

Models for extremely metal-poor halo stars

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Abstract. Two alternative scenarios concerning the origin and evolution of extremely metal-poor halo stars are investigated. The first one assumes that the stars have been completely metal-free initially and produced observed carbon and nitrogen overabundances during the peculiar core helium flash typical of low-mass Population III stars. The second scenario assumes that the initial composition resulted from a mixture of primordial material with ejecta from a single primordial supernova. Both scenarios are shown to have problems in reproducing C, N, and O abundances simultaneously, and both disagree with observed $^{12}\text{C}/^{13}\text{C}$ -ratios, although in different directions. We concentrate on the most iron-poor, carbon-rich object of this class, HE 0107–5240, and conclude that the second scenario presently offers the more promising approach to understand these objects, in particular because evolutionary tracks match observations very well.

Key words. stars: low mass, brown dwarfs – stars: interiors – stars: abundances – stars: evolution – stars: individual: HE 0107–5240

1. Introduction

The extremely (or ultra) metal-poor stars (UMPS) of the galactic halo are believed to be the closest links of the Galaxy to the first generation of stars, to Population III. We therefore hope to learn about the first epoch of star formation and the end of the “Dark Ages” because they either are members of Population III themselves or because they carry the immediate imprint of massive Pop. III stars or primordial supernovae. They have received considerable attention in the recent past because of the fact that they are at the crossroads of stellar evolution, star formation, galactic chemical evolution and cosmology, recent CMB results and the question of reionization by Pop. III stars.

The discovery of HE 0107–5240, with a record low abundance of heavy elements of $[\text{Fe}/\text{H}] = -5.3$, which is about a factor of 10 below the previously known lowest value, raised our interest to link this star to Pop. III. Remarkably, the total “metallicity” of HE 0107–5240 is not metal-poor due to a carbon and nitrogen overabundance of $[\text{C}/\text{Fe}] = 4.0$ and $[\text{N}/\text{Fe}] = 2.3$, putting it in a large subgroup of UMPS with similar peculiar composition.

From the point of view of stellar evolution theory, metal-free stars are interesting in themselves because of some aspects of their structure and evolution which differ drastically from those of ordinary Pop. II or I stars. One of these peculiarities is the fact that during the core helium flash, mixing

between the helium and hydrogen shell and the convective envelope can take place, resulting in a carbon- and nitrogen-rich envelope and a second red giant branch phase. Therefore, it is a plausible assumption that the UMPS are true Pop. III stars and that the carbon-rich subgroup consists of stars that experienced the first, peculiar helium flash. We want to emphasize that in this paper we are concerned only with the abundances of the CNO-elements, since heavier elements are unaffected by the nuclear processes in low-mass stars.

In our previous papers, we investigated the scenario mentioned above to explain the observed chemical composition of carbon-rich UMPS qualitatively and thus to link them to Population III. The main problem one faces is that the flash-induced mixing appears to result always, independent of the details and assumptions of the calculations, in the same amount of carbon and nitrogen, such that for $[\text{Fe}/\text{H}] \lesssim -3$ the predicted carbon overabundance is $[\text{C}/\text{Fe}] \gtrsim 3$, which is at the upper limit of observed values. Since the C overabundance of HE 0107–5240 is as high as the value found in our previous calculations, it appeared to be particularly worthwhile to apply our approach to this star. Similar calculations have recently been performed independently by Picardi et al. (2004)¹.

We therefore present a model for HE 0107–5240, based on the flash-induced mixing (FIM) in Sect. 2, repeating the basic features of this event. In Sect. 3, we will then show calculations for an alternative scenario, which assumes that this star (and

¹ Our results were presented at the First Stars II meeting in May 2003; see <http://www.astro.psu.edu/users/tabel/II/presentations/weiss.pdf>.

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Table 1. Stellar parameters and chemical composition of HE 0107–5240 (Christlieb et al. 2004), and two theoretical models as explained in Sects. 2 (M 1) and 3 (M 2). The column “M 1 (initial)” denotes the composition of the polluting SN ejecta; the interior of model M 1 has $Z = 0$ throughout.

Qty.	Value	σ	M 1 (initial)	M 1 (final)	M 2 (initial)	M 2 (final)
$T_{\text{eff}} (K)$	5100	150	–	4520	–	5026
$\log g$ (cgs)	2.2	0.3	–	1.7	–	2.3
M/M_{\odot}	≈ 0.8	–	0.820	0.817	0.810	0.807
[Fe/H]	–5.3	0.2	–1.3	–5.3	–5.3	–5.3
[C/Fe]	4.0	0.3	2.6	6.0	4.0	4.0
[N/Fe]	2.3	0.2	–0.6	6.2	0.0	2.9
[O/Fe]	2.4	0.4	2.6	2.7	4.0	4.0
$^{12}\text{C}/^{13}\text{C}$	≈ 60	(>50)	$\approx 10^6$	4.8	$\approx 10^6$	61

other UMPS) are formed directly from the ejecta of Pop. III supernovae, i.e. that UMPS are the immediate successors of true, massive Pop. III objects. This scenario is also applied to other extremely metal-poor halo stars. Sect. 4 summarizes our conclusions.

