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Cosmic Chemical Evolution with an Early Population of Intermediate Mass Stars

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ABSTRACT

We explore the consequences of an early population of intermediate mass stars in the $2 - 8 M_{\odot}$ range on cosmic chemical evolution. We discuss the implications of this population as it pertains to several cosmological and astrophysical observables. For example, some very metal-poor galactic stars show large enhancements of carbon, typical of the C-rich ejecta of low-mass stars but not of supernovae; moreover, halo star carbon and oxygen abundances show wide scatter, which imply a wide range of star-formation and nucleosynthetic histories contributed to the first generations of stars. Also, recent analyses of the ^4He abundance in metal-poor extragalactic H II regions suggest an elevated abundance $Y_p \simeq 0.256$ by mass, higher than the predicted result from big bang nucleosynthesis assuming the baryon density determined by WMAP, $Y_p = 0.249$. Although there are large uncertainties in the observational determination of ^4He , this offset may suggest a prompt initial enrichment of ^4He in early metal-poor structures. We also discuss the effect of intermediate mass stars on global cosmic evolution, the reionization of the Universe, the density of white dwarfs, as well as SNII and SNIa rates at

high redshift. We also comment on the early astration of D and ^7Li . We conclude that if intermediate mass stars are to be associated with Population III stars, their relevance is limited (primarily from observed abundance patterns) to low mass structures involving a limited fraction of the total baryon content of the Universe.

1. Introduction

One of the outstanding questions concerning the first epoch of star formation is the stellar mass distribution of Population III stars. Most often, Pop III stars are assumed to be very massive (40 - 100 $M_{\odot}$) or supermassive ($> 100 M_{\odot}$). Tracing chemical abundance patterns through cosmic chemical evolution allows one to test theories employing massive Pop III stars. For example, the abundance patterns seen in extremely iron-poor stars do not support the hypothesis that the first stars had masses between 140 – 250 $M_{\odot}$ and end as pair-instability supernovae (Venkatesan *et al.* 2004; Daigne *et al.* 2004). Yet other observations, such as those relating to the reionization history of the Universe, do point to an early population that is more massive than a standard Pop I or II distribution. Here, we will explore the consequences of an early population of intermediate mass (IM) (2 - 8 $M_{\odot}$) stars, which dominate at a redshift $z \sim 10$.

While there are many theoretical arguments pointing to very massive stars dominating Pop III (Bromm & Larson 2004; Bromm *et al.* 2009), there exist arguments pointing to a first generation of stars with an initial mass function (IMF) peaked around the intermediate mass range. For example, the metal-free IMF predicted from opacity-limited fragmentation theory would peak around 4 – 10 $M_{\odot}$ with steep declines at both larger and smaller masses (Yoshii & Saio 1986). Primordial CMB regulated-star formation also leads to the production of a population of early intermediate mass stars at low metallicity (Smith *et al.* 2009).

On the observational side, there is abundant evidence for an early contribution from IM stars. Intermediate mass stars have particular effects on chemical abundance patterns. Unlike their massive counterparts that end as core-collapse supernovae, these stars produce very little in the way of heavy elements (oxygen and above), but produce significant amounts of carbon and/or nitrogen and above all helium. Indeed, there is evidence that the number of carbon enhanced stars increases at low iron abundances (Rossi *et al.* 1999) necessitating a Pop III source of carbon, possibly in the asymptotic giant branch (AGB) phase of IM stars (Fujimoto *et al.* 2000; Aoki *et al.* 2002; Lucatello *et al.* 2005). To account for the large [C,N/Fe] ratios found in a large number of extremely iron-poor stars in our Galaxy, it was argued that an IMF peaked at 4 - 10 $M_{\odot}$ is needed (Abia *et al.* 2001). Furthermore, the presence of s-process elements, particularly Pb at very low metallicity also points to AGB enrichment very early on (Aoki *et al.* 2001; Sivarani *et al.* 2004). As a result, an early population of intermediate mass stars may lead to a plausible explanation of recently observed carbon enriched iron-poor stars.

Isotopic abundances of C and Mg also lend clues to the early nucleosynthetic history of the Galaxy. Isotopic studies of the latter show a considerable amount of dispersion at low metallicity ranging from low values of $^{25,26}\text{Mg}/^{24}\text{Mg}$, consistent with pollution from core col-

lapse supernovae, to high values of the Mg ratios indicating the presence of AGB production of the heavy Mg isotopes. Core collapse supernovae produce almost exclusively ^{24}Mg , while the observations of Yong *et al.* (2003a) show enhancements (relative to predictions based on standard chemical evolution models) in both $^{25,26}\text{Mg}$. AGB stars were also concluded to be the source of the high $^{25,26}\text{Mg}/^{24}\text{Mg}$ ratios seen in the globular cluster NGC 6752 with $[\text{Fe}/\text{H}] = -1.62$ (Yong *et al.* 2003b). A similar conclusion was drawn in Alibés *et al.* (2001); Fenner *et al.* (2003).

Determining the identity and nature of the first stars is a primary goal in any attempt to understand the physics of the first billion years of the universe. Cosmic chemical evolutionary models enable one to test many of the hypotheses for Pop III stars (Ciardi & Ferrara 2005). The bulk of the existing work in this area considers either massive stars ($M > 40 M_{\odot}$) or very massive stars ($M > 100 M_{\odot}$). However, given the indications discussed above for an early population of intermediate mass stars, it seems crucial to examine the consequences for cosmic chemical evolution with IM Pop III stars.

The paper is organized as follows: In section 2, we discuss some of the expected consequences for a population of intermediate mass stars. These include a) the effective prompt initial enrichment of helium, which we compare to recent determinations of primordial helium (Izotov & Thuan 2010; Aver *et al.* 2010) that show an excess relative to the predictions of big bang nucleosynthesis (BBN); b) the reionization of the universe, usually ascribed to very massive Pop III stars (Cen 2003; Haiman & Holder 2003; Wyithe & Loeb 2003; Bromm 2004); c) the evolution of the IMF; d) carbon-enhanced metal-poor stars; e) the density of white dwarfs; f) the rate of Type Ia supernovae at high redshift; and g) the evolution of N and Mg.

In section 3, we introduce a relatively simple model of galactic chemical evolution to highlight some of the (non-cosmological) effects of the IM stars, particularly on the evolution of element abundances based on the work of Fields *et al.* (2001). This model employs a bimodal star formation rate (SFR) which supplements a normal IMF and SFR, with one enhanced with IM stars. In section 4, we introduce a cosmic chemical evolutionary model based heavily on the hierarchical models developed in Daigne *et al.* (2006) and Rollinde *et al.* (2009). We present our results in section 5. Discussion and concluding remarks are given in section 6.

2. Consequences of an early population of intermediate mass stars

2.1. The primordial helium abundance

Among the successes of the WMAP determination of cosmological parameters is the accurate determination of the baryon density, $\Omega_B h^2$ or equivalently the baryon-to-photon ratio $\eta \equiv n_b/n_\gamma = 10^{-10}\eta_{10}$; Komatsu *et al.* (2009, 2010) find

$$\eta_{10} = 6.19 \pm 0.15 . \quad (1)$$

As a consequence, it has become possible to treat standard big bang nucleosynthesis (BBN) as a zero-parameter theory (Cyburt *et al.* 2002, 2003), resulting in relatively precise predictions of the light element abundances of D, ^3He , ^4He , ^7Li (Cyburt *et al.* 2001; Coc *et al.* 2002, 2004; Cyburt 2004; Descouvemont *et al.* 2004; Cuoco *et al.* 2004; Serpico *et al.* 2004; Cyburt *et al.* 2008; Coc and Vangioni 2010).

When compared with current observational determinations of the abundances of D, ^4He , and ^7Li , we find varying degrees of concordance, none of which are perfect. Deuterium is typically credited as being responsible for the concordance between BBN and the cosmic microwave background determination of η . At the current value of η (eq. 1), the deuterium abundance is predicted to be $\text{D}/\text{H} = 2.52 \pm 0.17 \times 10^{-5}$. This can be compared with the abundance of deuterium measured in quasar absorption systems. The weighted mean value of seven systems with reliable abundance determinations is $\text{D}/\text{H} = (2.82 \pm 0.21) \times 10^{-5}$ (Pettini *et al.* 2008, and references therein). However, the individual measurements of D/H shows considerable scatter (a variance of 0.53) and it is likely that systematic errors dominate the uncertainties. While the agreement is certainly reasonable, we do draw attention to the fact that the predicted abundance is somewhat *lower* than the observed mean and this (slight) discrepancy will serve as a constraint below.

The discrepancy between the predicted abundance of ^7Li and the value found in halo dwarf stars is well documented (Cyburt *et al.* 2008). At the WMAP value of $\eta_{10} = 6.19$, $^7\text{Li}/\text{H} = (5.12^{+0.71}_{-0.62}) \times 10^{-10}$ which is considerably higher than most observational determinations (Spite & Spite 1982; Spite *et al.* 1996; Ryan *et al.* 2000; Asplund *et al.* 2006; Bonifacio *et al.* 2007; Hosford *et al.* 2009, 2010). For example, the recent analysis of Sbordone *et al.* (2010) finds $^7\text{Li}/\text{H} = (1.58 \pm 0.31) \times 10^{-10}$. We comment below on the possible effects of astration in chemical evolution models on the lithium abundance.

Among the light elements, helium has the most accurately predicted primordial abundance. In addition, it is relatively insensitive to the baryon density and at $\eta = 6.19$, the helium mass fraction is

$$Y_p = 0.2487 \pm 0.0002. \quad (2)$$

The standard BBN results obtained in Coc and Vangioni (2010) are similar to those given above ($Y = 0.2475 \pm 0.0004$, $D/H = (2.68 \pm 0.15) \times 10^{-5}$, ${}^7\text{Li}/H = (5.14 \pm 0.50) \times 10^{-10}$).

On the observational side, the determination of the helium abundance in extragalactic HII regions is fraught with difficulties (Olive & Skillman 2001). Over the last 15 years, improvements in the analysis has led to a systematically higher ${}^4\text{He}$ abundance. Izotov, Thuan, & Lipovetsky (1994) and Peimbert, Peimbert, & Ruiz (2000) introduced a ‘self-consistent’ method for determining the abundance of ${}^4\text{He}$ simultaneously with the determination of the physical parameters associated with the HII region. They found $Y_p = 0.240 \pm 0.005$ and 0.235 ± 0.002 respectively. Using the Monte Carlo methods described in Olive & Skillman (2001) and selected high quality data from Izotov, Thuan, & Lipovetsky (1994), Olive & Skillman (2004) found a higher value with considerably larger uncertainties, $Y_p = 0.249 \pm 0.009$.

Further improvements to the analysis were aided by new atomic data (Porter, Ferland, & MacAdam 2007) used in Peimbert, Luridiana, & Peimbert (2007) and Izotov *et al.* (2007) where higher helium mass fractions were obtained 0.2477 ± 0.0029 and 0.2516 ± 0.0011 , respectively, based on the new He I emissivities and the collisional excitation of H I. The more recent work of Izotov & Thuan (2010) found a still higher value $Y_p = 0.2565 \pm 0.0010(\text{stat.}) \pm 0.0050(\text{syst.})$. Using the same relatively small set of high quality data from Izotov, Thuan, & Lipovetsky (1994), Aver *et al.* (2010) found a similarly high value of $Y_p = 0.2561 \pm 0.0108$. The latter was a combined and uniform treatment of both hydrogen and helium emission lines, the inclusion of the new He emissivities, wavelength-dependent effects of underlying absorption, and neutral hydrogen collisional corrections. A combination of strong degeneracies leading to large uncertainties in the individual helium abundance determinations found in an unrestricted Monte Carlo analysis as well as the relatively short baseline used in the regression with respect to O/H, the large uncertainty of 0.0108 makes certain that this determination is consistent with the BBN prediction at the WMAP value of η . Given, the short baseline of this data set, it may be argued that a weighted mean of the helium results is warranted rather than the commonly used regression of Y vs O/H as in the case of all results quoted above. The weighted mean found in Aver *et al.* (2010) is

$$Y_p = 0.2566 \pm 0.0028, \quad (3)$$

and one could be tempted to claim a slight discrepancy between the predicted and derived ${}^4\text{He}$ abundance.

