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Contributions of type II and Ib/c supernovae to Galactic chemical evolution

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Abstract Type II and Ib/c supernovae (SNe II and Ib/c) have made major stellar nucleosynthetic contributions to the inventories of stable nuclides during chemical evolution of the Galaxy. A case study is performed here with the help of recently developed numerical simulations of Galactic chemical evolution in the solar neighborhood to understand the contributions of SNe II and Ib/c by comparing the stellar nucleosynthetic yields obtained by two leading groups in this field. These stellar nucleosynthetic yields differ in terms of their treatment of stellar evolution and nucleosynthesis. The formulation describing Galactic chemical evolution is developed with the recently revised solar metallicity of $\sim$0.014. Furthermore, the recent nucleosynthetic yields of stellar models based on the revised solar metallicity are also used. The analysis suggests that it could be difficult to explain, in a self-consistent manner, the various features associated with the elemental evolutionary trends over Galactic timescales by any single adopted stellar nucleosynthetic model that incorporates SNe II and Ib/c.

Key words: Sun: abundances — stars: evolution — stars: supernovae — Galaxy: abundance — Galaxy: formation — Galaxy: evolution — nucleosynthesis

1 INTRODUCTION

Galactic chemical evolution (GCE) models deal with understanding the origin and the evolution of the Galaxy in the context of evolution associated with isotopic inventories of stable nuclides (Matteucci & Francois 1989; Alibés et al. 2001; Prantzos & Aubert 1995; Timmes et al. 1995; Chang et al. 1999, 2002; Goswami & Prantzos 2000; Sahijpal & Gupta 2013; Sahijpal 2013). The majority of these works deal with the abundance evolution of stable nuclides from hydrogen to zinc over Galactic timescales. Subsequent to the Big Bang origin of the Universe around 13.7 billion years ago, primordial nucleosynthesis established the initial abundance of hydrogen, helium and lithium in the Galaxy. The heavier elements were synthesized by stellar nucleosynthesis within several generations of stars formed over the timespan of $\sim$13 billion years (Alibés et al. 2001; Sahijpal & Gupta 2013).

Stellar nucleosynthetic yields of stars with different masses and metallicities are some of the most important ingredients in GCE models (Alibés et al. 2001; Sahijpal & Gupta 2013). The star formation rate, the stellar initial mass function (IMF) and the accretion scenario of the Galaxy are the other major ingredients necessary to understand the formation and chemical evolution of the Galaxy. Stars with distinct masses and metallicities evolve differently and produce a wide range of stable nuclides that contribute to Galactic inventories over varying timescales. In the present work, an assessment is made regarding the stellar nucleosynthetic contributions from stars that eventually explode as type II and Ib/c supernovae (SNe II and Ib/c) to the bulk Galactic inventories of stable nuclides from carbon to zinc. The assessment is based on the nucleosynthetic yields of SNe II and Ib/c resulting from the evolution of ($\geq$11 $M_\odot$) stars. The stellar yields of these stars obtained by Woosley & Weaver (1995) have been used in the majority of GCE models developed earlier. Another group has also provided the stellar nucleosynthetic yields of these stars (Chieffi & Limongi 2004, 2013; Limongi & Chieffi 2012). Some of the recent models developed by this group have incorporated refinements in stellar evolution theories by taking into account stellar rotation and stellar mass loss rates (Chieffi & Limongi 2013). In this work, we present results of our GCE models based on the stellar yields of these stars obtained by Chieffi & Limongi (2004; 2013) and Limongi & Chieffi (2012). We also make comparisons of the GCE models based on the stellar nucleosynthetic yields obtained by the two groups (Woosley & Weaver 1995; Chieffi & Limongi 2004, 2013) to study the contributions of SNe II and Ib/c to the bulk Galactic inventories of stable nuclides from carbon to zinc.

The majority of GCE models developed earlier were based on the conventional approach of solving integro-differential equations dealing with stable isotopic abundance evolution of all elements from hydrogen to zinc during Galactic evolution (e.g., Matteucci & Francois 1989; Prantzos & Aubert 1995; Timmes et al. 1995; Chang et al. 1999, 2002; Goswami & Prantzos 2000; Alibés et al. 2001). The stellar nucleosynthetic yields of various stellar phases, including those from asymptotic giant branch (AGB) stars, novae and different types of SNe (II, Ia and Ib/c) with different masses and metallicities, are incorporated in the equations to model the temporal isotopic abundance evolution of the Galaxy. An alternative numerical approach has been developed recently to simulate the evolution of the Galaxy by considering successive episodes of star formation and their evolution (Sahijpal & Gupta 2013). In this approach, the Galaxy evolves in a realistic manner in terms of formation and evolution of several generations of stars over Galactic timescales (Sahijpal & Gupta 2013). This recent GCE model incorporates a revised solar metallicity that has been reduced to a value of $\sim$0.014 (Asplund et al. 2009) from an earlier adopted value of $\sim$0.02. The present work is exclusively based on the recently revised solar metallicity. For the first time, it incorporates the stellar nucleosynthetic yields of SNe II and Ib/c that are based on the recently revised solar metallicity (Chieffi & Limongi 2013). It should be noted that the earlier stellar yields of SNe II (Woosley & Weaver 1995; Chieffi & Limongi 2004) were based on the earlier adopted solar metallicity of $\sim$0.02. Thus, the present work is the first attempt to model GCE with the yields of SNe II and Ib/c based on the revised solar metallicity (Asplund et al. 2009). In Section 2 we present a review of the stellar models of massive stars and the nucleosynthetic yields of SNe II and I b/c obtained by Woosley & Weaver (1995), Chieffi & Limongi (2004, 2013) and Limongi and Chieffi (2012). In Section 3 we present the details of the numerical simulations of the GCE model performed in the present work. The results and discussions based on the various simulations are presented in Section 4. In Section 5 we conclude with the major inferences drawn from the present work.