2. A Population III model for HE 0107–5240

The stellar parameters and chemical abundances of HE 0107–5240 (see Table 1) are taken from Christlieb et al. (2002), Christlieb et al. (2004), and Bessell et al. (2004). The value for oxygen is probably an upper limit and the error given is one-sided according to Bessell et al. (2004). The final value might be close to $[\text{O}/\text{Fe}] = 2.0$.

For the calculations of all our models we used our Garching stellar evolution code; details of the codes and of the calculations of metal-free stars were given in Schlattl et al. (2001). Mass and initial composition of the models will be specified below for each calculation. We use a constant mixing length parameter of 1.77, which results from a solar model calibration (see Schlattl & Weiss 1999). We neglect mass loss, but take into account the relativistic mass defect in nuclear burning; this is the reason for a slight reduction of stellar mass (see Table 1).

In our previous papers (Weiss et al. 2000; Schlattl et al. 2001, 2002) we followed the idea that the UMPS are proper Pop. III stars, i.e. their initial composition was completely metal-free ($Z = 0$), and that the observed surface metal abundances, in particular that of heavy elements and iron, are due to an external pollution or accretion event which took place in the early phases of the approximately 12 Gyr of main-sequence lifetime. Technically, we added a specific amount of *solar metallicity* material on top of the initial, zero-age model such that during the Red Giant phase, after dredge-up and dilution the observed $[\text{Fe}/\text{H}]$ values were reached (see Weiss et al. 2000, Paper I). With this approach, the interior, nuclear evolution of the model is that of a metal-free star. In this scenario the peculiar C and N abundances are then produced by the star itself during the core helium flash. This flash-induced mixing (FIM) has been described extensively by various authors (Fujimoto et al. 1990, 2000; Schlattl et al. 2001, Paper II), therefore it suffices to repeat that the convective region caused by the helium flash is able to extend well into the hydrogen burning shell and to mix protons into the carbon-helium inter-shell region, where the protons are immediately captured on

carbon nuclei to form nitrogen. The additional energy from this CN-flash leads to further expansion of the intershell layer such that the hydrogen and helium shells are extinguished at their previous locations and instead a rejuvenated hydrogen shell establishes itself within the previous intershell layer. The timescale for this event is of the order of less than one day, such that the $^{15}\text{N}(p, \gamma)^{16}\text{O}$ reaction is too slow to strongly affect the oxygen abundance. Additionally, there are not even enough protons to allow the $^{12}\text{C}/^{14}\text{N}$ equilibrium value of roughly 0.1 at this temperature to be reached. Later on, the convective envelope is able to penetrate into the CN-rich layers, mixing these elements to the surface. Figure 1 shows the whole sequence of events for a $0.82 M_{\odot}$ model of $Z_i = 0$ during the first 10^4 years after the flash; at this time the mixing to the surface has taken place and the nuclear shells have reached their final structure.

Fujimoto et al. (2000) already specified conditions under which the FIM could occur: broadly speaking, a (total) metallicity of $[M/\text{H}] \lesssim -4.5$ (where the M stands for the global metal abundance) and mass below $1 M_{\odot}$ are required. In Paper II we added the influence of such parameters as initial helium abundance, the amount of polluting material, and the effect of sedimentation on the main sequence. We found that the total metallicity might be slightly higher ($[M/\text{H}] \lesssim -4$) than quoted by Fujimoto et al. (2000), also due to the use of updated plasma neutrino emission rates. The reader should also refer to Picardi et al. (2004) for a detailed description of the FIM and further tests concerning the conditions under which it can occur.

Schlattl et al. (2002, Paper III) investigated in detail whether and how the resulting envelope composition after the FIM is influenced by a very small, but non-zero initial metallicity, or how it depends on details of convection theory, such as, for example, the inclusion of overshooting. We found that final abundances of $[\text{C}/\text{Fe}] \approx [\text{N}/\text{Fe}] \approx 4$ and $[\text{O}/\text{Fe}] \approx 0.7$ (starting with an α -element, i.e. oxygen, enhancement of +0.4) are very insensitive to all these variations with the exception of an artificial reduction of the convective mixing velocity by a significant factor of 10^4 or more. This could be the typical mixing velocity in semiconvective layers. For example, Merryfield (1995) found in numerical simulations of semiconvection mixing velocities of up to 10^3 cm/s, while Achatz, Müller & Weiss (2004, in preparation) quote fully convective velocities of 10^7 cm/s in their multidimensional hydro-simulations of the core helium flash. Interestingly,