If the central value of Y_p is indeed 0.256, rather than invoking non-standard BBN or a non-standard cosmological history, it may be possible to argue for a prompt initial enrichment of He by an early population of stars. While the helium data responsible for Y_p is at relatively low metallicity, the most metal-poor HII region used in the analysis leading to Eq. (3) is about 1/20 of solar metallicity. There is, therefore, a reasonable possibility that some helium

was produced early in the star formation history of pre-galactic structures. Here, we consider specific models of chemical evolution which may be responsible for such a prompt initial enrichment of ^4He remaining at the same time consistent with a multitude of evolutionary constraints.

2.2. Reionization

When WMAP first reported their result for a large optical depth due to electron scattering (Kogut *et al.* 2003), which suggested a very early epoch of reionization of the intergalactic medium (IGM), it had an immediate impact on theories of cosmic chemical evolution. The reported optical depth of $\tau_e = 0.17 \pm 0.04$ implied a redshift of reionization, $z_r \approx 20$. This put an immense amount of pressure on the models of the first stars, and certainly pointed towards very massive stars as a potential solution (Cen 2003; Haiman & Holder 2003; Wyithe & Loeb 2003; Bromm 2004; Daigne *et al.* 2004). In subsequent analyses by WMAP (Komatsu *et al.* 2010), the optical depth was lowered and currently it is reported to be $\tau_e = 0.088 \pm 0.015$, corresponding to $z_r = 10.5 \pm 1.2$. This change is significant as it greatly relaxes the constraints imposed on the models. First, reionization at the relatively late redshift of 11 allows more time for structures and stars to form, and more importantly at the later time, more baryons are incorporated in structures (in the hierarchical structure formation picture), and this decreases the ionizing flux per star needed for reionization.

The early epoch of reionization is one of the driving forces behind the identification of Pop III stars with supermassive stars. However, it has been argued that the number of very massive Pop III stars needed for reionization would produce metal enrichments in conflict with observations (Venkatesan *et al.* 2004; Daigne *et al.* 2004). On the other hand, it has been shown that a ‘normal’ population of stars (i.e., a model with a standard SFR and Salpeter IMF) does not produce enough ionization photons so as to reionize the IGM (Daigne *et al.* 2004, 2006). Because of the short timescales involved (to achieve reionization by a redshift of 11), only stars with masses $M \gtrsim 3M_\odot$ can contribute to reionizing the IGM by a redshift of 11. While it has been shown that massive stars (in the range 40-100 $M_\odot$) are fully capable of reionizing the IGM in a bimodal model of star formation (Daigne *et al.* 2004, 2006), to the best of our knowledge the capabilities of IM stars have yet to be explored in this context. We will show below that indeed IM stars are capable of reionizing the IGM sufficiently rapidly.

2.3. Evolution of the IMF

One can make a phenomenological case from galaxy evolution for an IM star-dominated IMF at $z \gtrsim 2$. The arguments are individually refutable but the cumulative effect is certainly suggestive.

- Comparison of the cosmic star formation rate with the rate of stellar mass assembly, inferred from integrating the luminosity function over various bands, reveals a discrepancy at $z \gtrsim 2$ that increases towards higher z . The discrepancy is such that one *apparently* requires a reduced ratio of stellar mass to luminosity in star-forming galaxies. This is achievable if the IMF has an excess of intermediate mass stars at these epochs. No universal power law fit is acceptable at $z \gtrsim 0.5$ according to Wilkins *et al.* (2008a). A similar discussion also leads to a preferred SFR at $z \gtrsim 3$ that is ~ 3 times higher than the best fit to the stellar mass density (Wilkins *et al.* 2008b). There are other possible explanations, including uncertainties in stellar mass measurements and dust extinction, but no one of these is preferred.
- Comparison of the rate of luminosity evolution of massive early-type galaxies in clusters at $0.02 < z < 0.83$ to the rate of their color evolution requires that the IMF is weighted towards more massive stars at earlier epochs. A specific interpretation is that the characteristic stellar mass ($\sim 0.3M_{\odot}$ today) had a value of $\sim 2M_{\odot}$ at $z \sim 4$, (van Dokkum 2008).
- The evolution of the galaxy stellar mass–star formation rate relationship for star-forming galaxies constrains the stellar mass assembly histories of galaxies. Simulations including gas accretion reproduce a tight correlation but the evolution with redshift disagrees with the data. The simulations generally prefer a constant specific star formation rate $\dot{M}_*/M_*$. The specific star formation rate is high at $z \gtrsim 2$, remains high to $z \sim 7$, but is low today (Gonzalez *et al.* 2010a). To reconcile these results with the simulations, Dave (2008) proposed that the stellar initial mass function (IMF) evolves towards more high-mass star formation at earlier epochs such that the critical stellar mass in the IMF varies approximately from the present as $(1+z)^2$ to $z \sim 2$.

The arguments listed above apply to the high redshift universe where the dominant contributors to both light and stellar mass are massive star-bursting galaxies. There is also some intriguing evidence from the local universe that differentiates the IMF in current epoch luminous star-forming galaxies from their lower luminosity counterparts.

Nearby massive star-forming galaxies seem to have an IMF that is more massive star-dominated than lower mass galaxies. There is evidence for a non-universal stellar initial mass

function from the integrated properties of SDSS galaxies, according to Hoversten & Glazebrook (2008). These authors inferred the stellar initial mass function from the integrated light properties of galaxies by comparing galaxy H-alpha equivalent widths (EW) with a broadband color index to constrain the IMF. They find that low luminosity galaxies have much lower EW(H) than expected for their colors and argue that this is due to the IMF in low luminosity galaxies having fewer massive stars, either by steeper slope or lower upper mass cutoff, than that for luminous galaxies.

A similar result for HI-selected galaxies emerges via the H-alpha and the far-ultraviolet continuum tracers of star formation. Meurer *et al.* (2009) find that the flux ratio H-alpha/FUV shows strong correlations with the surface-brightness in H-alpha and the R band: Low Surface Brightness (LSB) galaxies have lower ratios compared to High Surface Brightness galaxies. The most plausible explanation for the correlations are systematic variations of the upper mass limit and/or slope of the IMF at the upper end. Massive galaxies in the local universe have an IMF that is preferentially enhanced in massive stars relative to low mass galaxies.

It seems that a case can be made that galaxies which form stars rapidly, specifically massive galaxies at high redshift and their nearby counterparts, possess an IMF that is relatively top-heavy (or bottom-light). We can speculate that essentially all vigorously star-forming systems at high redshift may similarly possess an IMF enriched in intermediate mass stars. These at least are the building blocks that in our model provide the sources of the bulk of ionizing photons at z as high as ~ 10 and play a role in the recycling of processed gas.

2.4. CEMPs and CRUMPs and the transition discriminant D_{trans}

It is well known that massive Pop III stars have a very specific impact on the nucleosynthesis budget of the early Universe. In this context, it is useful to incorporate stellar halo observations, specifically from extremely metal-poor stars (EMPS, $[\text{Fe}/\text{H}] < -3$), ultra-metal-poor stars (UMPS, $[\text{Fe}/\text{H}] < -4$) and hyper-metal poor stars (HMPS, $[\text{Fe}/\text{H}] < -5$) to derive constraints on the mass range of massive Pop III stars. From the nucleosynthetic point of view, halo stars have long been used to constrain galactic chemical evolution models, but were, until recently, quite disconnected from cosmological models. Indeed, these old low mass stars preserve their pristine composition on their surface. The abundance patterns seen in these metal-poor stars, originating presumably from Pop III stars, can yield very precious information about the first nucleosynthesis processes in the Universe (subsequent to the Big Bang), and thus gives one the possibility of exploring the Universe during the

period of reionization (Frebel *et al.* 2007; Frebel 2010).

On the other hand, it has been shown (Bromm & Loeb 2003; Frebel *et al.* 2007) that the abundances of ionized carbon and neutral atomic oxygen are important for the transition from Pop III to Pop II/I star formation. Bromm & Loeb (2003) defined a transition discriminant,

$$D_{\text{trans}} = \log(10^{[C/H]} + 0.3 \times 10^{[O/H]}) \quad (4)$$

which clearly reveals the nucleosynthetic imprint of Pop III stars. This function has the great advantage of being able to connect aspects of cosmological evolution with the C/O abundances in low mass stars. In this context, carbon-enhanced metal-poor stars or carbon-rich ultra-metal-poor stars (CEMPS and CRUMPS) seem to indicate an overabundance of carbon (and oxygen) at early stages of evolution. CEMPS represent about 20 percent of the metal poor stars. Recent studies considering multi-zone chemical evolution models show that only models with increased C yields or an initial top-heavy IMF in the IM star mass range provide good fits of observations in the Milky Way (Mattsson 2010). Note that these models also predict a nitrogen enhancement which will be considered below. Therefore, from the nucleosynthesis viewpoint it is interesting to consider IM stars as Pop III candidates, since they are producers of both C and He.

Finally, observations of metal absorption features in the intergalactic medium (IGM) give important constraints on models of the formation and evolution of the earliest structures. Recent measurements of C in the IGM (Kramer *et al.* 2010) show an increase of this element at about $z = 6$. This seems to clearly indicate an increase in the star formation rate at this redshift able to produce carbon. Again, IM stars are good candidates for explaining this trend. Note that we also predict that IGM material could have a high C/O ratio; indeed, we can obtain insight into this ratio from observations, though presently, it is difficult to obtain reliable C/O ratios from ionized abundance data (namely CIV and OVI).

2.5. Element Abundances: N and Mg

In the course of standard stellar evolution, nitrogen is produced through He burning. Primary nitrogen is also synthesized in massive stars in the H burning layer via fresh carbon coming from the He burning core. In intermediate-mass stars, nitrogen is produced together with carbon. Hot bottom-burning plays a dominant role for the synthesis of N and the amount of nitrogen produced depends on the efficiency and the duration of nuclear burning. At lower metallicity, the production of nitrogen is favored over carbon. There are indeed systems at low metallicity, such as 47 Tuc and M71, which show large nitrogen enhancements (Harbeck *et al.* 2003; Briley *et al.* 2004). Abundance patterns found in these systems make

it difficult to argue that the nitrogen enhancements are due to internal contamination, and lend credence to the hypothesis of an early IM stellar population (Ashenfelter *et al.* 2004).

The evolution of the nitrogen abundance is very sensitive to specific parameter choices in the chemical evolution model (Ashenfelter *et al.* 2004). Included among these are the uncertainties stemming from the yields (Karakas & Latanzio 2007) particularly in the upper end of the IM mass range ($> 3 M_{\odot}$). Unfortunately, this element is difficult to observe. Indeed, the best measurements come from the CN BX electronic transition band which is not generally detected. In this context, it is difficult to confront the calculated evolution of this element with available observations. However, it is interesting to note that N is observed in the few CEMPS as shown below.

