta [X/H] \approx 0.4$ leads to the maximum and quite large values of $P_{\text{KS}}$ for both C and N. Neglecting the initial CN abundances, as compared to their accreted and post-FDU values, we estimate $\langle M_{\text{acc}} \rangle \approx 10^{-\Delta [X/H]} M_{\odot} \approx 0.2 M_\odot$.

The fact that the pre-FDU and post-FDU C and N abundance distributions are surprisingly well separated implies a low efficiency of thermohaline convection in MS CEMP stars, which has immediate implications for RGB mixing. In Figure 7, we illustrate the $\mu$-profiles in our MS ($\text{red curve}$) and upper RGB ($\text{blue curve}$) CEMP models. On the scale of the MS inversion ($\Delta \mu/\mu_{\text{MS}} \approx 0.1$, the tiny RGB depression ($\Delta \mu/\mu_{\text{RGB}} \approx 10^{-4}$ at $r \approx 0.067 R_\odot$ can hardly be seen. When comparing these profiles, one should keep in mind that the efficiency of thermohaline convection is also proportional to the thermal diffusivity $K$ (eq. [1]). In the MS model, $K$ is $3-4$ orders of magnitude

true for both the C (Figs. 6a, 6c) and N (Fig. 6b) abundances. There is a difference in the mean too, but it is not statistically significant because of the large star-to-star scatter. However, there is a clearly defined median, and we employ a median based test. We interpret the abundance distribution shifts as a signature of the FDU dilution. In this interpretation, the amplitude of the shift depends on both the average accreted mass ($M_{\text{acc}}$) and the maximum mass of convective envelope attained during the FDU $M_{\text{CE}} \approx 0.5 M_\odot$. To estimate their ratio, and hence ($M_{\text{acc}}$, we shifted the shaded histograms to the left by small steps in $[X/H]$, where $X$ stands for C and N (the shifts were applied to each star in the group), and, after each step, we calculated the Kolmogorov-Smirnov probability $P_{\text{KS}}$ that the shifted shaded and thick solid histograms were drawn from the same (real) parent distribution. Results of this statistical test are plotted in Figure 6d. They show that the same shift $\Delta [X/H] \approx 0.4$ leads to the maximum and quite large values of $P_{\text{KS}}$ for both C and N. Neglecting the initial CN abundances, as compared to their accreted and post-FDU values, we estimate $\langle M_{\text{acc}} \rangle \approx 10^{-\Delta [X/H]} M_{\odot} \approx 0.2 M_\odot$.

While our paper was being reviewed, Aoki et al. (2008) supported this conclusion by comparing the $[C/H]$ ratios in MS turnoff and RGB CEMP stars.
the latter effect in the data; the observed carbon anomalies are well-separated from the normal halo star pattern. Effective temperature scale estimates are a more significant concern, especially for color-based estimates, because of the spectral energy distribution distortions from very high [C/Fe] ratios. Aoki et al. (2007), for example, found evidence for iron abundances dependent on the excitation potential of the lines, which is usually a signature of an incorrect effective temperature. However, to have an impact on our results there would need to be a differential impact on the abundances derived in dwarfs and giants, rather than an overall systematic effective temperature shift, and Aoki et al. did not report such an effect. We also note that very similar relative trends appear in samples where spectroscopic and color-based effective temperature estimates are employed.

Is there a theoretical mechanism that could differentially suppress thermohaline convection in MS (but not RGB) stars? Denissenkov & Pinsonneault (2007) have proposed that thermohaline convection can be suppressed by horizontal turbulent diffusion. It is, at least in principle, possible to invoke stronger horizontal turbulence in dwarfs than in giants. Angular momentum constraints from the existence of rapid rotation in horizontal branch stars do imply strong differential rotation with depth in the convective envelopes of RGB stars (Peterson 1983; Pinsonneault et al. 1992; Sills & Pinsonneault 2000). One would therefore expect rotation rates in the RGB envelope comparable to those in MS radiative interiors, and as a result comparable degrees of horizontal turbulence. This is an area that deserves further theoretical scrutiny.