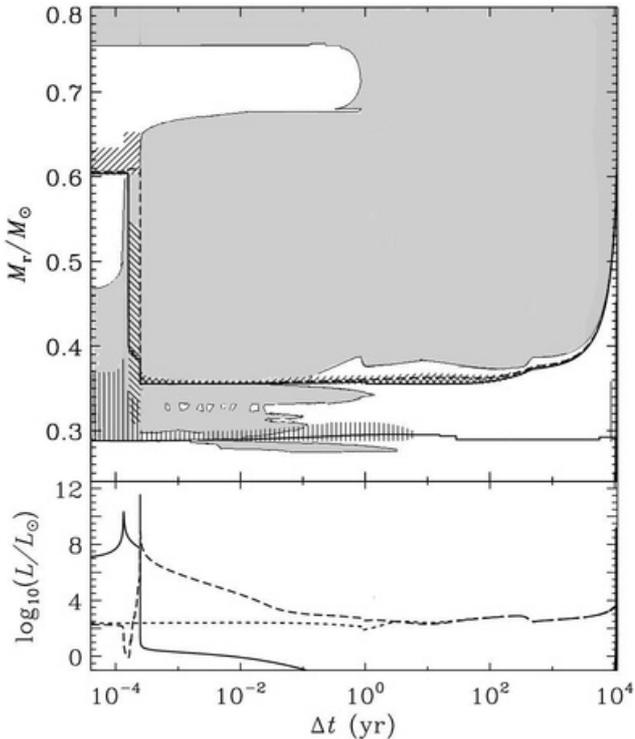


Fig. 1. *Upper panel:* evolution of the nuclear shells (hatched) and convective layers (shaded) in an initially metal-free model for HE 0107-5240 of $0.82 M_{\odot}$ during and after the core helium flash, illustrating the flash-induced mixing. The dashed line denotes the maximum of H-burning via pp-chains, the solid one that via CNO-cycle. The lower solid line is the maximum of He-burning. The hatched shells cover those regions where the energy generation is larger than 0.001 of the maximum in that particular shell, denoted by the corresponding line. *Lower panel:* total luminosity (dotted) and those from He-burning (solid) and H-burning (dashed). Time is in years since $\log L_{\text{He}}/L_{\odot} \geq 6$, i.e. since the He-flash has fully started.

Herwig (2002) states that in order to model “Sakurai’s Object” (V3443 Sgr), where a similar mixing-and-burning might have taken place, mixing velocities reduced by a factor of 10^4 are needed, too, in order to reproduce the peculiar surface composition. Nevertheless, it remains to be investigated whether the inclusion of semiconvection would modify our results in the desired direction. Similarly, a final $^{12}\text{C}/^{13}\text{C}$ ratio of less than 6 was the rule, slightly lower than the quoted numbers in the literature, which were around 10. Since hardly any oxygen is produced during the FIM we concluded that [O/Fe]-values would be necessary to decide whether the FIM-scenario could be the explanation for the observed anomalies.

In the past we had assumed that the additional envelope material from pollution is of solar composition, both for simplicity and because we were interested rather in the interior evolution than in detailed surface abundances. Modelling a particular star, of course, warrants a realistic composition of the polluting material. The $^{12}\text{C}/^{13}\text{C}$ isotope ratio of HE 0107-5240 (>30 ; Christlieb et al. 2002) is definitely higher than the values in our published FIM-models. In them, it is ≈ 5 , somewhat larger than the CN-equilibrium values found in the intershell layers. This slight enhancement is due to the assumption that the additional

surface material had solar composition with a carbon isotope ratio of 90. Obviously, a still higher value will also raise the final ratio of the model, bringing it in better agreement with observations.

Umeda & Nomoto (2003) showed that the pattern of elements heavier than Mg in HE 0107-5240 agrees with that predicted from nucleosynthesis in zero-metallicity type II supernovae of initial mass $20\text{--}130 M_{\odot}$ (Umeda & Nomoto 2002), under the assumption of severe fall-back to a massive black hole and complete mixing of the ejected material. Specifically they use a $25 M_{\odot}$ model with explosion energy of 3×10^{50} erg, complete mixing of material within the helium core of $6 M_{\odot}$ and severe fallback of matter interior to $1.8 M_{\odot}$, such that only $8 \times 10^{-6} M_{\odot}$ of ^{56}Ni (or Fe, after the nuclear decay) are ejected. The latter condition comes from the requirement that $[\text{C}/\text{Fe}] \approx 4$ is achieved.