Magnesium is produced predominantly in Type II supernovae where it is formed in the carbon and neon burning shells in massive stars. The dominant isotope formed in SNII is ^{24}Mg . The neutron-rich isotopes ^{25}Mg and ^{26}Mg are produced in the outer carbon layer through α capture on neon. The yield of the heavier isotopes scales with the metallicity in the carbon layer and as a result, very little of these isotopes are produced at low metallicity. In contrast, significant amounts of $^{25,26}\text{Mg}$ are produced during hot bottom-burning in the asymptotic giant branch phase in IM stars (Boothroyd, Sackmann, & Wasserburg 1995). These stars are hot enough for efficient proton capture processes on Mg leading to Al (which decays to the heavier Mg isotopes). The neutron-rich isotopes are also produced during thermal pulses of the helium burning shell. Here, α capture on ^{22}Ne (which is produced from α capture on ^{14}N) lead to both ^{25}Mg and ^{26}Mg . The latter process is very important for $\approx 3 M_{\odot}$ (Karakas & Latanzio 2003). Several observations (Shetrone 1996; Yong *et al.* 2003a,b) indicate enhancements of the neutron-rich isotopes in low metallicity stars which could necessitate the presence of an early population of IM stars (Alibés *et al.* 2001; Fenner *et al.* 2003; Ashenfelter *et al.* 2004).

Finally, it is interesting to note that Mg has been observed in ultra-faint dwarfs galaxies (Frebel and Bromm 2010) which are representative of the nucleosynthetic processes in the first galaxies. Specifically, in spite of the uncertainties related to the Mg data in these objects, we also note that [Mg/Fe] ratio is somewhat higher (about 1) in these structures compared to the local data (about 0.3) in figure 1 of Frebel and Bromm (2010). Once again this could be a signature of the presence of IM stars in these primitive galaxies.

2.6. White Dwarfs

The best current limits on the halo old white dwarf population come from a combination of interpreting the MACHO and EROS microlensing events with improved white dwarf atmosphere modeling (Torres *et al.* 2010). The upper limit, including white dwarfs with hydrogen-deficient atmospheres, allows an increased microlensing optical depth. The upper limit to the contribution of halo white dwarfs is comparable to that of the thick disk, and accounts for at most 10% of the halo dark matter between the MWG and the LMC. The MACHO upper limit, which has not been affected by subsequent microlensing studies, is approximately 20% (Alcock *et al.* (2000)). For comparison, our IM Pop III component gives a white dwarf mass fraction very comparable to the standard one ; it differs only by 15 % (see Figure 3 below).

2.7. Supernova rates

Among the important constraints imposed on the models of cosmic chemical evolution are the rates of supernovae (SN). These are intimately linked to the choice of an IMF and SFR and represent an independent probe of the star-forming universe. While Type II rates directly trace the star formation history, there is a model-dependent time delay between the formation (and lifetime) of the progenitor star and the Type Ia explosion. Since existing data is available only for relatively low redshifts, we discuss the predicted SN rates in the context of three different models and give some constraints related to the SNIa rate coming from the IM star mode.

Our early IM stellar population hypothesis inevitably produces many SN at high redshift. The predicted SFR and SN rates are presented below. The SFR rate corrections (for dust, luminosity function etc) are notoriously unreliable at $z \gtrsim 8$ where our IM population (predominantly formed earlier than $z \sim 10$) makes a significant contribution. The SN Ia rates provide a potentially more robust discriminant. However we note here that three issues help reconcile our SN rate predictions with observations of SNIa at $z \gtrsim 1$. Most importantly, the selection efficiency of SNIa, in the absence of near infrared selection, dives rapidly to zero at high redshift (beyond $z \sim 1.5$). Indeed, from Perrett *et al.* (2010), the extrapolation of the efficiency to $z = 2$ implies a steep drop (to only a fraction of a percent). Moreover the SNIa precursors are predominantly in low mass galaxies, which contain sub-luminous SNIa, by as much as 0.5 magnitude (Sullivan *et al.* 2010). Thirdly, it may be that at low metallicity ($[\text{Fe}/\text{H}] < -1.1$), the absence of iron lines driving optically thick winds may greatly inhibit the number of SNIa (Nomoto *et al.* 2003). Finally, note that there are large uncertainties related to the time delay between IM star formation and the resulting SNIa

explosion. These uncertainties add to the complexity of the question, since the predicted bulk of SNIa can be found at higher or lower high redshift, according to the value of this time delay (Totani *et al.* 2010).

3. Standard chemical evolution model

There are only a few basic ingredients to a standard (non-cosmological) galactic evolution model. These include: the specification of an IMF, usually assumed to be a power law of the form $\phi(m) \sim m^{-x}$; a star formation rate, which may be proportional to some power of the gas mass fraction or a specified function of time; a specification of stellar properties such as lifetimes and elemental yields. More complex models will include infall of gas from the IGM, and outflows from stellar induced winds. Certain observations such as the metallicity distribution in low mass stars may call for the prompt initial enrichment of metals which can be accomplished using bi-modal models of chemical evolution in which a standard mode (e.g. a Salpeter IMF and a SFR proportional to the gas fraction) is supplemented with a shallow IMF providing predominantly massive stars over a brief period of time (or metallicity). In this section, we will show that this approach cannot work for the prompt enrichment of ${}^4\text{He}$ as the most massive stars would produce heavy elements very early and thus would not enhance the ratio of He to metals. In other words, the enrichment of helium would occur too late and would not explain the enhancement in low metallicity regions.

In contrast, bi-modal models which are augmented with a population of intermediate mass stars (with mass between 2 and 8 $M_{\odot}$), can indeed provide an enrichment of helium at low metallicity in simple galactic chemical evolution models. While the model presented in this section cannot directly be extended to a model of cosmic chemical evolution, it does provide some insight to the needed bimodality involving IM stars that will carry over into a more sophisticated model based on hierarchical structure formation as in Daigne *et al.* (2006).

In Fields *et al.* (2001), we constructed chemical evolution models which led to significant D astration at low metallicity and also had significant white dwarf production. These models were based on a bimodal construction where the ‘massive’ mode consisted of IM stars. Here we consider the effect of such models on ${}^4\text{He}$ production at low metallicity.

We illustrate results with the simple closed-box model of Fields *et al.* (2001), which neglects both infall and outflow of baryons. Baryonic cycling through stars is determined by the creation function $C(m, t)$

$$dN_{\star} = C(m, t) dm dt, \quad (5)$$

which describes the mass distribution of new stars and the total star-formation rate $\Psi(t) = \int C(m, t) dm$. We adopt a “bimodal” creation function

$$C(m, t) = \psi_1(t)\phi_1(m) + \psi_2(t)\phi_2(m), \quad (6)$$

each term of which represents a distinct star-formation mode.

In the first term of eq. (6) we encode an early burst of IM star formation; to do this we adopt the star formation rate

$$\psi_1 = x_{\text{burst}} \frac{M_{\text{B}}}{\tau_1} e^{-t/\tau_1}, \quad (7)$$

with a burst timescale $\tau_1 = 100$ Myr. The parameter x_{burst} controls the fraction of the baryonic mass M_{b} which is processed in the burst; we will show results for different values of this parameter, but clearly we must have $x_{\text{burst}} \leq 1$. Since our focus is on IM stars, the IMF for this mode is a power-law (Salpeter) form: $\phi(m) \propto m^{-2.3}$, for $m \in [2M_{\odot}, 8M_{\odot}]$.

The second term in eq. (6) describes normal star formation. Again, following Fields *et al.* (2001), we adopt the classic form $\psi_2 = \lambda g(t) M_{\text{gas}}$, with $\lambda = 0.3 \text{ Gyr}^{-1}$, and a smoothing factor $g(t) = 1 - e^{-t/0.5 \text{ Gyr}}$ which ensures that star formation begins in the bursting IM mode, which then smoothly goes over to the standard mode. The normal-mode IMF is of the Salpeter form $\phi_2(m) \propto m^{-2.6}$, but now with $m \in [0.1M_{\odot}, 100M_{\odot}]$. Both IMFs are normalized in the usual way $\int m \phi_2(m) dm = 1$.

In Fig. 1, we show the evolution of the ^4He mass fraction, Y as a function of the oxygen abundance (relative to solar oxygen). Curves are shown for different values of the burst mass fraction x_{burst} in eq. (7). In the case of normal star formation (i.e., when $x_{\text{burst}} = 0$ and the IM mode is absent), as O increases we see He rise from its primordial value, but undershoots the low-metallicity data. That normal star formation fails to match the data traces back to nucleosynthesis patterns in high-mass stars, which dominate the production of O and of new He in this scenario. Specifically, for high-mass stars, the ejecta have $\Delta Y / \Delta Z_{\text{O}} \sim 1$, i.e., comparable masses of new He and of O (Woosley & Weaver 1995). Thus at low metallicity $Z_{\text{O}} \ll Z_{\text{O},\odot} \sim 0.01$, we have $\Delta Y \ll 0.01$, whereas the data seem to require $\Delta Y_{\text{obs}} \simeq 0.01$. This not only explains the problem with this simple scenario, but also suggests the solution: invoke a stellar population which has substantially different helium and metal nucleosynthesis.

Indeed, Fig. 1 shows that as we turn on the bursting IM mode via $x_{\text{burst}} > 0$, there is an abrupt rise in He at low O abundances, with a larger rise for larger x_{burst} . As anticipated, this rise now allows for the predictions to match the data, with good fits for $x_{\text{burst}} \sim 10\% - 20\%$. The origin of this rise clearly reflects the nucleosynthesis patterns of IM stars, whose ejecta are much more enriched in new He than in O, relative to massive stars. Specifically,

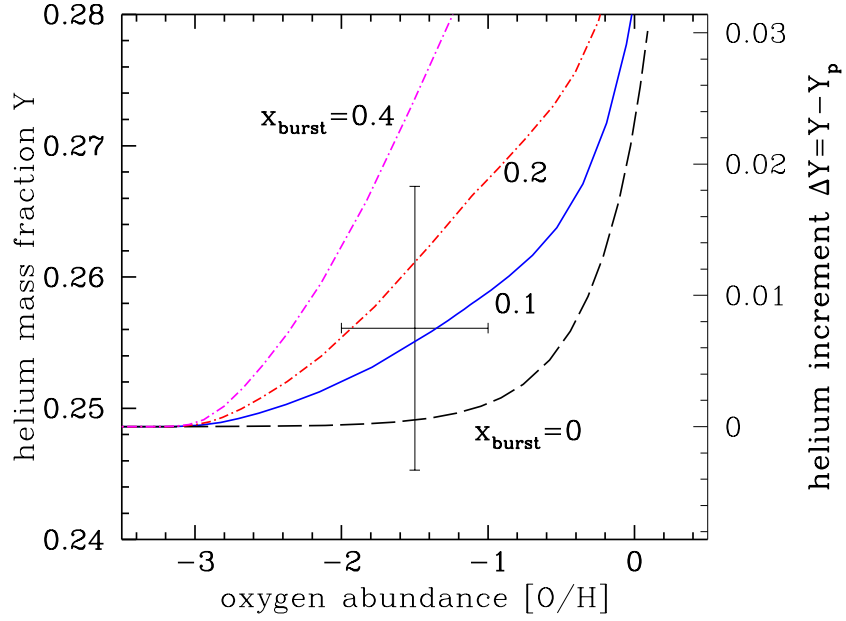


Fig. 1.— The ${}^4\text{He}$ mass fraction in several bimodal models of chemical evolution. Curves show different fractions x_{burst} (eq. 7) of baryons processed through the burst phase. The data point is representative of the helium data in low metallicity extragalactic HII regions.

for IM stars at low metallicity in the $m = (4M_{\odot}, 8M_{\odot})$ we have $\Delta Y/\Delta Z_{\text{O}} \sim (50, 300)$ (van den Hoek & Groenewegen 1997). These large ratios trace back to the very small O production in these stars.

The results thus far are for the simplest possible model: a single-zone closed box. Staying with single-zone models, even if we include infall and/or outflow the results should be similar. In the case of primordial infall, both the metal and new He yields will be diluted, and by the same factor. Thus the He-O trends should stay the same. Similarly, in the case of outflows, the abundances in the gas remaining in the box are only affected if the flow ejects one element preferentially relative to the other. But again, given that the O and new He are produced in the same environments, any physically realizable winds will remove them together, leaving the remaining gas with He-O trends unaffected.