2 SNE II AND IB/C

The majority of stable isotopes from carbon to zinc are produced by stars with mass $\geq$11 $M_\odot$ (e.g., Woosley & Weaver 1995). Stars in the mass range $\sim$11–30 $M_\odot$ eventually explode as core collapse SNe (type II) subsequent to the last stages of their evolution (Sahijpal & Soni 2006; Sahijpal & Gupta 2009). This typically occurs rapidly over a timescale of $\leq$25 Myr after the formation of the stars within a cluster, thereby, rapidly recycling the stellar nucleosynthetic debris into the interstellar medium. However, stars with mass $\geq$30 $M_\odot$ evolve through the Wolf-Rayet stage during which these stars gradually lose significant mass to the interstellar medium (Sahijpal & Soni 2006; Sahijpal & Gupta 2009 and references therein). These stars eventually explode as core collapse SNe Ib/c over a timescale that is even shorter than stars undergoing SNe II (Sahijpal & Gupta 2009). Several factors associated with stellar evolution in these stars influence the stellar nucleosynthetic yields (Chieffi &

Limongi 2013), and hence, the temporal evolution of stable isotopic inventories of various elements from carbon to zinc in the Galaxy. The mass loss rate during the Wolf-Rayet stage is one of the major factors that influence the evolution and the stellar nucleosynthetic yields of these stars (Sahijpal & Soni 2006; Chieffi & Limongi 2013). Other major issues that influence the nucleosynthetic yields include the final mass of the stellar remnant at the time the SN occurs, the inclusion of rotation in the stellar models, the adopted convective criteria and the incorporation of neutrino induced reactions for the synthesis of nuclides (Woosley & Weaver 1995; Sahijpal & Soni 2006; Chieffi & Limongi 2013).

Woosley & Weaver (1995) provided the first comprehensive stellar nucleosynthetic models for stars with mass $\geq$11 $M_\odot$. Stellar yields were obtained for stable and radionuclides from hydrogen to gallium for stellar models in the mass range 11–40 $M_\odot$ with initial metallicities in the range 0 to $\sim$0.02. The upper range of the metallicity refers to the earlier adopted solar metallicity that has been recently revised to a value of $\sim$0.014. These stellar models incorporated neutrino induced nuclear reactions and distinct stellar remnant mass cuts for stars with mass beyond 25 $M_\odot$. The stellar yields provided by Woosley & Weaver (1995) formed the basis for the development of most GCE models till now. However, the absence of stellar nucleosynthetic yields for stars with mass beyond 40 $M_\odot$ was one of the major shortcomings associated with that work. In the majority of GCE models, the stellar yields of stars beyond 40 $M_\odot$ stars were obtained by extrapolating the stellar yields of stars with mass 11–40 $M_\odot$. The uncertainties associated with extrapolation eventually propagate to uncertainties in the GCE models. Moreover, the influence of the mass loss rate during the evolution of the stars was not incorporated in the stellar yields obtained by Woosley & Weaver (1995).

Chieffi & Limongi (2004) developed an independent set of stellar models for stars in the mass range 13–35 $M_\odot$ with initial metallicities in the range 0 to $\sim$0.02. These models provided an alternative set of stellar nucleosynthetic yields which were used to develop GCE models that were earlier based exclusively on the stellar yields obtained by Woosley & Weaver (1995). It was demonstrated by Chieffi & Limongi (2004) that the stellar yields of stars with low metallicity ($\leq 10^{-4}$) do not depend on the initial stellar composition. As a part of the present work, we compare the GCE models developed based on the stellar yields obtained by Woosley & Weaver (1995) with those developed by Chieffi & Limongi (2004). The stellar models developed by Chieffi & Limongi (2004) had limitations identical to those of the models developed by Woosley & Weaver (1995) in terms of their limited stellar mass range and the exclusion of mass loss rates during stellar evolution.

For the first time, Limongi & Chieffi (2012) have recently developed stellar models for stars in a wide mass range of 13–80 $M_\odot$ with an initial metallicity of zero. Furthermore, Chieffi & Limongi (2013) developed stellar models for stars in a wide mass range of 13–120 $M_\odot$ with the revised solar metallicity of $\sim$0.014. The recent stellar models incorporate stellar rotation and mass loss rates. In the present work, we have developed GCE models based on the stellar nucleosynthetic yields of stars obtained earlier by Woosley & Weaver (1995), and recently by Chieffi & Limongi (2004; 2013) and Limongi & Chieffi (2012). In comparison to the limited mass range of 11–40 $M_\odot$ (Woosley & Weaver 1995), the recent works cover a wide range of 11–100 $M_\odot$ in terms of stellar nucleosynthetic yields. This reduces the uncertainties associated with the extrapolation of nucleosynthetic yields for stars with masses greater than 40 $M_\odot$. The entire discussion in the present work is exclusively based on the available stellar nucleosynthetic yields from these two groups. We have not made any further attempt to understand the complexities associated with stellar evolution and its influence on nucleosynthesis (see e.g., Georgy et al. 2013). Except for SNe Ia, we have also avoided the possibilities of massive binary systems exploding as SNe and hypernovae (see e.g., Sahijpal & Soni 2006).