We therefore took the composition for the polluting material to be that of a theoretical Pop. III supernova explosion from Chieffi & Limongi (2002), selecting the $35 M_{\odot}$ model. The explosion energy in this model had been set to 1.2×10^{51} erg. The results of Chieffi & Limongi (2002) do not differ significantly from those of Umeda & Nomoto (2002) for comparable parameters (progenitor mass, mass cut, explosion energy), at least with respect to the elements of interest for us. In this SN model, a total of $32.5 M_{\odot}$ is ejected, of which there are $14.7 M_{\odot}$ of hydrogen, $10.7 M_{\odot}$ of helium, $1.2 M_{\odot}$ of carbon, $2.2 \times 10^{-4} M_{\odot}$ of nitrogen, and $3.6 M_{\odot}$ of oxygen. This matter is assumed to be completely mixed. The amount of polluting material actually dumped onto the initial model and the mass cut have to be selected such that the final iron abundance on the RGB after dredge-up and helium flash mixing matches that of HE 0107-5240. Note that we do not have to care about [C/Fe] in the polluting material, since carbon production during the helium flash and subsequent mixing will dominate the final abundances. In model “M 1” presented here (see Table 1 and Fig. 1), the ^{56}Ni mass was $0.001 M_{\odot}$, and the amount of polluting material $6 \times 10^{-5} M_{\odot}$. Its initial composition is given in Table 1, column “M 1 (initial)”. While $[\text{Fe}/\text{H}] = -1.3$ in the SN ejecta, this is reduced to -3.6 already in the initial main sequence model, which has a convective envelope of $0.016 M_{\odot}$. After the convective envelope has reached its deepest extent of about $0.4 M_{\odot}$, the correct final $[\text{Fe}/\text{H}]$ of -5.3 is reached. We have also run models with a ^{56}Ni mass increased respectively reduced by a factor of 10, implying opposite factors for the additional polluting mass.

The core helium flash and the induced mixing that takes place are illustrated in Fig. 1. The resulting abundances after the flash can be found in Table 1, column “M 1 (final)”. Obviously, there is again too much C and N produced, and $^{12}\text{C}/^{13}\text{C}$ is much too close to the equilibrium value, because of the small amount of polluting matter added to the star. As stated before, we have modified this parameter, but found only marginal variations in the resulting abundances, except in the most extreme case of $6 \times 10^{-3} M_{\odot}$ of polluting material, with only $10^{-4} M_{\odot}$ of ^{56}Ni . In this case, the final C and N abundances were lower by one order of magnitude due to the large amount of polluting matter and the carbon isotope ratio increased slightly to 5.0. However, in this case $[\text{Fe}/\text{H}] = -4.2$ is too

high. While one could try to find better suited initial SN-yields, for example by choosing another SN-progenitor mass, inspection of the corresponding tables in the papers quoted reveal that in order to achieve the very low Fe abundance one always has to add such small amounts of SN-ejecta that the dilution of the carbon-rich intershell matter of approximately $0.3 M_{\odot}$ by the carbon-poorer envelope is almost negligible, such that the final C and N abundances can hardly be reduced to the level of HE 0107–5240. Additionally, the $^{12}\text{C}/^{13}\text{C}$ is always too low, even if the SNe is basically ^{13}C -free. We therefore conclude that – as in the case of other, more iron-rich UMPS – the amount of carbon and nitrogen relative to iron is too high. In fact it appears that in the observed stars $[\text{C}/\text{H}]$ and $[\text{N}/\text{H}]$ are constant within a factor of 10, and that this value is lower by a factor of 10–100 than that of the models. In addition, the carbon isotope ratio reflects that the observed material has been exposed to CN-burning to a much lower degree than our models predict. The oxygen abundance in M 1, which nicely fits that of HE 0107–5240 is solely due to the initial SN-composition, since hardly any oxygen is produced in the model.

3. Population II.5 models

3.1. Model for HE 0107–5240

Umeda & Nomoto (2003) and Nomoto et al. (2003) advocate the idea, based on the heavy element abundances, that HE 0107–5240 and other UMPS are second generation stars, forming immediately after only one Pop. III supernova has exploded and thus carrying the immediate imprint of it. Such objects have also been termed “Pop. II.5”, to discriminate them from Pop. II, where the heavy metal composition is the result of many, well mixed SNe. We add that Limongi et al. (2003) criticized this idea on grounds of incompatible Ni and C abundances, which require very different mass cuts and because of the relative abundances among lighter elements like Na and Mg. Instead, they suggest the superposition of two primordial supernovae of 15 and $25 M_{\odot}$. Since we are concerned here with only a few elements (C, N, O, Fe), this alternative scenario, which predicts a too large oxygen abundance of $[\text{O}/\text{Fe}] = 4.1$, does not differ qualitatively for our purposes, such that we follow the simpler suggestion of Umeda & Nomoto (2003). Both scenarios imply that HE 0107–5240 had a homogeneous initial composition with a heavy metal abundance throughout the interior as is observed today, in contrast to the model of the last section, which had this only in the polluted envelope layers. We therefore calculated the straightforward evolution of such a model (M 2) up the RGB and through the helium core flash.