The lessons we draw from our simple model are that an increase in helium at low metallicity, as suggested by observations, can be accomplished at the cost of processing 10%–20% of observable cosmic baryons through IM stars. But as shown in Fields *et al.*

(2001) and discussed above, such a scenario also has substantial consequences, including other element abundances, white dwarfs, and Type Ia supernovae. To examine all of these issues in a more realistic manner requires a chemical evolution model in a cosmological context.

4. A cosmological chemical evolution model

4.1. Generalities

The study of star formation in a cosmological context requires the inclusion of i) a model of dark matter structure formation, and ii) accretion and outflow of baryonic matter with respect to existing and forming structures.

We have developed a detailed model of cosmological chemical evolution (Daigne *et al.* 2006; Rollinde *et al.* 2009) using a description of non linear structures, based on the standard Press-Schechter (PS) formalism (Press & Schechter 1974). Baryons are placed 1) within stars or their remnants within collapsed structures, 2) in gas within collapsed structures (the interstellar medium (ISM)), or 3) outside of structures (the intergalactic medium, IGM). The rate at which structures accrete mass is determined by a Press-Schechter distribution function, $f_{PS}(M, z)$. The model included mass (baryon) exchange between the IGM and ISM, and between the ISM and stellar component. In this study we assume that the minimum mass of dark matter halos for star-forming structures is $10^7 M_\odot$.

Once the model is specified, we can follow many astrophysical quantities such as: the global SFR, the optical depth, the supernova (SN) rates and the abundances of individual elements (Y, D, Li, Fe, C, N, O, Mg abundances) which are used to tackle specific questions related to early star formation and the reionization epoch. In this study, we consider two distinct modes of star formation: a normal mode of Pop II/I and a massive or intermediate mass mode of Pop III stars.

Throughout this paper, a primordial power spectrum with a power law index $n = 1$ is assumed and we adopt the cosmological parameters of the so-called concordance model (Komatsu *et al.* 2010), i.e. $\Omega_m = 0.27$, $\Omega_\Lambda = 0.73$, $h = 0.71$ and $\sigma_8 = 0.9$.

4.2. Star formation rate scenarios

As in the simple model described in section 3, the models considered are bimodal. Each model contains a normal mode with stellar masses between $0.1 M_\odot$ and $100 M_\odot$, with a near

Salpeter IMF ($x = 1.6$) (hereafter called model 2).

We fit the SFR history of Pop II/I stars to the data compiled in Hopkins & Beacom (2006) (from $z = 0$ to 5), and to the recent measurements at high redshift by Bouwens *et al.* (2010) and Gonzalez *et al.* (2010b). These observations place strong constraints on the Pop II/I SFR. The fit for the SFR, $\psi(z)$, is based on the mathematical form proposed in Springel and Hernquist (2003)

$$\psi(z) = \nu \frac{a \exp(b(z - z_m))}{a - b + b \exp(a(z - z_m))}. \quad (8)$$

The amplitude (astration rate) and the redshift of the SFR maximum are given by ν and z_m respectively, while b and $b - a$ are related to its slope at low and high redshifts respectively. The normal mode is fitted using: $\nu_{\text{II/I}} = 0.3 \text{ M}_\odot \text{ yr}^{-1} \text{ Mpc}^{-3}$, $z_{\text{m II/I}} = 2.6$, $a_{\text{II/I}} = 1.9$ and $b_{\text{II/I}} = 1.1$. The SFR of this mode peaks at $z \approx 3$.

In addition to the normal mode, we add a mode for Pop III stars. Our primary interest here is a model for IM Pop III stars, and we choose an IM component of stars with 2 - 8 $\text{M}_\odot$ (hereafter model 3), assuming an IMF with slope 1.3. Some fraction of the IM stars become SNIa. The SFR parameters are the following: $\nu_{\text{IIIa}} = 3 \text{ M}_\odot \text{ yr}^{-1} \text{ Mpc}^{-3}$, $z_{\text{m IIIa}} = 10$, $a_{\text{IIIa}} = 1.9$ and $b_{\text{IIIa}} = 1.1$. The redshift peak is chosen so that the IM stars are born in time to affect low-metallicity abundances, and the normalization is chosen to allow a substantial effect on ^4He .

For comparative purposes, we also consider a massive component with stars between 36 - 100 $\text{M}_\odot$ with an IMF slope of 1.6, which terminate as Type II supernovae (SNII) (hereafter model 1). The SFR parameters are the following: $\nu_{\text{IIIb}} = 0.0016 \text{ M}_\odot \text{ yr}^{-1} \text{ Mpc}^{-3}$, $z_{\text{m IIIb}} = 22.8$, $a_{\text{IIIb}} = 4$ and $b_{\text{IIIb}} = 3.3$. For a detailed description of the model see Rollinde *et al.* (2009) and Daigne *et al.* (2006). Note that both models 1 (massive) and 3 (IM) include the normal mode (model 2).

In Fig. 2, we show the adopted SFR for each of the three cases considered. As one can see, the normal mode is chosen to fit the observations also plotted in the figure. As the data extend only up to $z \approx 8$, there is essentially no constraint on the massive mode which dominates at $z \gtrsim 20$. Data at $z \gtrsim 8$ is highly uncertain due to unknown systematics involving, among other effects, the dust corrections and adopted rest-frame UV luminosity function, and presents essentially no conflict with our models (Labbe *et al.* (2010)).

Fig. 2 also shows that the IM mode represents a significant processing of baryons. The peak of the IM star formation rate is about a factor ~ 10 higher than the peak of the normal star formation rate, and a factor $\sim 10^3$ higher than the massive Pop III star formation rate.

On the other hand, the IM star formation peak lasts for about a factor ~ 10 less time than the normal star formation rate. Thus we expect that roughly comparable amounts of baryons will be processed through these two modes. In contrast, a much smaller fraction of baryons are processed through the massive Pop III mode. One should recall, however, that in our model many baryons always remain in the IGM and never reside in galaxies nor are processed through stars.

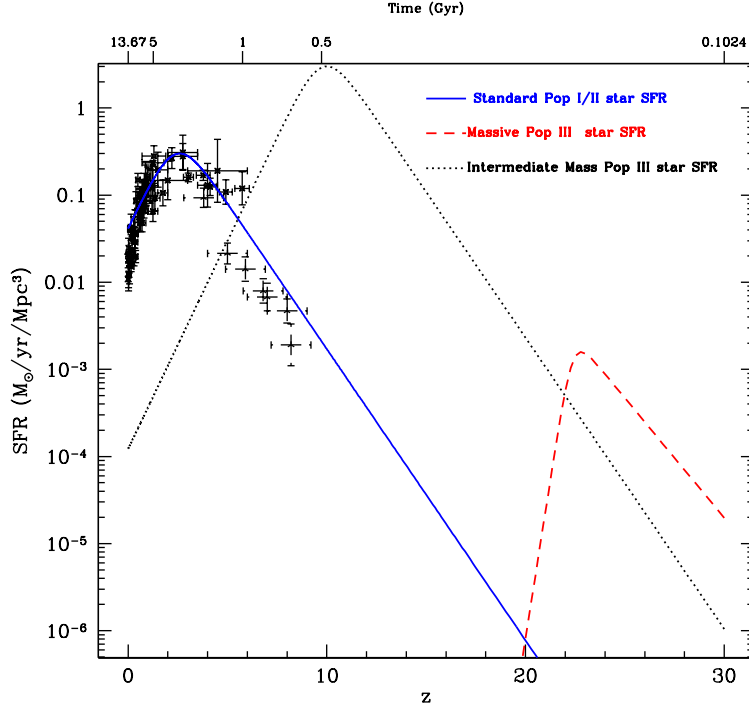


Fig. 2.— The cosmic star formation rate (SFR) as a function of redshift. The data (solid black points) are taken from Hopkins & Beacom (2006). Dashed black points come from Bouwens *et al.* (2010) and from Gonzalez *et al.* (2010b). The blue solid line represents the standard SFR with a Salpeter IMF and a mass range: $0.1 < M/M_{\odot} < 100$. The dashed red line represents the massive Pop III stellar mode, with a Salpeter IMF and a mass range: $36 < M/M_{\odot} < 100$. The dotted black curve represents the IM SFR mode, with a Salpeter IMF and a mass range: $2 < M/M_{\odot} < 8$.

Figure 3 represents the mass fraction of each component related to the total mass of baryons: IGM, Galaxies and stars. Note that the addition of the IM star component does not affect the mass fraction of stars (including remnants) at low redshift .

Note that the star fraction in the IM mode has an initial peak at about $\sim 10\%$ of all baryons. This occurs at $z \sim 10$. The star fraction then drops as the IM stars die off, then rises with normal star formation. Thus we see that in our model, about 10% of the baryons are processed through the IM mode. In contrast, we see that the massive Pop III mode only processes about $\sim 10^{-6}$ of all baryons.

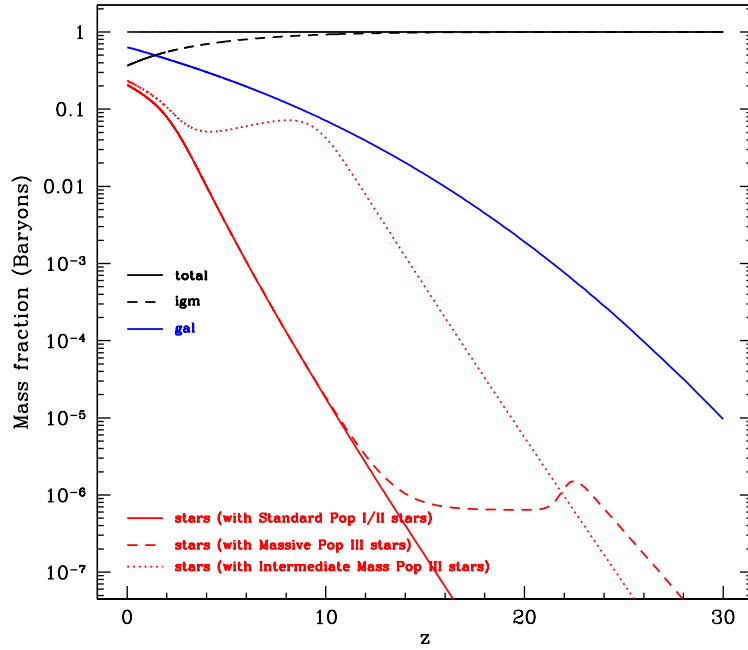


Fig. 3.— Different mass fractions as a function of redshift. The flat solid black line (top of the figure) represents the total baryons in the Universe. The IGM fraction is shown by the dashed black curve, the galactic fraction is shown by the growing solid blue curve. The mass fraction of stars is plotted for the three models considered (red curves): solid line for model 2 (normal mode), dashed line for the model 1 (with massive Pop III stars) and the dotted line for model 3 (with IM stars).

4.3. Yields and lifetimes

The lifetimes of intermediate mass stars ($0.9 < M/M_{\odot} < 8$) are taken from Maeder and Meynet (1989) and from Schaerer (2002) for more massive stars. Old halo stars with masses below

$\sim 0.9 M_{\odot}$ have a lifetime long enough to be observed today. They are assumed to inherit the abundances of the ISM at the time of their formation. Thus, their observed abundances reflect, in a complex way (due to exchanges with the IGM), the yields of all massive stars that have exploded earlier.

The yields of stars depend on their mass and their metallicity, but not on their status (i.e. Pop II/I or Pop III). Some Pop II/I stars are massive, although in only a very small proportion since we use a slightly steeper than Salpeter IMF. Pop III stars are all massive stars. We use the tables of yields (and remnant types) given in van den Hoek & Groenewegen (1997) for intermediate mass stars ($< 8M_{\odot}$), and the tables in Woosley & Weaver (1995) for massive stars ($8 < M/M_{\odot} < 40$). An interpolation is made between different metallicities ($Z=0$ and $Z=10^{-4}, -3, -2, -1, 0Z_{\odot}$) and we extrapolate the tabulated values beyond $40 M_{\odot}$.