3 NUMERICAL SIMULATIONS

The simulations of the GCE were performed assuming a gradual accretion of the Galaxy occurred in two episodes (Chiappini et al. 1997). The initial accretionary phase resulted in the growth of the

Galactic halo and the thick disk over an assumed timescale of one billion years. The second episode followed the gradual accretion growth of the Galactic thin disk over a timescale of around seven billion years. It has been observed that these adopted criteria describing the accretion of the Galaxy are able to explain the majority of trends shown by the abundance evolution of elements. Moreover, in order to avoid the G-dwarf metallicity problem, the metallicity of the accreting matter on the Galaxy was assumed to be 0.1 times the final metallicity acquired by the Sun (e.g., Alibés et al. 2001; Sahijpal & Gupta 2013).

We simulated the evolution of the Galaxy around the present position of the Sun, which is defined as the solar neighborhood. The solar neighborhood was confined to an annular ring within 7 to 8.9 kiloparsecs from the center of the Galaxy (Sahijpal & Gupta 2013). The simulations were performed with a timestep of 1 Myr, which is less than the timescale of $\sim$ 3.5 Myr that was used for the evolution of the most massive star formed within the simulation. The simulations were implemented by modeling the synthesis of stellar populations of successive generations from the interstellar medium with an evolving metallicity. The simulated stars were synthesized and evolved according to their masses and metallicities. The nucleosynthetic contributions of the evolved stars in the form of stellar ejecta were incorporated into the evolving interstellar medium (Sahijpal & Gupta 2013). Successive generations of stars were formed within the solar annular ring on the basis of an assumed star formation rate that depends upon the surface mass density of the prevailing interstellar gas and the surface mass density of all matter in the ring. We have made use of the star formation rate formulation developed by Alibés et al. (2001). This formulation is based on the star formation rate proposed by Talbot & Arnett (1975) and Dopita & Ryder (1994). Based on our recent works investigating the influence of GCE on the star formation rate in the earliest one billion years of the evolution of the Galaxy that corresponds to the accretion era of the Galactic halo and the thick disk (Sahijpal 2012, 2013), we have assumed a general enhancement in the star formation rate in the era by a factor of three. This corresponds to the use of a value of 3 for ν in the star formation rate (Alibés et al. 2001) during the initial one billion years and a value of 1 for ν for subsequent times in the evolution of the Galaxy. The essential trends in the elemental evolution, specifically in the case of oxygen and iron, can be explained in a better manner with this choice of parameters for star formation rate (Sahijpal 2012, 2013).

A normalized three stage stellar IMF, $\phi(m) = Am^{-(1+x)}$, was assumed in the mass range 0.1–100 $M_\odot$ to synthesize the simulated stars at the time of star formation (Matteucci 2003) based on the criteria used by Sahijpal & Gupta (2013). According to the adopted criteria, the IMF differential spectra consist of stars with masses represented by integer numbers in the mass range 3–100 $M_\odot$. However, in the low mass range, we choose stellar masses to be 0.1, 0.4, 0.8, 1.0, 1.25, 1.75 and 2.5 $M_\odot$ in order to cover the critically important mass range in an appropriate manner. This choice was also partially motivated by the availability of stellar nucleosynthetic yields of AGB stars corresponding to some specific masses (Karakas & Lattanzio 2007). The power index x was assumed to be 0 and 1.7 in the mass ranges 0.1–1 $M_\odot$ and 1–8 $M_\odot$, respectively. This is almost consistent with earlier works regarding the choice of the IMF parameter values in this mass range (Matteucci 2003; Sahijpal & Gupta 2013). It should be mentioned that there have been several proposals for values of the power index for the IMF (Matteucci 2003). The normalizing constant A was chosen to synthesize the IMF according to the star formation rate prevailing at any epoch. This constant will determine the total number of stars formed corresponding to different masses at any specific time with a uniquely defined metallicity that will depend upon the metallicity of the interstellar medium prevailing at that time. The value of the power index in the stellar mass range 11–100 $M_\odot$ was treated as one of the free parameters in the simulation used to obtain the value of $\sim$0.014 for the solar metallicity at the time the solar system formed around 4.56 billion years ago. Even though the power index in the stellar mass range 11–100 $M_\odot$ is treated as a free parameter, it was observed that in all the simulations it adopted a value within the range predicted in earlier works (Matteucci 2003). The detailed parametric analyses regarding various parameters used in the simulations have been performed earlier (Sahijpal & Gupta 2013; Sahijpal 2013). In the present work, we only choose a selective range of parameters to understand the role of massive stars in the GCE.

Stars with different masses and metallicities evolve in diverse ways over differing timespans. We have considered the stellar nucleosynthetic contributions of AGB stars, SNe Ia, SNe II and SNe Ib/c to the evolving interstellar medium. The detailed mass balance calculations were performed to incorporate stellar contributions to the interstellar medium subsequent to the evolution of separate populations of stars.