The initial homogeneous composition for our model was obtained as follows: We chose the same SN model of $35 M_{\odot}$ by Chieffi & Limongi (2002) as before. This yields the total amount of mass for each element as a function of mass cut. All lighter elements are present only outside the Ni core. Thus, in order to obtain the observed $[\text{C}/\text{Fe}]$, the mass cut must be set accordingly. For HE 0107–5240 a Ni mass of $M(^{56}\text{Ni}) = 6 \times 10^{-5} M_{\odot}$ is needed (Ni will decay into Fe). Furthermore, the SN material is assumed to be completely mixed. To set the

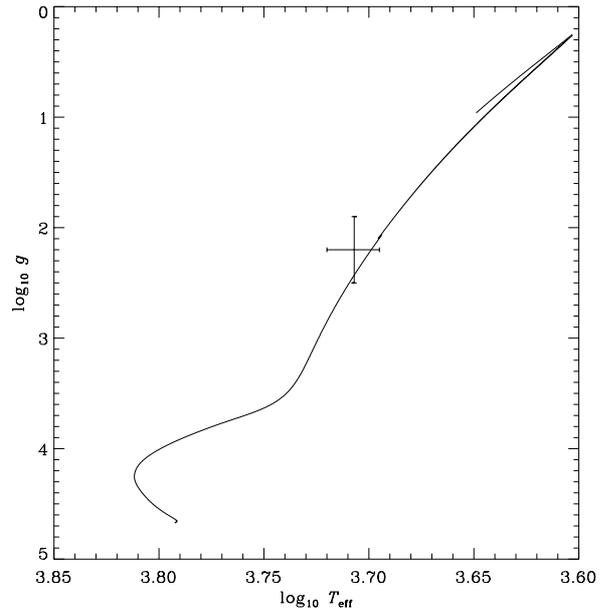


Fig. 2. Evolution of model M 2 ($\log g$ vs. $\log T_{\text{eff}}$), which is a star of $0.81 M_{\odot}$ and initial iron abundance of $[\text{Fe}/\text{H}] = -5.3$ (see text for details). The error cross marks the position of HE 0107–5240.

Fe abundance for the model’s initial composition correctly, a dilution with primordial H/He-matter is needed (the SN ejecta being hydrogen-poor). In the present case, a dilution factor of 1:360 leads to $[\text{Fe}/\text{H}] = -5.3$. All other element abundances result from the SN model (see Table 1). In particular, the initial nitrogen abundance is approximately solar, and $^{12}\text{C}/^{13}\text{C}$ very high.

The main sequence and red giant evolution is that of an ordinary, moderately metal-poor low-mass star. The mass was chosen as $0.81 M_{\odot}$ to obtain an age of 13.1 Gyr at the RGB tip. During core hydrogen burning CN-conversion takes place and the nuclear results become evident after the first dredge-up. The final nitrogen abundance as well as the carbon isotope ratio are quite similar to those observed in HE 0107–5240 (Table 1). Oxygen is hardly changed during the evolution, and reflects completely the choice of the SN model. A survey of the quoted Pop. III SNe model literature reveals that $[\text{O}/\text{C}]$ varies between -0.2 and 1.1 ; in our selected model it is close to the solar value. The very high carbon abundance of HE 0107–5240 thus implies a similar oxygen enrichment, which is therefore too abundant by more than one order of magnitude and poses one of the problems of the present scenario for the nature of HE 0107–5240. Figure 2 shows the evolutionary track of M 2 (in the $\log g$ vs. $\log T_{\text{eff}}$ diagram), on top of which the observed position of HE 0107–5240 and error bars (Christlieb et al. 2004) are plotted. Obviously, there is a very good agreement, and indeed HE 0107–5240 is in a post-dredge-up phase. The assumption that HE 0107–5240 is a star on the first red giant branch, which has evolved as a single star, is supported by the result of Bessell et al. (2004).

Due to the rather high total metallicity, which is one of the basic parameters influencing the appearance of the FIM event, the core helium flash happens at high luminosity and without any non-canonical or extended mixing.

Table 2. Observational data for our selection of extremely metal-poor halo stars; HE 0107–5240 is repeated for completeness.

Object	[Fe/H]	T_{eff}	$\log g$	[C/Fe]	[N/Fe]	[O/Fe]	$^{12}\text{C}/^{13}\text{C}$	Reference
HE 0107-5240	-5.30	5100	2.2	4.0	2.3	2.4	60	Christlieb et al. (2004); Bessell et al. (2004)
CS 22943-037	-4.00	4900	1.5	1.2	2.7	2.0	4	Depagne et al. (2002)
CS 29498-043	-3.75	4400	0.6	1.9	2.3	–	6	Aoki et al. (2002)
CS 22957-027	-3.11	5100	1.9	2.4	1.6	–	8	Aoki et al. (2002)
CS 22892-052	-2.97	4850	1.5	1.1	1.0	0.7	–	Norris et al. (1997); Sneden et al. (2003)
CS 31082-001	-2.90	4850	1.5	0.2	<0.2	0.6	<20	Hill et al. (2002)

We close this part with a comment on opacities. So far we have used tables with appropriate H, He, and metal abundances, where the internal metal distribution is assumed to be that of α -element rich Pop. II stars. Indeed, in the present models a large part of the metals is actually carbon and nitrogen. Since the total metallicity is $Z = 7.1 \times 10^{-4} = 0.037 Z_{\odot}$, one can no longer assume that the individual metal abundances are unimportant (see Salaris & Weiss 1998, for a discussion of this issue). As in Schlattl et al. (2001) we have therefore also computed a model with opacities for C- and N-enhanced matter (see this paper for detail), and found no significant differences, except that the model is younger by 0.7 Gyr after the main sequence. Due to lack of appropriate tables we could not account for the increased oxygen abundance.