5. Results

Having specified the models under consideration, we can now systematically consider the consequences of our particular choices for Pop III stars. For most of the results which follow, we will compare three distinct model choices. 1) model 2 alone, ie, only Pop II/I stars; 2) model 3, a bimodal model including the normal mode (model 2) plus the IM mode of Pop III stars ; 3) model 1, a bimodal model including the normal model (model 2) plus the massive mode of Pop III stars.

5.1. Reionization

Having set the SFR in our model, we now compute the electron scattering optical depth for our choice of IMF. The evolution of the volume filling fraction of ionized regions is given by:

$$\frac{dQ_{\text{ion}}(z)}{dz} = \frac{1}{n_b} \frac{dn_{\text{ion}}(z)}{dz} - \alpha_B n_b C(z) Q_{\text{ion}}^2(z) (1+z)^3 \left| \frac{dt}{dz} \right|, \quad (9)$$

where n_b is the comoving density in baryons, $n_{\text{ion}}(z)$ the comoving density of ionizing photons, α_B the recombination coefficient, and $C(z)$ the clumping factor. This factor is taken from Greif & Bromm (2006) and varies from a value of 2 at $z \leq 20$ to a constant value of 10 for $z < 6$. The escape fraction, f_{esc} , is set to 0.2 for both Pop III and PopII/I. The number of ionizing photons for massive stars is calculated using the tables given in Schaerer (2002).

Finally, the Thomson optical depth is computed as in Greif & Bromm (2006):

$$\tau = c\sigma_{\text{T}}n_{\text{b}} \int_0^z dz' Q_{\text{ion}}(z') (1+z')^3 \left| \frac{dt}{dz'} \right|, \quad (10)$$

where z is the redshift of emission, and σ_{T} the Thomson scattering cross-section.

In Figure 4, we plot the integrated optical depth from $z = 0$ to z . The red band represents the observed results from WMAP7 (Komatsu *et al.* 2010). As one might expect, the normal mode alone (model 2 shown as the solid blue curve) is not capable of producing a sufficiently large optical depth. The massive mode (model 1 shown by the red dashed curve) does manage to reionize the IGM, but only barely. Of course more reionization is possible by increasing the SFR for the massive mode, but this would lead to complications in elemental abundances. We see that the IM mode (model 3 - shown by the black dotted curve) is able to easily reionize the Universe compared to models 1 and 2. Our models allow an escape fraction as low as $\sim 0.1 - 0.2$, which provides considerable flexibility in accounting for reionization. While the ratio of ionizing photons from a $6M_{\odot}$ star vs that of a $20M_{\odot}$ star is small, one has many additional stars in the IM scenario relative to the number in the massive mode.

5.2. Nucleosynthesis evolution

We next consider the evolution of the abundances of He, CNO, Fe and Mg as a function of the redshift and/or the metallicity. We also show the evolution of D and ^7Li due to early astration.

We begin with the evolution of the ^4He abundance. In the left panel of Fig. 5, we show the analogue of Fig. 1 for the bimodal models based on hierarchical structure formation. Plotted is the ^4He mass fraction, Y , vs. $[\text{O}/\text{H}]$. The solid blue curve corresponds to the model with only a Pop II/I contribution. This result is indistinguishable from that produced by models including the massive Pop III contribution (not shown). This can be understood as the bulk of the ^4He and oxygen are derived from the same stars in the two models. In both cases, the helium abundance begins at the BBN primordial value and remains rather flat until the oxygen abundance is roughly 1/10th of solar. In contrast, as shown by the black dotted curve, in the IM Pop III model, ^4He is produced early in IM stars with little or no accompanied oxygen. As a result, the ^4He mass fraction begins to grow at very low $[\text{O}/\text{H}]$ and for the model parameters chosen, plateaus at value close to $Y \approx 0.256$, in good agreement with recent determinations (Izotov & Thuan 2010; Aver *et al.* 2010). As in the case of the simple model discussed in section 3, this model, therefore produces an effective

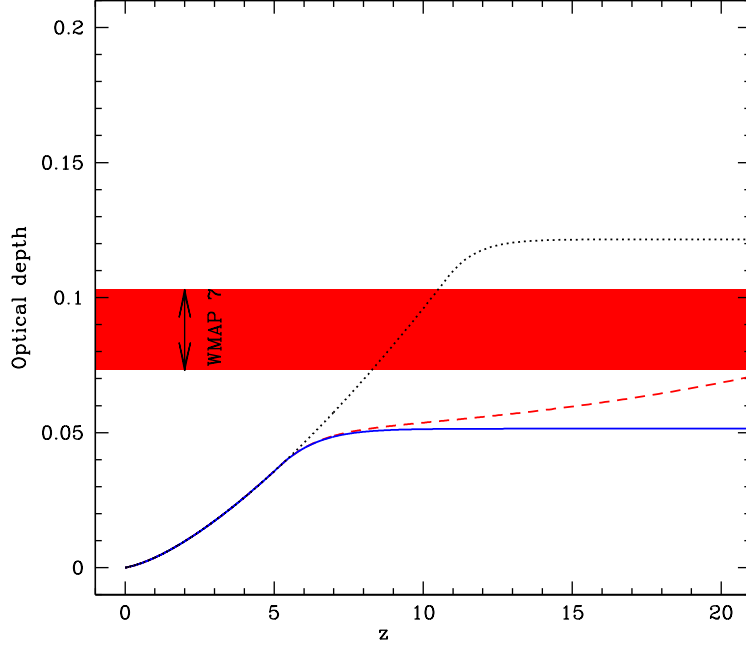


Fig. 4.— The optical depth as a function of the redshift. The red range corresponds to the observed results from WMAP7(Komatsu *et al.* (2010)). The red dashed line corresponds to model 1 (with Massive Pop III stars), the blue solid line to model 2 (the normal mode) and the black dotted line to model 3 (with IM stars).

prompt initial enrichment of ^4He in low metallicity galaxies. Note however, that due to the size of the error bar associated with the observations, we cannot exclude the possibility that no enrichment occurred, leaving models 1 and 2 viable.

It is helpful to compare the helium–oxygen trend in Fig 5(a) with the simple closed box results in Fig. 1. The latter shows results for different fractions x_{burst} of baryons processed through the IM mode. As noted above, our full hierarchical model cycles about 10% of all baryons through IM stars; thus Fig. 5(a) should be compared to the $x_{\text{burst}} = 0.1$ curve in Fig. 1. Indeed, we see that both show very similar ^4He evolution.

In the right panel of Fig. 5, we show the corresponding evolution of the ^4He abundance with redshift. The dashed red curve corresponds to the massive Pop III mode. Once again, the standard model and the massive Pop III model show nearly identical histories. We do see however, a modest increase in the helium mass fraction at high redshift due to the massive

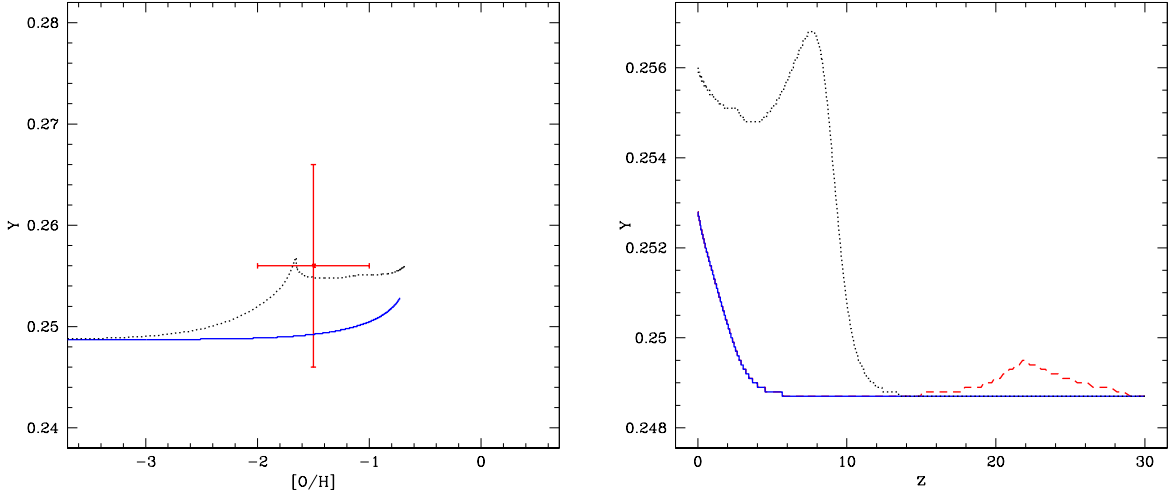


Fig. 5.— *Left:* Evolution of the helium mass fraction as a function of $[O/H]$ (relative to the solar value). The solid blue line corresponds to the both models: 2 (standard model) and 1 (with a massive Pop III mode). The dotted black curve corresponds to model 3 (with IM Pop III stars). The red point comes from Aver *et al.* (2010). *Right:* Evolution of the helium mass fraction as a function of redshift. The red dashed line corresponds to the Massive Pop III model, the blue solid line to the standard model, and the black dotted one to the IM Pop III model.

Pop III mode. This is diluted by further infall as structures continue to grow. In the IM Pop III model, there is a significant enhancement in the helium mass fraction around $z \sim 8$. This too is slightly diluted with infall at later times.

We also show in Figs. 6 - 7 the corresponding evolution for D and ${}^7\text{Li}$; note that the vertical axes have zero offset in order to more clearly distinguish the model predictions. In each case, there is little difference between the standard model and the massive Pop III model. Intermediate mass stars on the other hand are known to deplete D/H (Fields *et al.* 2001). In this case, the degree of depletion is not severe (about 15%) but it does move the BBN value further away from the abundance determined in quasar absorption systems. The ${}^7\text{Li}$ astration factor is the same as for D/H and in this case moves the BBN value closer to the abundance determined in halo stars. However, an abundance of $\sim 4 \times 10^{-10}$ is still very far from the observed plateau value between 1 and 2×10^{-10} .

Consider now the abundance evolution of CNOMg together with their abundance ratios.

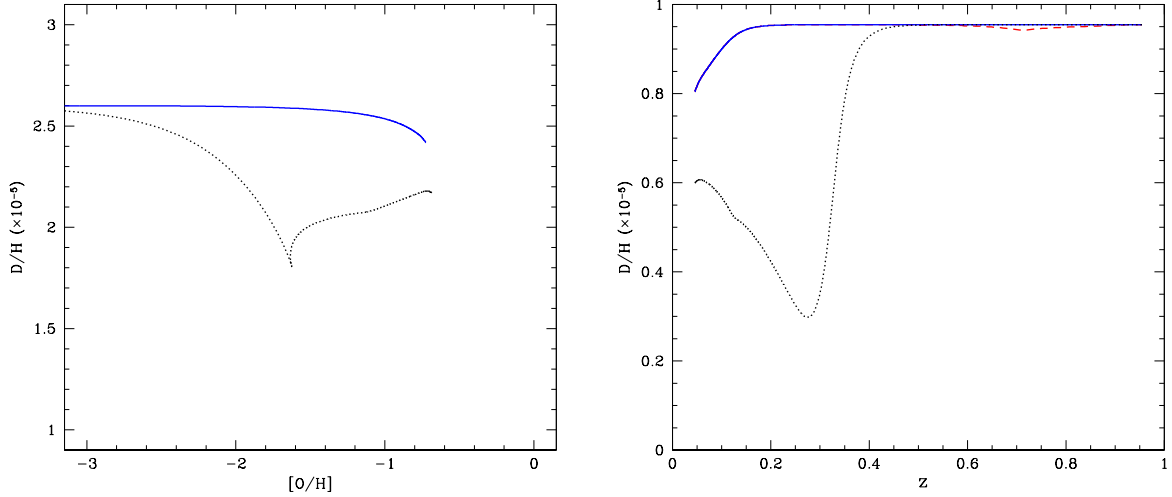


Fig. 6.— *Left:* As in Fig. 5 showing the evolution of the deuterium abundance as a function of $[O/H]$, *Right:* showing the evolution of the deuterium abundance with redshift. Note that the vertical axis is offset from zero, in order to more clearly show the (relatively small) effect on D.