3.1 Nucleosynthetic Contributions of AGB Stars and SNe Ia

The stars in the mass range 0.1–8 $M_{\odot}$ evolve through the AGB phase (Karakas & Lattanzio 2007). These stars produce intermediate mass nuclei through the s-process and neutron-rich nuclei. We have considered the stellar nucleosynthetic yields of the AGB stars in the mass range 1.25–8 $M_{\odot}$ for a wide range of stellar metallicities (Karakas & Lattanzio 2007). As mentioned earlier, the choice of stellar IMF in the low and intermediate mass range was partially motivated by the availability of stellar yields for some specific masses.

The nucleosynthetic yields of SNe Ia obtained by Iwamoto et al. (1999) for the various stellar models were used. The SN Ia rate adopted in the present work is based on the normalized time delay distribution function for the SN Ia rate that was adopted by Matteucci et al. (2009) to trigger the SN Ia. This normalized distribution function is based on the essential requirement of an initiation of the rapid rich nucleosynthetic contributions from SNe Ia within the timescales of $\sim$100 Myr from the time of formation of the binary systems that eventually produce SNe Ia. Along with an enhanced star formation rate during the initial one billion years after the formation of the Galaxy, the adopted prompt SN Ia contribution explains the majority of Galactic evolutionary trends in the elemental abundance distribution of the solar neighborhood (Sahijpal 2013). A fraction f of the stars produced during any single episode of star formation was treated as binary star pairs that would eventually undergo SN Ia (Sahijpal & Gupta 2013). The parameter f and the power index x corresponding to the stellar IMF in the stellar mass range 11–100 $M_{\odot}$ were considered to be free parameters in order to reproduce the solar metallicity of $\sim$0.014 and [Fe/H] = 0 at the time the solar system formed around 4.56 billion years ago (Sahijpal & Gupta 2013). It should be mentioned here that when we fix the value of the power index x, corresponding to the stellar IMF in the stellar mass range 11–100 $M_{\odot}$ on the basis of its value used in the literature (see e.g., Matteucci 2003), we will end up with a distinct solar metallicity at the time of the formation of the solar system. Since the composition of the Sun is one of the most important ingredients for understanding the GCE, we adopted the criteria for parameterizing the power index. However, it should be noted that values obtained for the parameter in the various simulations are well within the range predicted earlier (Matteucci 2003).

3.2 Nucleosynthetic Contributions of SNe II and Ib/c

As mentioned earlier, we have made comparisons with the GCE models based on stellar nucleosynthetic yields of SNe II and Ib/c obtained by Woosley & Weaver (1995), Chieffi & Limongi (2004; 2013) and Limongi & Chieffi (2012). We performed three simulations in order to make comparisons. The GCE model WW95 is based on the stellar yields obtained by Woosley & Weaver (1995). The stellar yields obtained by Chieffi & Limongi (2004) were used in the GCE model CL04. In the GCE model CL13, the stellar yields of the stars with zero metallicity in the mass range 13–80 $M_{\odot}$, obtained recently by Limongi & Chieffi (2012), were used. Furthermore, the stellar yields of the revised solar metallicity of $\sim$0.014 in the stellar mass range 13–120 $M_{\odot}$ (Chieffi & Limongi 2013) were used in this simulation. These stellar models incorporate stellar rotation and mass loss. Due to the absence of stellar yields corresponding to intermediate metallicities, the stellar yields corresponding to the available intermediate stellar metallicities were taken from the earlier work by the same group (Chieffi & Limongi 2004) in the GCE model. This will remain one of the limitations of the present approach until the stellar yields corresponding to intermediate metallicities become available in literature. We have addressed the associated repercussions in the following discussion. The stellar yields of the remaining intermediate stellar masses and metallicities were appropriately interpolated during the simulation (Sahijpal & Gupta 2013). Due to uncertainties in the mass fall-back at the time of SNe II and Ib/c, the iron yields of all stars beyond 30 $M_{\odot}$ were systematically reduced by a factor of two as a standard practice (e.g., Timmes et al. 1995; Sahijpal & Gupta 2013).

4 RESULTS AND DISCUSSION

A comparison of the GCE models based on the distinct set of nucleosynthetic yields of SN II and Ib/c is performed in the present work to understand the influence of the GCE on the nucleosynthetic yields of SN II and Ib/c. The GCE models have been developed based on the recently adopted approach of numerically simulating the evolution of the Galaxy in terms of the formation of successive generations of stars. Moreover, the GCE models have been developed to reproduce the recently revised solar metallicity of $\sim$0.014 at the time the solar system formed around 4.56 billion years ago. As mentioned earlier, this was achieved by fitting the parameters x and f, which are related to the stellar IMF power index in the mass range 11–100 $M_{\odot}$ and the fraction of stars produced in binary systems at the time of star formation, respectively. The assumed binary systems will eventually evolve to SNe Ia. We obtained the values of $\sim$0.042 and $\sim$1.51 for f and x, respectively, in the case of model WW95. In case of the model CL04, we deduced these values to be $\sim$0.053 and $\sim$1.57, respectively, whereas, the model CL13 implies the values of $\sim$0.054 and $\sim$1.64, respectively. The deduced power exponents are well within the range anticipated for the IMF in the earlier works (Matteucci 2003). As mentioned earlier, the compulsion to reproduce the solar metallicity at the time of formation of the solar system necessitates the role of the power index as one of the critical free parameters. The CL13 GCE model infers there is a steeper slope for the IMF in the mass range 11–100 $M_{\odot}$ compared to the GCE model CL04 which in turn signifies a steeper slope compared to the GCE model WW95. In addition, the GCE WW95 model implies there are the least SN Ia contributions, whereas the model CL13 exhibits the highest SN Ia contributions.