3.2. Models for other objects

In addition to HE 0107–5240 we calculated additional models for several other objects with abundances taken from the literature (see Table 2), which are believed to be first ascent giants on the grounds of their surface gravity and effective temperature. The composition of the initial, homogeneous model was always obtained by mixing ejected material of the $35 M_{\odot}$ supernova model by Chieffi & Limongi (2002) with pristine matter. The mass cut and mixing factor are the free parameters chosen in such a way as to obtain approximately the observed iron and carbon abundance.

Figure 3 shows the resulting evolutionary track of the model for CS22957-027 together with the Pop. III model of Sect. 2 (dashed line) and a solar-type Pop. I star to emphasize the effect of the strong C and N enrichment after the FIM. Since T_{eff} and $\log g$ of HE 0107–5240 are very similar to that of CS 22957-027, this plot also illustrates the fact that the post-flash Pop. III model is slightly too cool for HE 0107–5240.

Table 3 contains the summary of these calculations. Since the evolutionary tracks cross the observationally allowed range in $\log g$ and T_{eff} several times, we offer various possible choices along the RGB and AGB evolution. We note in particular that some stars have high enough surface gravities to be still on the lower RGB, before the hydrogen shell encounters the composition discontinuity left behind by the convective envelope when it had reached its deepest extension. This phase is commonly referred to as the “bump”, because of the slower evolutionary speed of red giants when they reach the suddenly increasing hydrogen supply above the discontinuity (see Salaris et al. 2002, for a review on low-mass red giant evolution).

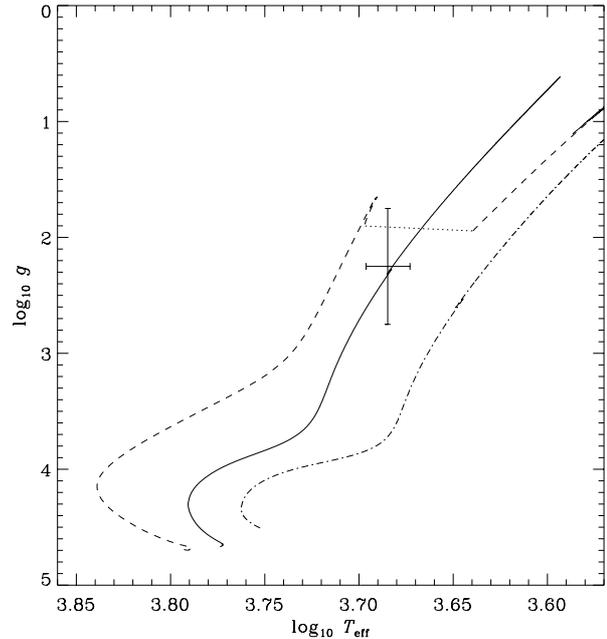


Fig. 3. Evolution of our model for CS22957-027 (Table 3; solid line) compared to that of a Pop. III model similar to M1 ($0.82 M_{\odot}$; dashed) experiencing the flash-induced mixing at the tip of the first RGB and one of a $1 M_{\odot}$ star of typical Pop. I composition (dash-dotted line).

Comparing the final abundances with those observed it becomes obvious that no star can easily be modelled. For all of them the carbon isotope ratios are much too high; we are therefore facing the opposite problem we have with the FIM-scenario. In addition, nitrogen abundances for most stars, but in particular for CS 22943-037 and CS 31082-001 are too low, indicating a lack of mixing. Both problems could be cured if one assumes that these stars experience at or after the bump additional mixing between the hydrogen shell and the convective envelope. Such extra-mixing is now known to take place in basically all low-mass metal-poor stars, both in the field and in clusters, and leads to reduced carbon and increased nitrogen abundances as well as to reduced carbon isotope ratios. We refer the reader to Gratton et al. (2000) for an observational overview and to Denissenkov et al. (1998) for a comprehensive theoretical paper².

² A summary of state-of-the-art-data and ideas can be found in the proceedings of Joint Discussion 4 (Astrophysical impact of abundances in globular cluster stars) of the IAU General Assembly XXV (Sydney 2003), D’Antona & da Costa (2004).

Table 3. Pop. II.5 models using the $M = 35 M_{\odot}$ SN yields of Chieffi & Limongi (2002). The mass cut has been found by inter- or extrapolating between SN models with different $M_{\text{SN}}(\text{Ni})/M_{\odot}$ to obtain the correct $[\text{C}/\text{Fe}]$. $M(\text{prim})/M(\text{SN})$ is the mixing proportion between primordial and SN matter, needed to reach (approximately) the observed $[\text{Fe}/\text{H}]$ -value. The various parameters of the models start at Col. 5 (age). Evolutionary models that could represent the objects are marked by the following labels: E-RGB: on RGB, but before bump; B-RGB: at bump; AB-RGB: after bump; L-RGB: close to tip; E-AGB: on early AGB, after 2nd dredge-up; L-AGB: immediately before thermal pulses commence; TP-AGB: thermal pulse phase on AGB. The last two lines refer to models for CS 22943-037, for which we have used alternative SN-yields from a $15 M_{\odot}$ model by Umeda & Nomoto 2002 (see text).