Figures 8 and 9 display the abundance evolution with z . As in all of the previous figures, each of the following figures shows three curves corresponding to a model with no Pop III contribution (solid blue curve), a model with a massive Pop III component (red dashed curve) and a model with an IM Pop III component (black dotted curve). The evolutionary behaviour of these model choices is well understood. Normal mode stars produce a moderate abundance of heavy elements at high redshift from the IMF-suppressed massive stars in that mode. The same stars, nevertheless are effective at low redshift and produce the bulk of metals observed in the Milky Way. The Massive Pop III component produces C, O and Mg at high redshift, though these abundances are diluted at low redshift by infall as structures continue to grow. The IM stellar component produces a rather specific nucleosynthetic signature: essentially C and N.

Figures 10 and 11 show the evolution of the abundance ratios as a function of redshift. As one might expect, at lower redshifts, the IM star Pop III component produces the highest $[O/Fe]$, $[C/Fe]$, $[N/Fe]$. The evolution of $[Mg/Fe]$ corresponds to ^{24}Mg coming from massive stars and the highest value comes from the massive population III component. The ratio of the neutron-rich isotopes to ^{24}Mg remains small in the Pop III model dominated by massive stars, but this ratio can become large ($\mathcal{O}(1)$) in the IM Pop III model. Also shown in these

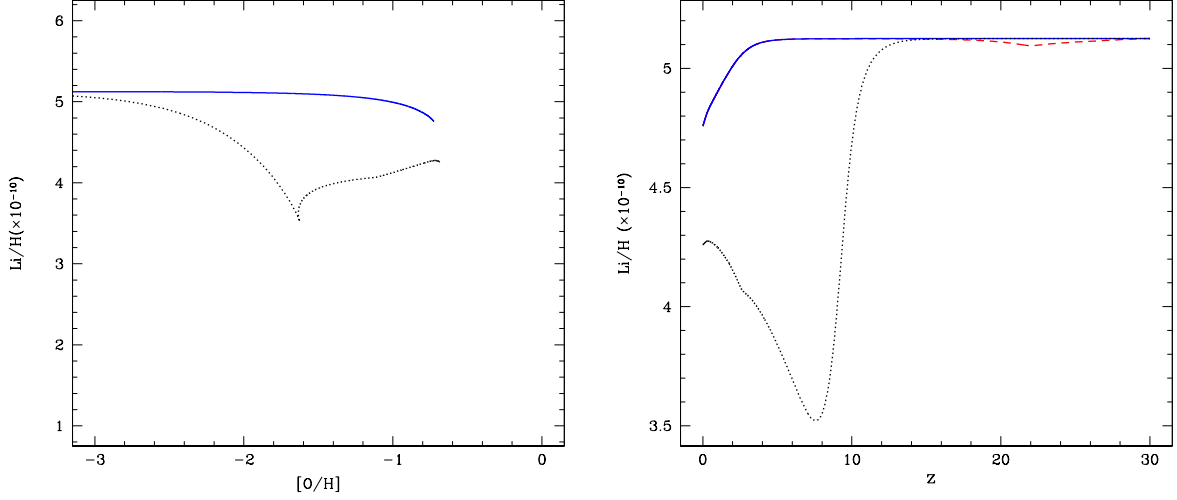


Fig. 7.— *Left*: As in Fig. 5 showing the evolution of the lithium abundance as a function of $[\text{O}/\text{H}]$. *Right*: showing the evolution of the lithium abundance with redshift.

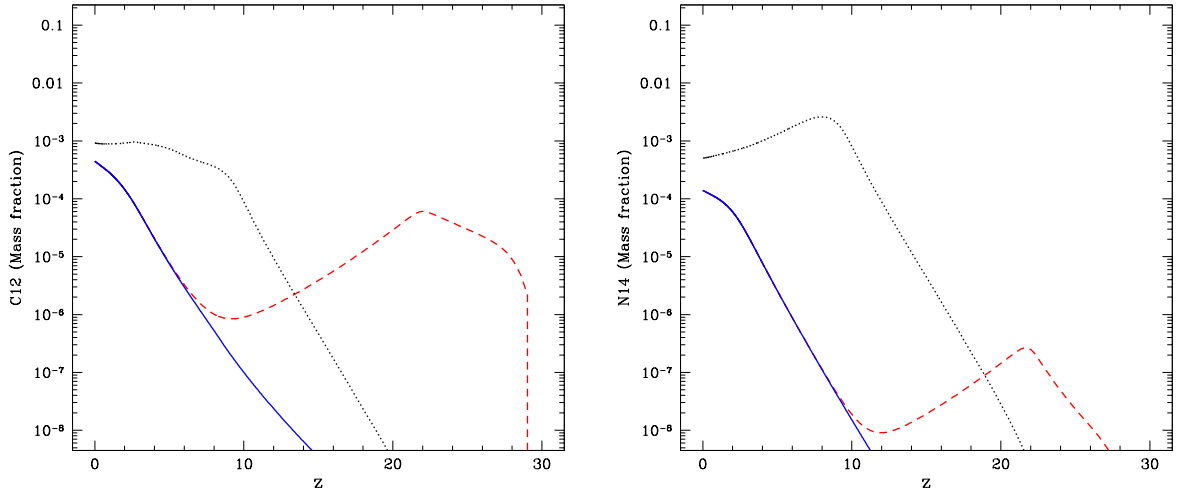


Fig. 8.— As in Fig. 5 for Carbon (*Left*), and Nitrogen (*Right*).

figures are the abundance ratios seen in several CEMPS.

Surprisingly, the $[\text{C}/\text{O}]$ ratio shown in Figure 12 is high in this model as oxygen is

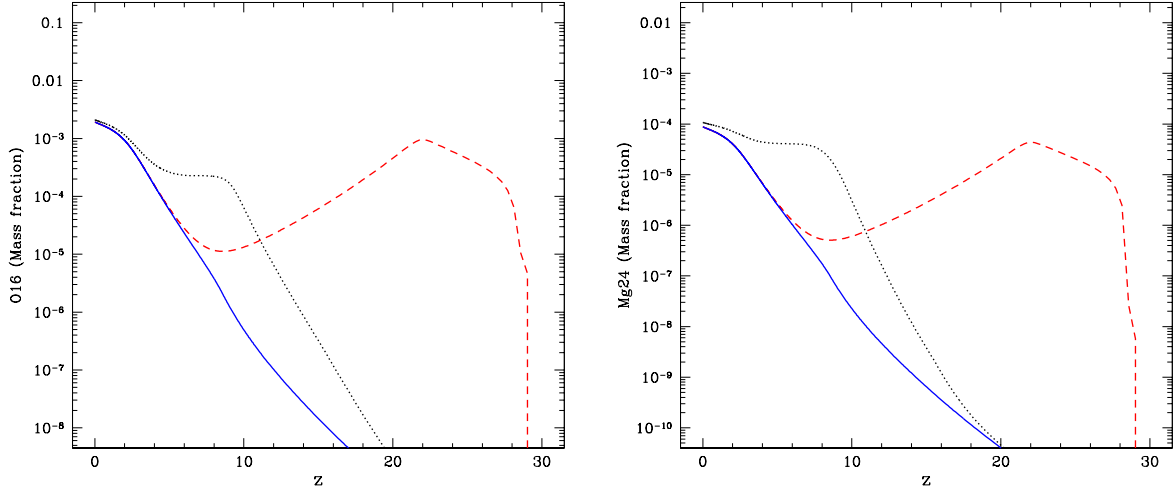


Fig. 9.— As in Fig. 5 for Oxygen (*Left*) and Magnesium (*Right*).

also primarily produced in more massive stars whose role is diminished in this model at intermediate redshifts. In contrast, the massive Pop III component reaches very high ratios of $[C/Fe]$ and $[O/Fe]$. Only the massive Pop III model is capable of reproducing the $[O/Fe]$ abundance ratios observed in these stars. Similarly, the IM model has difficulty in achieving $[C/Fe]$ ratios as high as the two HE stars with $[C/Fe] \approx 4$ as seen in the figure, although the model does a reasonable job of accounting for the $[C/O]$ ratios seen in these stars. The abundance patterns found in these CEMPS continues to confirm that the formation of massive stars at very high redshift is plausible.

Finally we consider the evolution of the parameter D_{trans} defined above in eq. (4). Figure 13 shows the D_{trans} parameter as a function of the metal enrichment. Black circles come from a compilation of Frebel *et al.* (2007). We see that this representation allows one to clearly distinguish the effects of the different choices of stellar mass ranges: the normal mode fits the bulk of standard stellar data. The massive mode can explain the few CRUMPS (Rollinde *et al.* 2009) and the IM stellar mode can explain the bulk of stars very enriched in C between $-3 < [Fe/H] < -1$ range (red box). Indeed, we can see that the black dotted line (IM stars) is always much higher than the blue one (normal mode).

In particular, for $[Fe/H] > -3$, IM stars give $D_{\text{trans}} \gtrsim -1$. In Figure 1 of Frebel *et al.* (2007), a specific stellar population is found exactly there: C rich stars. It is very interesting to note that only the IM component is able to explain this part of the diagram. Indeed,

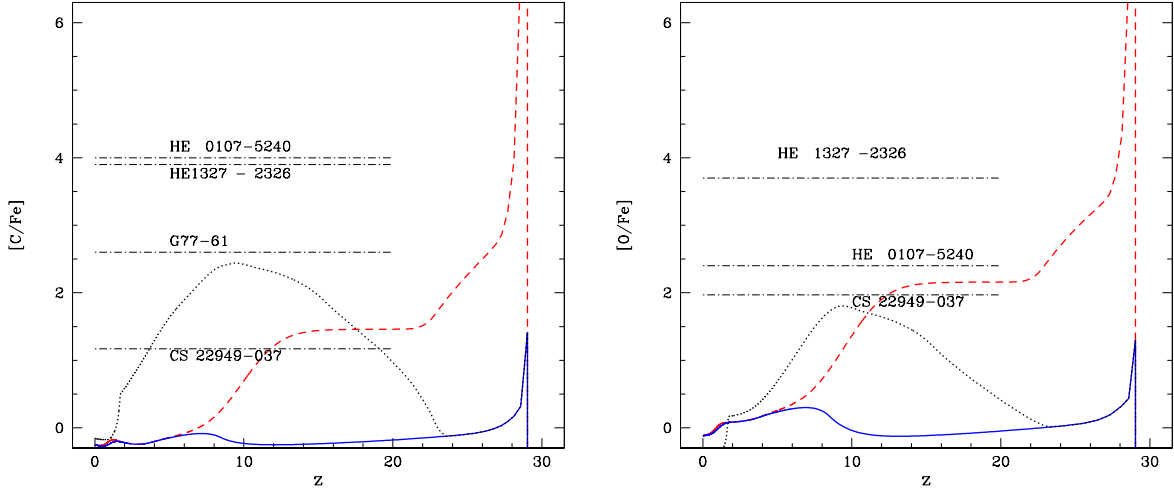


Fig. 10.— *Left*: As in Fig. 5, the evolution of the $[C/Fe]$ ratio (relative to the solar value) as a function of redshift. *Right*: Idem for $[O/Fe]$ ratio. Observational data (horizontal dashed lines) represent measured abundances in the following very iron poor halo stars: CS 22949-037 (Depagne *et al.* 2002), He 0107-2240 (Bessel *et al.* 2004), He 1327-2326 (Frebel *et al.* 2005) and G77-61 (Plez & Cohen 2005).

to the best of our knowledge, the yield patterns of IM stars are the only ones which can correctly fit the abundances seen in C stars. Thus is it tempting to interpret the metal-poor, C-rich stellar population as an indication of the presence of an early IM population. One could even push this further: of the stars in Figure 13, about $\sim 10 - 20\%$ fall in the C-rich red box fit by IM stars. To the extent that the data in the figure faithfully trace the ensemble of star-forming histories in the early universe, we would then estimate that Pop III IM stars form at $\sim 10 - 20\%$ of our model rate. Since our IM model has $\sim 10\%$ of baryons processed through this mode, the C-rich stars would in turn imply that $\sim 1 - 2\%$ of baryons participate in IM star formation.