The predicted star formation rates for the three simulations, corresponding to distinct SN nucleosynthetic yields, are presented in Figure 1. As discussed earlier, the enhanced star formation rate during the initial one billion years of the evolution of the Galaxy that is represented by a choice of the value of 3 for ν in the star formation rate (Alibés et al. 2001) explains the essential features of the elemental evolution trends (Sahijpal 2012, 2013). The differences in the star formation rates for the three simulations originate due to differences in the SN II and Ib/c stellar contributions of the major elements, e.g., carbon, oxygen, etc. to the bulk inventories of the interstellar medium, as is discussed in the following.

The predicted evolutions in the metallicity of the solar neighborhood for the three models, WW95, CL04 and CL13, over Galactic timescales are presented in Figure 2. It should be noted that the WW95 model based on the nucleosynthetic yields obtained by Woosley & Weaver (1995) results in an almost identical evolutionary trend as compared to the model CL04 based on the yields obtained by Chieffi & Limongi (2004). However, the evolutionary trend for the CL13 model is quite distinct compared to the other two models. The CL13 model differs from the CL04 model due to the incorporation of the recent nucleosynthetic yields of the stellar models based on the revised solar metallicity of $\sim$0.014 along with the inclusion of stellar rotation and mass loss rates during the evolution of the stars (Chieffi & Limongi 2013). Furthermore, the stellar nucleosynthetic yields of zero metallicity stars (Limongi & Chieffi 2012) have been used in the CL13 model instead of the earlier used stellar yields of the zero metallicity models (Chieffi & Limongi 2004).

Oxygen, followed by carbon, are the main contributors to the metallicity of the evolving Galaxy. The steeper slope in the metallicity rise of the CL13 model compared to the other models can be

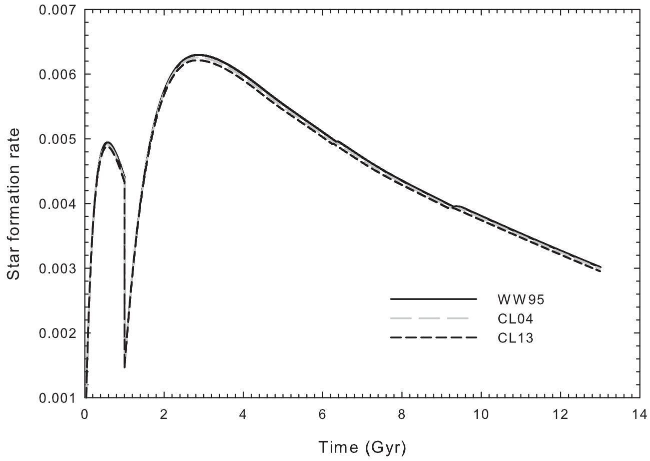

Fig. 1 The star formation rate (in $M_\odot$ pc^{-2} Myr^{-1}) for the three distinct GCE models, WW95, CL04 and CL13, with differing stellar nucleosynthetic yields.

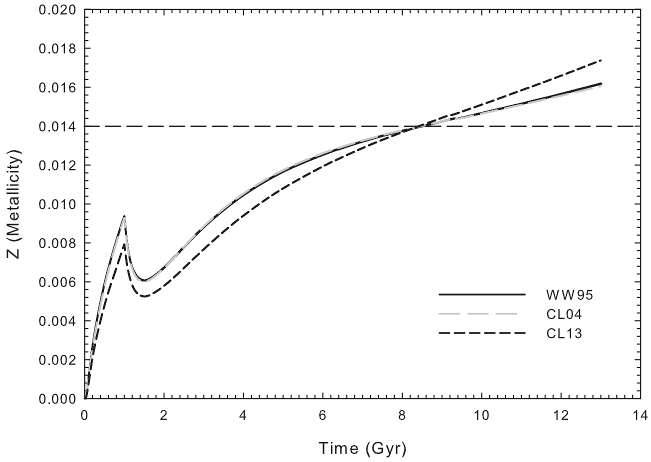

Fig. 2 The predicted evolution of the metallicity for the three distinct GCE models, WW95, CL04 and CL13, with differing stellar nucleosynthetic yields. The revised solar metallicity is presented as a horizontal dashed line.

attributed to the higher carbon and oxygen yields of the stellar models by Chieffi & Limongi (2013) compared to earlier stellar models (Woosley & Weaver 1995; Chieffi & Limongi 2004) corresponding to the solar metallicity. As mentioned earlier, GCE model CL13 implies the steepest stellar IMF among all the models. Thus, the higher production of oxygen and carbon by SNe II and Ib/c in the CL13 GCE model would necessitate a slow rise in the metallicity during the initial epoch of the Galaxy. This will gradually rise to the solar metallicity value around 4.56 billion years ago. However, it should be noted that in the CL13 model, due to the absence of the stellar yields for stellar models with less than solar metallicity, we have used the corresponding yields obtained earlier by Chieffi & Limongi (2004) that exclude the effects of stellar rotation and mass loss. It is anticipated that the stellar yields of at least the primary nuclides, e.g. ^{12}C and ^{16}O, do not substantially change with a change in the stellar metallicity, but the incorporation of stellar rotation will result in a further en-