Object	$\frac{M_{\star}}{M_{\odot}}$	$\frac{M(\text{prim})}{M(\text{SN})}$	$\frac{M_{\text{SN}}(\text{Ni})}{M_{\odot}}$	$\frac{\text{Age}}{\text{Gyr}}$	$[\text{Fe}/\text{H}]$	$T_{\text{eff}} [\text{K}]$	$\log g$	$\log \frac{L}{L_{\odot}}$	$[\text{C}/\text{Fe}]$	$[\text{N}/\text{Fe}]$	$[\text{O}/\text{Fe}]$	$\frac{^{12}\text{C}}{^{13}\text{C}}$	
HE 0107-5240	0.81	350	6×10^{-5}	13.1	-5.31	5026	2.3	1.8	4.0	2.9	4.0	61	E-RGB
CS 22943-037	0.79	10500	0.06	13.5	-4.03	4880	1.5	2.5	1.2	-1.8	1.2	340	AB-RGB
				13.6	-4.02	4800	1.2	2.8	1.1	1.1	1.2	56	E-AGB
CS 29498-043	0.79	1170	0.1	13.7	-3.77	4380	0.7	3.2	1.9	0.1	1.9	97	L-RGB
				13.8	-3.77	4400	0.6	3.2	1.8	1.9	1.9	43	L-AGB
				13.8	-3.77	4400	0.6	3.2	1.8	2.0	1.9	43	TP-AGB
CS 22957-027	0.85	84	0.003	13.5	-3.12	4800	2.4	1.7	2.4	1.7	2.4	55	B-RGB
CS 22892-052	0.795	1230	0.075	13.4	-2.99	4790	1.5	2.5	1.1	-0.6	1.1	94	AB-RGB
				13.5	-2.99	4740	1.1	2.8	1.0	0.9	1.1	33	E-AGB
CS 31082-001	0.79	0.79	0.6	13.5	-2.93	4850	1.5	2.5	0.2	-2.7	0.2	280	AB-RGB
CS 22943-037	0.79	2720	0.067	13.5	-4.00	4920	1.5	2.5	1.2	0.6	1.1	370	AB-RGB
				13.6	-4.00	4833	1.3	2.8	1.1	1.1	1.1	59	E-AGB

The bottom two lines of Table 3 refer to a case, for which we used a $15 M_{\odot}$ model by Umeda & Nomoto (2002) instead of our standard SN-model, to show the influence of the initial composition. The iron abundance of these ejecta is too high ($[\text{Fe}/\text{H}] = 0.7$; $[\text{C}/\text{Fe}] = 0.0$) for the required $[\text{Fe}/\text{C}]$, such that we multiplied it by a factor 0.067 (given in Col. 4). Nitrogen and oxygen have abundances of -0.6 and -0.1 in the standard spectroscopic scale. The explosion energy was 10^{51} erg. In spite of the different initial composition there is hardly a change in the final one, with the exception of the nitrogen abundance on the RGB.

4. Discussion

In earlier papers (Papers II and III) we have applied our scenario for the evolution of initially metal-free Pop. III stars with additional surface pollution to some known objects of the galactic halo, investigating the possibility that the observed severe carbon and nitrogen enhancements are due to internal production and mixing in the course of the first core helium flash. These models indicated that both the abundances of C and N in the models are too high, and that the carbon isotope ratio is too close to equilibrium values. In addition, we noticed at that time that a statistically representative sample of UMPS is needed to verify that the number of carbon-enhanced objects is in agreement with the predictions from the models, which would be post-flash, and therefore short-lived compared to lower RGB stars. The detection of HE 0107-5240 with the lowest iron abundance of $[\text{Fe}/\text{H}] = -5.3$ and highest carbon enhancement of $[\text{C}/\text{Fe}] = 4.0$, allowed us to investigate this scenario more closely. We thus computed specific models using realistic SN yields from the literature.