There is indirect evidence for extra mixing in low-mass AGB stars (e.g., see Fig. 5 and its discussion in § 3). However, if extra mixing in RGB stars is really driven by 3He burning, then it should die out by the end of the RGB evolution because of the 3He exhaustion. In this case, the 3He-driven thermohaline convection could not resume working in the same stars on the asymptotic giant branch (AGB). So, we would expect the absence of observational signatures of extra mixing in low-mass ($M \leq 2 M_\odot$) AGB stars unless the mixing in them is of a different nature. However, given the similarities in their depth and in the structure of the radiative zone where they operate, it is unlikely that the RGB and AGB mixing have different physical mechanisms.

Further observational work would be extremely fruitful. Samples should be examined for their binary nature in order to generate binary mass transfer samples, and both the reliability of temperature estimates and the relative and absolute abundance errors should be rigorously examined. If thermohaline convection occurs over an intermediate timescale, there should be a difference in the mean abundance level between MS stars that experienced mass transfer recently and stars with older mass transfer episodes. Hotter white dwarfs can be detected photometrically, particularly for dwarf CEMP stars, and a difference in surface abundance between systems with younger and older white dwarf companions would be definitive evidence for (or argument against) a moderate timescale for thermohaline mixing.

We are grateful to Sara Lucatello for sending us the C and N abundance data for the CEMP stars. It is our pleasure to thank Jennifer Johnson, Thomas Masseron, Grant Newsham, Kristen Sellgren, and Don Terndrup for useful discussions. We acknowledge support from the NASA grant NNG05 GG20G.