Thus we see that C-rich halo stars seem to demand *some* early IM star formation. Moreover, the large *scatter* in C and O abundance patterns over the full metal-poor halo star population demand that no single nucleosynthesis (and thus star-forming) history will suffice. Indeed, given that C-rich stars are outliers to the main trend, the IM population appears to be probably sub-dominant, acting only in low mass galactic structures at high z .

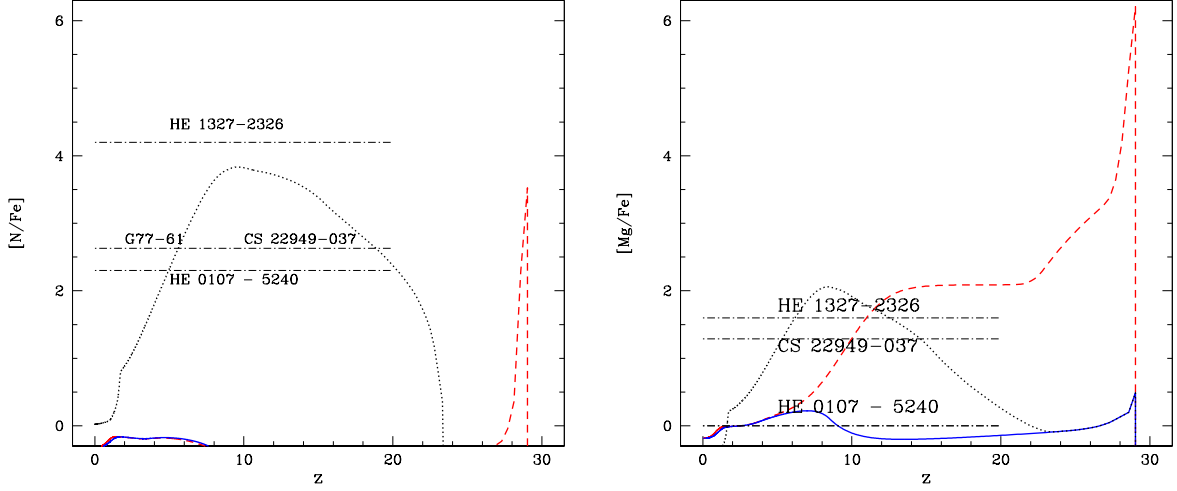


Fig. 11.— As in Fig. 10 for the $[N/Fe]$ and $[Mg/Fe]$ ratios.

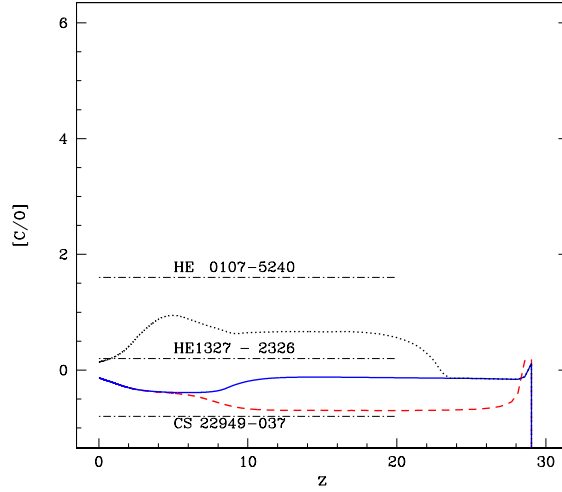


Fig. 12.— As in Fig. 10 for the $[C/O]$ ratio.

5.3. Type II supernovae

In Figure 14, at high redshift, we show the resulting evolution of the Type II SN rate along with the data at relatively low redshift. The GOODS data for core collapse supernovae

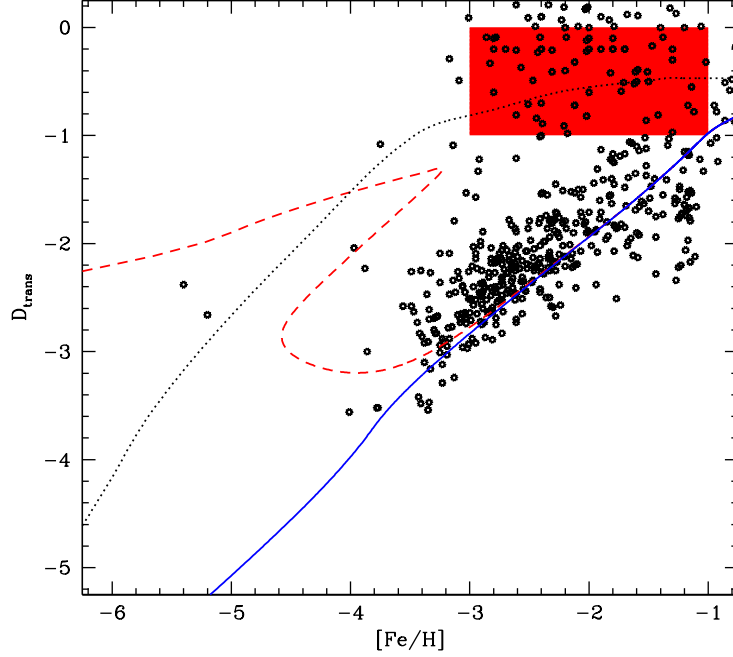


Fig. 13.— As in Fig. 5, the evolution of the D_{trans} parameter (transition discriminant D_{trans} - see eq. (4)) as a function of $[\text{Fe}/\text{H}]$. The black circles come from the compilation of Frebel *et al.* (2007). The red box corresponds to the region corresponding to C rich stars.

have been placed in two bins at $z = 0.4 \pm 0.2$, and $z = 0.7 \pm 0.2$ (Dalhen *et al.* (2004, 2008)). Their results (which have been corrected for the effects of extinction) show SNI rates which are significantly higher than the local rate (at $z = 0$; Cappellaro *et al.* 1999; Li *et al.* 2010). Since the timescale between star formation and the core collapse explosion is very short, there will be no significant contribution of Population III stars to Type II rates at any z . The SN Type II rate is directly related to the overall SFR and therefore to the astration rate ν and the slope of the SFR at high redshift.

The data at low z is well described by the models. This result is independent of our choice of the mass range for Pop III since massive Pop III stars will only contribute to the SN rate at very high redshift and our IM Pop III stars produce no SNI. However, the model predicts much higher SN rates at higher redshift. Indeed, the SN Type II rate peaks at a redshift $z \approx 3$ at a rate which is nearly 8 times the observed rate at low z . It will be interesting to see whether future data will be able to probe the SN rate at higher redshift.

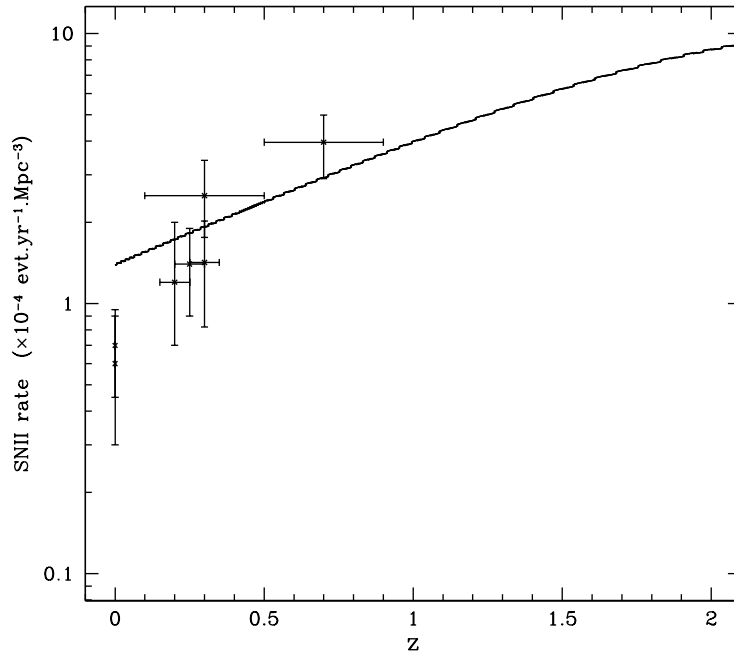


Fig. 14.— Evolution of the SNII rate as a function of redshift. The observed rates are taken from Cappelaro *et al.* (1999); Capellaro *et al.* (2005); Dalhen *et al.* (2004, 2008); Botticella *et al.* (2008); Bazin *et al.* (2009); Li *et al.* (2010). The evolution is the same for all three models.

These elevated rates may be detectable in spite of the expected increase in dust extinction due to the early production of metals.

5.4. Type Ia supernovae

Our calculation of the Type Ia SN rate depends on two additional assumptions beyond the specification of the models present in the previous section. The Type Ia rate will depend on the fraction of low and IM mass stars which end up as SNIa, as well as the time delay between formation and explosion. Furthermore, it is not clear that either of these quantities are universal constants. That is, they may vary with redshift, metallicity, or the size of the structure the stars are formed in. We have assumed that the SNIa rate is proportional to the IM star SFR ($2 - 8M_{\odot}$). The coefficients adopted are $\epsilon = 0.02$ and 0.01 for the models

2, 1 and 3 respectively.

In Fig. 15, we show the SNIa rate contrasted with the observational data. As in the case for Type II supernovae, at high redshift, the data (also taken from GOODS; Dalhen *et al.* 2004, 2008) is binned into four redshift bins at $z = 0.4, 0.8, 1.2$, and 1.6 , each with a spread of ± 0.2 . Other data references are given in the caption. We see that, in contrast to the case of SNII, the evolution of the SNI rate is very different for the two models with and without IM stars. Adding the IM stellar mode implies a high SNIa rate at high redshift. The position of this bump depends on the time delay of the SNIa.