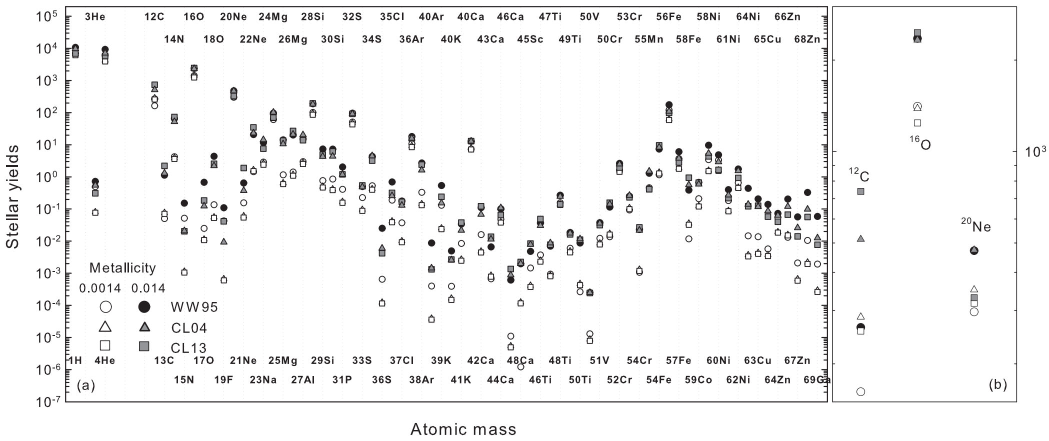

Fig. 3 The accumulative stellar yields (in $M_\odot$) of the various nuclides from SNe II and Ib/c of the stars from a single stellar population that formed at a specific time with a defined metallicity and IMF.

hancement in the stellar yields of these nuclides for stellar models with less than solar metallicity. This will further alter the evolutionary trend for the rise of metallicity in the CL13 model. In order to make a direct comparison between the stellar nucleosynthetic yields for the three stellar models, the net accumulative stellar yields (in $M_\odot$) for the various stable nuclides from SNe II and Ib/c of the stars from a single stellar population could represent either a single stellar cluster or associated stellar clusters that formed together at a specific time in the simulations with the defined stellar IMF estimated at metallicities of 0.0014 ($0.1 \times Z_\odot$) and 0.014 ($Z_\odot$) for the three models. These are presented in Figure 3 and the yields were numerically obtained for each stable isotope by multiplying the stellar yields of the massive stars with mass greater than 11 $M_\odot$ by the stellar IMF value for the specific stellar mass prevailing at the specific time corresponding to the metallicities of 0.0014 ($0.1 \times Z_\odot$) and 0.014 ($Z_\odot$) in the interstellar medium. The net accumulative yields were obtained by adding the stellar yields corresponding to the various stellar masses. It should be noted that the star formation rate prevailing at the specific time will determine the total mass of the stellar population.

The evolutionary trends for [Fe/H] are presented in Figure 4 for the three GCE models. All the GCE models are able to explain the observed spread in the [Fe/H] value for the F, G and K dwarf stars in the solar neighborhood. It should be noted that the GCE trends are exactly fitted to explain [Fe/H] = 0 at the time of formation of the solar system around 4.56 billion years ago rather than the average of the observed spread around 4.56 billion years ago. The differences in the [Fe/H] evolutionary trends between the WW95 model and the other two models, namely CL04 and CL13, are due to lower iron yields (Fig. 3) of the stars by Chieffi & Limongi (2004; 2013) compared to those obtained by Woosley & Weaver (1995). Since SNe Ia are the major source of iron (e.g., Alibés et al. 2001; Sahijpal & Gupta 2013; Sahijpal 2013), the lower iron yields of SNe II and Ib/c in the CL04 and CL13 models compared to the model WW95 (Fig. 3) are compensated by higher rates of SNe Ia. As mentioned earlier, this is reflected in the higher anticipated fraction, f, of the binary stellar systems formed that eventually explode as SNe Ia in the models CL04 and CL13 compared to the model WW95.

The evolutionary trends in the metallicity (Fig. 2) and [Fe/H] (Fig. 4) for the three GCE models also influence the anticipated SN history of the Galaxy that is separate from the predicted star formation rates (Fig. 1). The predicted trends in the SN II + Ib/c and SN Ia rates are presented in Figure 5. As mentioned earlier, the oxygen and carbon yields of recent stellar models (Chieffi & Limongi

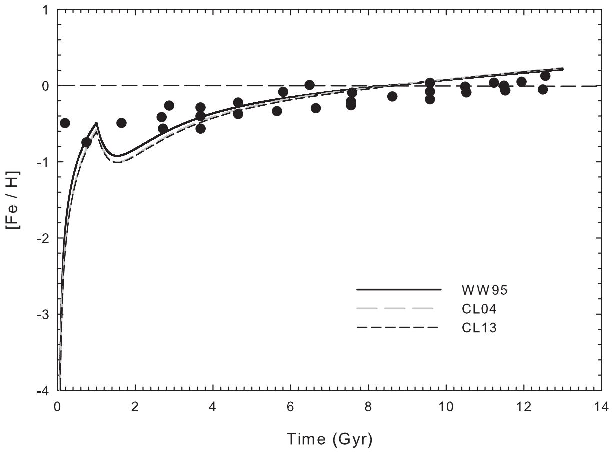

Fig. 4 The predicted evolution of [Fe/H] for the three GCE models with a distinct set of stellar nucleosynthetic yields. The solar value is represented by the dashed line. The observed spread of F, G and K dwarf stars in the solar neighborhood obtained by three groups is presented for comparison (Alibés et al. 2001; Edvardsson et al. 1993; Meusinger et al. 1991; Rocha-Pinto et al. 2000).