REFERENCES

Aoki, W., Beers, T. C., Christlieb, N., Norris, J. E., Ryan, S. G., & Tsangarides, S. 2007, ApJ, 655, 492
Aoki, W., Beers, T. C., Sivarani, T., Marsteller, B., Lee, Y. S., Honda, S., Norris, J. E., Ryan, S. G., & Carollo, D. 2008, ApJ, 678, 1351
Barklem, P. S., et al. 2005, A&A, 439, 129
Beers, T. C., & Christlieb, N. 2005, ARA&A, 43, 531
Chanamé, J., Pinsonneault, M., & Terndrup, D. M. 2005, ApJ, 631, 540
Charbonnel, C., Brown, J. A., & Wallerstein, G. 1998, A&A, 332, 204
Charbonnel, C., & Zahn, J.-P. 2007, A&A, 467, L15
Christlieb, N., et al. 2004, A&A, 428, 1027
Denissenkov, P. A., Chaboyer, B., & Li, K. 2006, ApJ, 641, 1087
Denissenkov, P. A., & Pinsonneault, M. 2007, ApJ, submitted (arXiv:0708.3864v1)
Denissenkov, P. A., & Tout, C. A. 2000, MNRAS, 316, 395
Denissenkov, P. A., & Vandenberg, D. A. 2003, ApJ, 593, 509
Eggleton, P. P., Dearborn, D. S. P., & Lattanzio, J. C. 2006, Science, 314, 1580
Frebel, A., Aoki, W., Christlieb, N., et al. 2005, Nature, 434, 871
Gilroy, K. K., & Brown, J. A. 1991, ApJ, 371, 578
Gratton, R. G., Sneden, C., Carretta, E., & Bragaglia, A. 2000, A&A, 354, 169
Herwig, F. 2004, ApJS, 155, 651
———. 2005, ARA&A, 43, 435
Johnson, J. A., Herwig, F., Beers, T. C., & Christlieb, N. 2007, ApJ, 658, 1203
Kimpenhahn, B., Ruschenplatt, G., & Thomas, H.-C. 1980, A&A, 91, 175
Komiyama, Y., Suda, T., Minaguchi, H., Shigeysama, T., Aoki, W., & Fujimoto, M. Y. 2007, ApJ, 658, 367
Komiya, Y., Suda, T., Minaguchi, H., Shigeysama, T., Aoki, W., & Fujimoto, M. Y. 2007, ApJ, 658, 367
Kippenhahn, R., Ruschenplatt, G., & Thomas, H.-C. 1980, A&A, 91, 175
Knobben, C., & Zahn, J.-P. 2007, A&A, 467, L15
Lucatello, S., Beers, T. C., Christlieb, N., Barklem, P. S., Rossi, S., Marsteller, B., Sivarani, T., & Lee, Y. S. 2006, ApJ, 652, L37
Lucatello, S., Sivarani, S., Beers, T. C., Gratton, R. G., & Ryan, S. G. 2005, ApJ, 625, 825
Maseron, T., Van Eck, S., Famaey, B., Goriely, S., Plez, B., Siess, L., Beers, T. C., Primas, F., & Jorissen, A. 2006, A&A, 455, 1059
Nollett, K.-M., Busso, M., & Wasserburg, G. J. 2003, ApJ, 582, 1036
Origlia, L., Valenti, E., Rich, R. M., & Ferraro, F. R. 2006, ApJ, 649, 499
Palacios, A., Charbonnel, C., Tafon, S., & Siess, L. 2006, A&A, 453, 261
Peterson, R. C. 1983, ApJ, 275, 737
Pinsonneault, M. H., Deliyannis, T. P., & Demeanque, P. 1992, ApJS, 78, 179
Rogers, F. J., Swenson, F. I., & Iglesias, C. A. 1996, ApJ, 456, 902
Ryan, S. G., Aoki, W., Norris, J. E., & Beers, T. C. 2005, ApJ, 635, 349
Sils, A., & Pinsonneault, M. H. 2000, ApJ, 540, 489
Sivarani, T., et al. 2006, A&A, 459, 125
Smith, G. H., & Martell, S. L. 2003, PASP, 115, 1211
Spite, M., et al. 2005, A&A, 430, 655
Stanghellini, R. C., Giesick, E., Izard, R. G., & Pols, O. R. 2007, A&A, 464, 157
Spite, M., et al. 2007, A&A, 464, 157
Sweigart, A. V., & Mengel, J. G. 1979, ApJ, 229, 624
Sweigart, A. V., & Mengel, J. G. 1979, ApJ, 229, 624
Ulrich, R. K. 1972, ApJ, 172, 165
VandenBerg, D. A., & Stetson, P. B. 2004, PASP, 116, 997

3He exhaustion. In this case, the 3He-driven thermohaline convection could not resume working in the same stars on the asymptotic giant branch (AGB). So, we would expect the absence of observational signatures of extra mixing in low-mass ($M \leq 2 M_\odot$) AGB stars unless the mixing in them is of a different nature. However, given the similarities in their depth and in the structure of the radiative zone where they operate, it is unlikely that the RGB and AGB mixing have different physical mechanisms.

Further observational work would be extremely fruitful. Samples should be examined for their binary nature in order to generate binary mass transfer samples, and both the reliability of temperature estimates and the relative and absolute abundance errors should be rigorously examined. If thermohaline convection occurs over an intermediate timescale, there should be a difference in the mean abundance level between MS stars that experienced mass transfer recently and stars with older mass transfer episodes. Hotter white dwarfs can be detected photometrically, particularly for dwarf CEMP stars, and a difference in surface abundance between systems with younger and older white dwarf companions would be definitive evidence for (or argument against) a moderate timescale for thermohaline mixing.

We are grateful to Sara Lucatello for sending us the C and N abundance data for the CEMP stars. It is our pleasure to thank Jennifer Johnson, Thomas Masseron, Grant Newsham, Kristen Sellgren, and Don Terndrup for useful discussions. We acknowledge support from the NASA grant NNG05 GG20G.