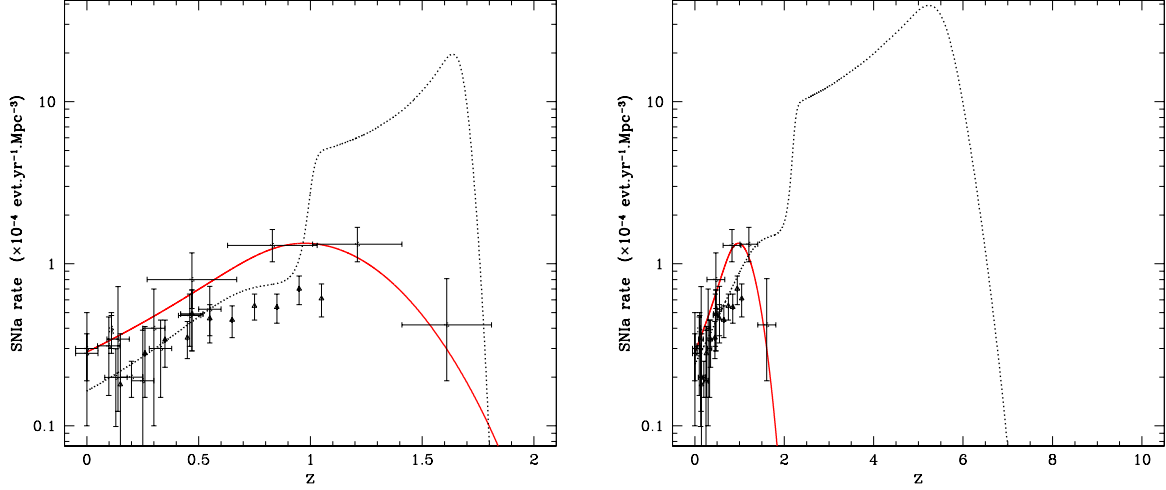


Fig. 15.— Evolution of the SNI rate as a function of redshift. The observed rates are taken from Cappelaro *et al.* (1999); Reiss (2000); Hardin *et al.* (2000); Dalhen *et al.* (2004); Pain *et al.* (2002); Madgwick *et al.* (2003); Tonry *et al.* (2003); Stogler *et al.* (2004); Blanc *et al.* (2004); Li *et al.* (2010); Perrett *et al.* (2010). The red solid curve corresponds to the both models 1 (normal mode) and 2 (with Massive Pop III stars). The black dotted curve corresponds to model 3 (with IM stars). *Left:* The assumed time delays for IM stars in model 2 and model 3 are 2.5 and 3.4 Gyr (including the lifetime of stars) respectively, and the fraction of the white dwarfs which become SNIa are $\epsilon = 2$ and 1 per cent, respectively. *Right:* The time delay for IM stars to become SNIa in model 3 is reduced to 0.5 Gyr and ϵ is 2 per cent for both models.

Due to large uncertainties concerning the time delay, we present two cases (Maoz *et al.* 2010; Totani *et al.* 2010). We hold the delay fixed at 2.5 Gyr for normal mode stars, but in the left panel of Fig. 15, we choose a delay of 3.4 Gyr and in the right panel we take 0.5 Gyr

for model 3. While the normal mode fits the data quite well, we see that the population of IM stars creates a significant bump in the SNIa rate at high redshift. Unless the time delay for these supernovae is reduced from the nominal value of 2.5 Gyr (as in the right panel of Fig. 15) the SNIa rate would greatly exceed the observed rate at redshifts between 1 and 1.5. If the delay is smaller, the bump in the SNIa rate is pushed to higher redshift. Of course, it may be that for Pop III stars, the fraction ϵ of IM stars becoming SNIa is reduced as discussed in section 2.7.

In the upper panel Fig. 16, the SNI/SNII ratio is plotted as a function of the redshift for models 1 and 3. In the lower panel of the figure both SNIa and SNII rates are plotted, as in 14 and 15. The IM stellar mode predicts that the bulk of SNIa occur at high redshift, though this results depends on the time delay of these SN. However, at such a high redshift the selection efficiency drops rapidly towards zero (Perrett *et al.* (2010)) and we cannot exclude the existence of this SNIa component. In the future it would be interesting to have observational insight into low mass galaxies, which could contain sub-luminous SNIa. An alternative, if these sub luminous SNIa are not observed we could put strong constraints on the early helium abundance in the primitive structures.

It is interesting to note the interplay between the IM constraints from halo star carbon abundances and from Type Ia SNe. Namely, at the end of §5.2 we argued that the existence of C-rich metal-poor halo stars seems to *require* an early cosmic IM star population, but the relative rarity of such C-rich stars also seems to imply the IM population was sub-dominant, perhaps accounting for $\sim 10 - 20\%$ of early star formation. Note that if we apply this same $\sim 10 - 20\%$ factor to the IM predictions for Type Ia SNe in Figs. 15 and 16, the predictions would be brought into agreement with the observations. Similarly, we could argue the other direction, demanding that the IM fraction be small enough to agree with the Type Ia SN observations; this would again give $\sim 10 - 20\%$ of our all-IM Pop III model, and thus would agree with the rough statistics suggested by the counts of C-rich metal poor stars. This rough concordance may be coincidental but is nonetheless both encouraging and intriguing.

6. Discussion

By definition, as the first stars formed in a metal-free environment, Pop III stars existed and played a role in our past history. However, the identity and mass distribution of these stars is largely unknown. We expect that they played an important role in re-ionizing the Universe at high redshift, as well as laid the chemical seeds for future generations of stars (population II/I). We also know that a Salpeter IMF, typical of population I with a mass

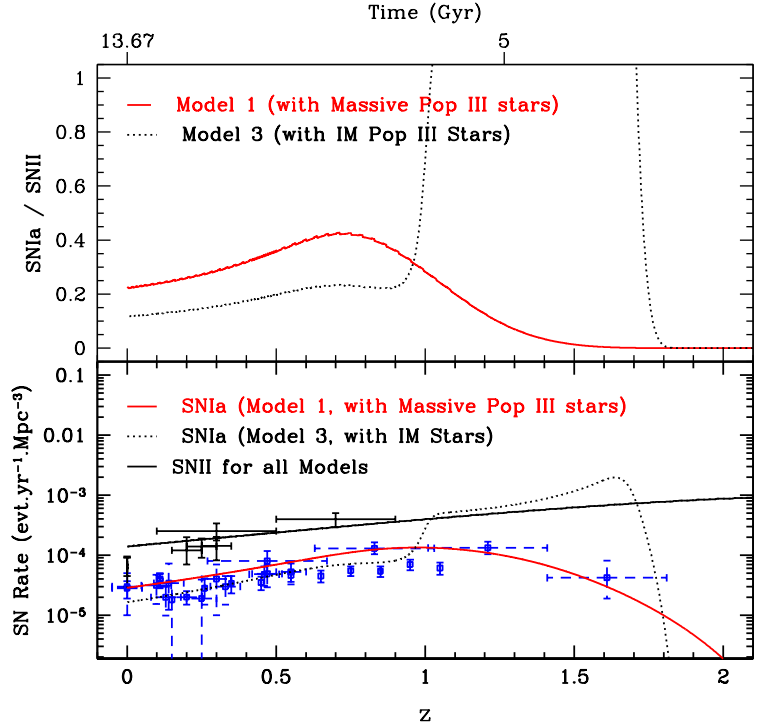


Fig. 16.— Evolution of the ratio of SNIa and SNII event rates as a function of redshift. (top panel) for model 1 and model 3. In the bottom panel, the rates plotted of SNI and SNII as presented in 14 and 15. The delay of SNIa is taken as 3.4 Gyr.

range of $0.1 - 100 M_{\odot}$ is not capable of producing a sufficient optical depth for reionization or of producing the specific abundance patterns in EMPs. Very massive stars ($> 100 M_{\odot}$) also fail in producing the observed abundance patterns, though they are certainly capable of reionizing the Universe. A top-heavy IMF for Pop III was studied in the cosmological context in Daigne *et al.* (2006); Rollinde *et al.* (2009) and while successful in many aspects, is not capable of producing the (albeit weak) evidence for an enhancement in ^4He at low metallicity over BBN predictions or the large carbon enhancements which are made manifest in the parameter D_{trans} . To the best of our knowledge, IM stars as candidates for Pop III have not been studied in the cosmological context.

We have shown that an early generation of IM stars is indeed capable of providing an effective prompt initial enrichment of He. We have also shown, perhaps surprisingly, that these stars normalized in abundance to the required He enrichment, are more than capable of providing a sufficient number of ionizing photons to the early IGM. Also as a bonus, IM

stars can provide the large abundance ratios of C, N, O, and Mg relative to Fe in EMP stars. However, our results indicate that one cannot simply assume a homogeneous and well-mixed IGM and/or ISM as smaller structures grow to large galaxies and clusters of galaxies. The CNO abundance that this model predicts at metallicities between $-1 < [\text{Fe}/\text{H}] < -3$ far surpasses the abundances observed in the IGM.

We are thus led to an interesting dilemma which is best characterized by the data displayed in Fig. 13. Recall that the discriminant D_{trans} represents a measure of carbon and oxygen produced in prior generations of stars. As discussed earlier, the data show two distinct populations: the bulk of the data show increasing D_{trans} with $[\text{Fe}/\text{H}]$ and is very well modeled by either a standard or top-heavy IMF; and a second population with very large D_{trans} between $-1 < [\text{Fe}/\text{H}] < -3$. The latter is well explained by our Pop III IM stellar mode. How can one model explain both populations?

It is perhaps too naive to expect a homogeneous model as the type we have been describing to explain this discrepancy. Indeed one can imagine that the impact of the generation of IM stars was effective only early on in the building of higher mass objects in the hierarchical structure formation scenario. That is, this generation was active only in the smallest scale structures, here taken to be typically $10^7 M_{\odot}$. These structures and the low mass stars and remnants left behind were in some cases incorporated into the halos of larger objects to become galaxies. Others remain as low mass dwarfs. In this way, one can perhaps explain the bulk of the observations of low and increasing D_{trans} in stars formed in larger scale objects involving a larger baryon fraction, while those stars with large D_{trans} would be explained by the impact of IM stars in the smallest structures formed. Indeed, using both carbon data on metal-poor stars, and Type Ia SN observations, we roughly estimate that a Pop III IM mode operates at $\sim 10 - 20\%$ of our model rate. Since our IM mode processes about 10% of baryons, this in turn implies that $\sim 1 - 2\%$ of baryons participate in IM star formation.

In this interpretation, the prompt initial enrichment of ^4He , which is observed largely in dwarf irregular galaxies, was also impacted by IM stars as these objects were evidently not incorporated into larger scale structures. In the context of the light element abundances, it is interesting to note further that some of the stars which show large carbon enhancements also show deficiencies in ^7Li . Furthermore, there is increasing evidence (Sbordone *et al.* 2010; Meléndez *et al.* 2010) for a breakdown of the Spite plateau at metallicities below $[\text{Fe}/\text{H}] < -3$. In Sbordone *et al.* (2010), it is argued that the depletion (which shows considerable dispersion *below* the plateau) at low metallicity may have been due to stellar astration. The model discussed here (given the above interpretation) can account for most of the astration seen in these stars. The model cannot, however, account for the discrepancy between the

BBN prediction at the WMAP baryon density and the Spite plateau value as speculated in Piau *et al.* (2006). Note that the depletion in D/H is probably not an issue, as the absorption systems with measured D/H are presumably larger scale structures for which our abundance patterns would not be expected to apply.

Unfortunately, neither of the two Pop III models delivers entirely satisfactory results. While the massive mode, is capable of producing sufficiently high ratios of [C,O,Mg/Fe] to explain the observations of extremely iron-poor stars, the high ratios occur almost instantly after the first stars are born, and thus require these stars to be born at that time at very high redshift. This model also has difficulty in explaining the high [N/Fe] or [C/O] ratios seen. As a result, the massive Pop III model cannot explain the high values of D_{trans} seen in some stars. The model cannot account for the effective prompt initial enrichment of ^4He nor can it be used to account for the astration of ^7Li below the Spite plateau. On the other hand, the IM model for Pop III underproduces [O/Fe] and because of the large amounts of C and N produced cannot explain the bulk of the values of D_{trans} observed, but the top panel data is explained due to the overabundances of C,N. Indeed, the overproduction of these elements would preclude the homogeneous and well-mixed treatment of gas in ever increasingly large scale structures.

Another distinctive feature of the IM Pop III model is the prediction for the rate of Type Ia supernovae at high redshift. This model naturally predicts a large increase in the Type Ia rate *if* the efficiency for supernovae is constant and the time delay is not small. It is relevant to speculate that a small high mass tail in the IM population could lead to possible GRBs in the redshift range 10-20. This would fill the “GRB desert” between Pop II and the usual high redshift Pop III stars.

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