The low iron content of HE 0107-5240 can only be achieved by adding tiny amounts of SN-ejecta matter or to

impose rigid mass cuts for the SN explosion. We find that, independent of the particular choice of polluting matter, the final carbon and nitrogen abundances, which result from the core helium flash and the subsequent mixing, exceed the observed abundances by orders of magnitude, similar to the case of the less extreme cases we modelled in our previous papers. It appears that both in nature, and in our models, the *amount* of overabundant C and N is rather constant, such that with decreasing Fe-abundance the relative overabundance is increasing. This effect can actually be seen in Fig. 2 of Rossi et al. (1999) by looking at the upper envelope of the $[\text{C}/\text{Fe}]$ vs. $[\text{Fe}/\text{H}]$ distribution. However, the models appear to produce 10–100 times too much carbon and nitrogen. Additionally, the carbon isotope ratio in HE 0107-5240 is definitely above equilibrium values, which are always obtained in our simulations. These results, with the exception of the oxygen abundance, are widely independent on whether we use solar or early SNe material for the pollution. Therefore, HE 0107-5240 contradicts most strongly our flash-induced mixing models. This conclusion has been reached independently by Picardi et al. (2004) on the grounds of very similar results, a fact which is encouraging for the reliability of the models. In particular, $[\text{C}/\text{Fe}]$ and $[\text{N}/\text{Fe}]$ are 6.1 and 5.8, respectively, to be compared to our values of 6.0 and 6.2. The fact that we have a higher nitrogen abundance we ascribe to the sensitivity of nitrogen production to the competition between mixing and nuclear processing. The carbon isotope ratio in both cases is close to 4. For a more detailed comparison of the internal processes we refer the reader to Picardi et al. (2004). In both cases the post-FIM evolution up to a second, more classical core helium flash (see Schlattl et al. 2001, for details) is by a factor of 10 or more shorter than that before the FIM, such that a much larger number of C-normal UMP giants are to be expected. This is in contradiction with the statistics of UMPS so far. As a final argument against the

FIM-scenario for HE 0107–5240, Picardi et al. also stress that this scenario predicts a very high Li abundance after the FIM of $[Li/H] = 5.5$, which is above the (conservative) upper limit of 5.3 obtained by Christlieb et al. (2004).

We then investigated an alternative scenario, assuming that HE 0107–5240 and other extremely metal-poor stars are representing a kind of “early Pop. II” or Pop. II.5 class of objects. Their homogeneous initial composition is of low, but finite metallicity. However, contrary to standard Pop. II stars, the material still carries the imprint of one or few individual SNe of Pop. III. We restricted ourselves to one particular SN model, since in terms of CNO-elements the various models available (mass, explosion energy, author) do not vary drastically. The choice was made according to inferences based on reproducing the heavy elements in HE 0107–5240.

We find that, after the mass cut and dilution with pristine interstellar material have been fixed, the stars are carbon and oxygen rich already on the main sequence, and produce large amounts of nitrogen in CN-cycling; as a consequence of standard first dredge-up the nitrogen will be transported to the surface after main-sequence termination. The evolution is quite standard, as for Pop. II models. C and N abundances agree naturally very well with the observations, but carbon isotope ratios are in this scenario definitely *higher* than for most stars under consideration (with the exception of HE 0107–5240). Therefore, for $^{12}C/^{13}C$ we face the opposite problem of the one we have for the FIM-models. Oxygen is always enriched, due to the composition of SN ejecta. It would therefore be necessary to obtain results for oxygen for UMP stars³ to put further constraints on the various possibilities for the nature of the UMPS. In case of the objects we tried to model and for which we had oxygen abundances, it appears that we can roughly reproduce the observations. However, in the case of HE 0107–5240 the SN yields predict too much oxygen. This problem can also be noticed in the models by Limongi et al. (2003), while it seems to be less severe in Umeda & Nomoto (2002) using a less massive SN progenitor with only 0.3×10^{51} erg explosion energy. The composition of one of the objects we investigated could be matched satisfactorily.

The observed stars lie very nicely on the tracks for our Pop. II.5 scenario, although the errors are too large to allow excluding the FIM-possibility on those grounds. It is possible to identify different evolutionary stages for the observed objects. Generally, the later the evolutionary phase, the higher the N abundance and the lower the $^{12}C/^{13}C$ ratio, reducing some of the problems. If the star would be on the AGB, a better agreement is possible, in particular, if the 3rd dredge-up happens during the thermal pulses, because in this case, the carbon isotope ratio would be reduced strongly. However, we have not followed the evolution of the models this far. Again, statistically significant samples of UMPs would be necessary to further look into this question.

In spite of the remaining problems, we presently favor the idea that the observed extremely metal-poor stars of the galactic halo are stars formed directly from the ejecta of one or a few

Pop. III SNe of intermediate mass (15–60 M_{\odot}), which are diluted with metal-free primordial gas. Overall, the agreement between model and observations appears to be better, and there is still a large uncertainty concerning the SN yield composition. Also, whether one or two or a few SNe have contributed to the initial composition of an UMP (see the discussion in Limongi et al. 2003), allows further fine-tuning of models. Nevertheless, solid statistical samples are clearly needed for further progress. Finally, we point out that all SN models favored indicate progenitor masses of ≈ 20 –60 M_{\odot} . Currently, the primordial star formation scenario is favouring much higher initial masses for Pop. III stars. This question, too, remains to be resolved. The extremely metal-poor stars with their particular composition may guide us in this.

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³ It appears that indeed several of them have $[O/Fe] \approx 2$, similar to HE 0107–5240 (V. Hill, private communication).