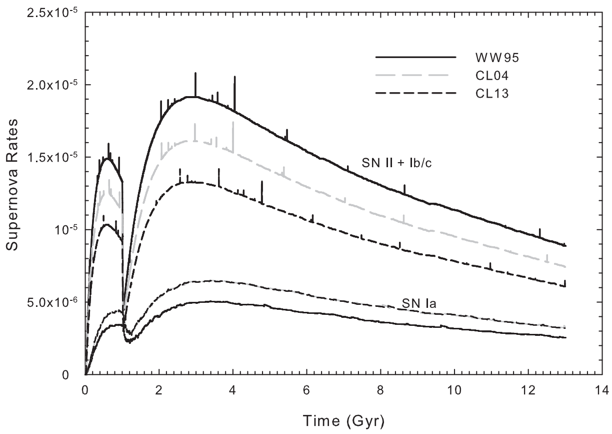

Fig. 5 The predicted SN rates (in pc^{-2} Myr^{-1}) for the three GCE models.

2004, 2013) are higher than those of the earlier models (Woosley & Weaver 1995), whereas the iron yields of the recent models are low, corresponding to solar metallicity (Fig. 3). In comparison with the WW95 GCE model, this results in a reduction in the SN II + Ib/c rates in the CL04 and CL13 GCE models with an increase in the SN Ia rates. This also influences the predicted surface mass density of the stellar remnants of SN II + Ib/c, i.e. the neutron stars and black holes (Fig. 6) that show a corresponding reduction in the surface mass densities of models CL04 and CL13 with respect to the model WW95. Apart from the surface mass densities of the stellar remnants, the predicted total surface mass density, the stellar mass density and the gas mass density are also presented in Figure 6. The predicted total surface mass density of the present epoch was fitted to explain the present observed value of $\sim 54\ M_{\odot}$ pc^{-2} (Alibés et al. 2001) in all the simulations. Since a case study of the stellar contributions from massive stars is presented in the present work, the white dwarfs that are remnants of red giant and AGB stars exhibit identical trends in their predicted surface mass densities for the various models.

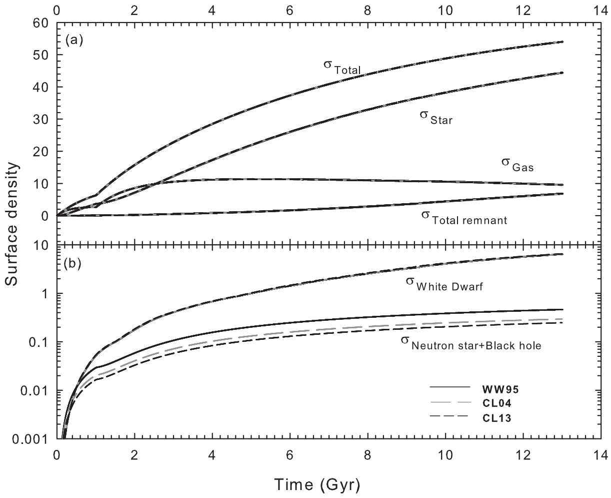

Fig. 6 (a) The predicted surface mass density (in $M_\odot$ pc^{-2}) of the total surface mass distribution, the stellar mass density, the gas mass density and the stellar remnant mass densities for the three GCE models. (b) The predicted surface mass density of the stellar remnants that includes white dwarfs, neutron stars and black holes.

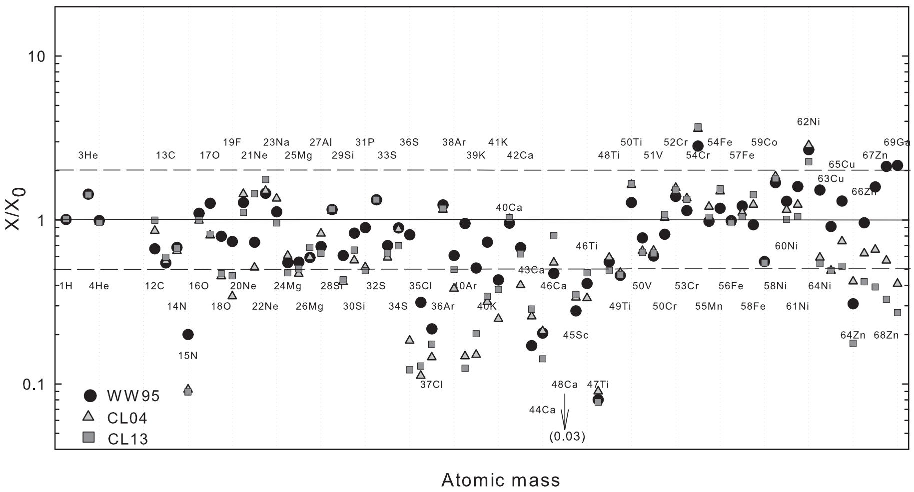

Fig. 7 The predicted normalized isotopic abundances for the three GCE models with a distinct set of stellar nucleosynthetic yields. The abundances were estimated at the time the solar system formed around 4.56 Gyr ago. The revised solar metallicity was assumed to be 0.014.

The normalized stable isotopic yields obtained from the three GCE models are presented in Figure 7 at the time of formation of the solar system around 4.56 billion years ago. It should be noted that due to uncertainties associated with the various physical processes related to Galactic and stellar evolution, variation by a factor of two over the anticipated normalized value is considered to be tolerable. The three GCE models based on the distinct set of stellar yields predict almost identical stable isotopic abundances for the elements lighter than sulphur within a factor of two. An identical trend continues even in the case of elements from titanium to nickel. However, the GCE predictions

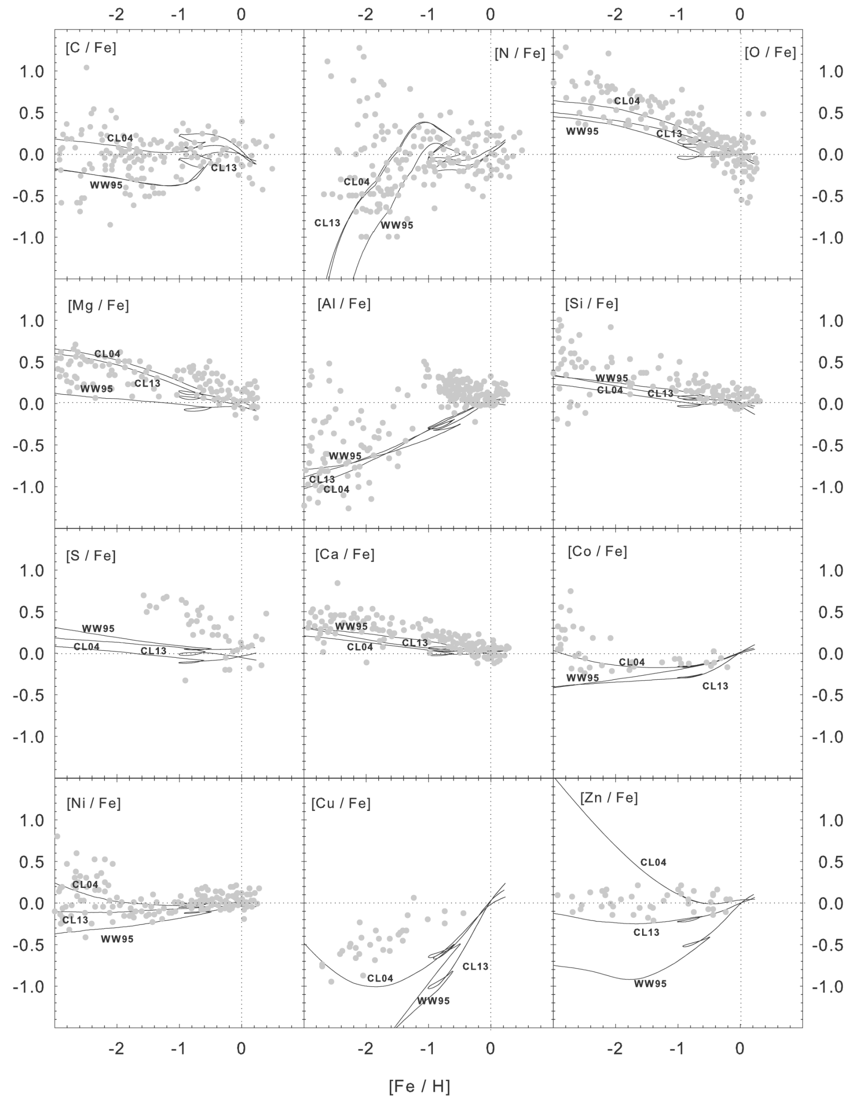

Fig. 8 The predicted normalized elemental abundance evolution for the various models corresponding to a different set of stellar yields. The observed data of F, G and K dwarf stars in the solar neighborhood have been adopted for comparison. Detailed references can be found in the recent work by Sahijpal & Gupta (2013).

for the three models are significantly different in the case of fluorine, chlorine, argon, potassium, copper, zinc and gallium, with the recent stellar nucleosynthetic models (Chieffi & Limongi 2004, 2013) inferring lesser stellar yields compared to earlier models (Woosley & Weaver 1995).

The results obtained from the normalized elemental abundance evolution of twelve elements over Galactic timescales are presented in Figure 8. Compared to the WW95 GCE model, the Galactic evolutionary trends of the CL04 GCE model indicate better matches for carbon, nitrogen, oxygen, magnesium, cobalt and nickel. The Galactic evolutionary trend for nickel becomes even better in the CL13 GCE model. The normalized trends for the CL04 and CL13 GCE models are almost identical for nitrogen, magnesium, aluminium, silicon, sulphur and calcium. The Galactic evolutions of nickel and zinc are best explained by the CL13 model. However, it is not possible to consistently explain the GCE of all the elements by any single adopted nucleosynthetic model.

5 CONCLUSIONS

Numerical simulations of the GCE have been performed in the present work to understand the contributions of SNe II and Ib/c. A comparison of the stellar nucleosynthetic yields of the stars (11–100 $M_{\odot}$) obtained by distinct groups is performed based on these numerical simulations. Some of these adopted recent stellar models incorporate stellar rotation and mass loss rates. Based on the present analysis it seems that it could be difficult to explain all the features of the GCE for all the elements from hydrogen to zinc in a self-consistent manner by any single adopted stellar nucleosynthetic model of the SNe II and Ib/c.

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