The Evolution Of Carbon, Sulphur, and Titanium Isotopes from High-Redshift to the Local Universe

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ABSTRACT

Recent observations of carbon, sulphur, and titanium isotopes at redshifts \(z \sim 1\) and in the local stellar disc and halo have opened a new window into the study of isotopic abundance patterns and the origin of the chemical elements. Using our Galactic chemical evolution code GEtool, we have examined the evolution of these isotopes within the framework of a Milky Way-like system. We have three aims in this work: first, to test the claim that novae are required, in order to explain the carbon isotope patterns in the Milky Way; second, to test the claim that sulphur isotope patterns at high-redshift require an initial mass function biased towards massive stars; and third, to test extant chemical evolution models against new observations of titanium isotopes that suggest an anti-correlation between trace-to-dominant isotopes with metallicity.

Based upon our dual-infall galactic chemical evolution modelling of a Milky Way-like system, and the subsequent comparison with these new and unique datasets, we conclude the following: novae are not required to understand the evolution of \(^{12}\)C/\(^{13}\)C in the solar neighbourhood; a massive star-biased initial mass function is consistent with the low ratios of \(^{12}\)C/\(^{13}\)C and \(^{32}\)S/\(^{34}\)S seen in one high-redshift late-type spiral, but the consequent super-solar metallicity prediction for the interstellar medium in this system seems highly unlikely; and deficient isotopes of titanium are predicted to correlate positively with metallicity, in apparent disagreement with the new datasets; if confirmed, classical chemical evolution models of the Milky Way (and the associated supernovae nucleosynthetic yields) may need a substantial overhaul to be made consistent.

Key words: galaxies: evolution – galaxies: abundances – galaxies: ISM – galaxies: high-redshift

1 INTRODUCTION

Galactic chemical evolution models are employed to study the spatial and temporal evolution of elements and isotopes throughout the Universe. When coupled to phenomenological representations of galaxy assembly, such models can be compared directly with exquisite elemental and isotopic abundance patterns observed locally in the Milky Way. From these comparisons, conclusions can be drawn regarding the veracity of the underlying micro-physics governing stellar evolution and nucleosynthesis, in addition to the macro-physics governing the assembly of galaxies, the redistribution of the interstellar medium (ISM) over galactic timescales, and the relative birthrate of stars of various masses (the so-called initial mass function, or IMF). While most galactic chemical evolution models to date have concentrated on predictions related to the total elemental abundance patterns, in unique circumstances, the availability of detailed isotopic patterns can enhance the predictive power of these models; such isotopic patterns afford additional leverage for discriminating between the various origin sites for the chemical elements. A full literature review of the field would be unwieldy, but we refer the reader to any number of comprehensive reviews and the many important references therein - e.g. Timmes, Woosley & Weaver (1995, hereafter TWW95), Prantzos, Aubert & Audouze (1996), Fenner & Gibson (2003), Romano & Matteucci (2003, hereafter, RM03), and Chiappini et al. (2008).

Recent observational work has opened a new window into the study of isotopic abundance patterns - specifically, the identification (for the first time) of carbon and sulphur isotopes at redshifts \(z \sim 1\) (Muller et al. 2006, hereafter M06;
Levshakov et al. 2006), coupled with the recent determination of titanium isotopic abundances in the local stellar disc and halo (Chavez 2008). The abundances of each of these isotopes, and their evolution with redshift, hold clues as to the relative importance of supernovae versus asymptotic giant branch stars versus novae in seeding the Universe with these important elements.

In this work, we present predictions for isotopic ratios of carbon, sulphur, and titanium within the framework of a classical Milky-Way-like disc galaxy model. The paper is organised as follows: the fundamental nucleosynthetic origins of the relevant carbon, sulphur, and titanium isotopes are first (briefly) reviewed in § 2; in § 3, we introduce the chemical evolution code (GEtool) and the four stellar yield compilations employed in our modelling; finally, the results are presented and summarised in § 4 and § 5, respectively.

2 ORIGIN OF CARBON, SULPHUR, AND TITANIUM ISOTOPIES

Because we in the astronomical community are generally more accustomed to discussing elemental abundance patterns, rather than isotopic patterns, we felt it would be useful to provide an overview of the nucleosynthetic origins of these relevant isotopes. Much of this section has been derived and summarised from Clayton’s (2007) exceptional handbook, to which the reader is referred for definitive and comprehensive descriptions. Complementary discussions of the relevant nucleosynthesis processes and their products can be found in Woosley & Weaver (1995), Arnett (1996), Pagel (1997), and Matteucci (2001).

2.1 Carbon-12

As the initial product of helium burning (the classical triple-$\alpha$ process), $^{12}$C is the second most abundant nucleus formed by nucleosynthesis in stars. While the exact accounting remains uncertain, significant carbon production can likely be traced to massive stars that eventually become Type II supernovae (e.g. Chiappini et al. 1997), with a substantial contribution also derived from intermediate mass asymptotic giant branch (AGB) stars (e.g. Carigi et al. 2005). The newly created $^{12}$C nuclei in these latter stars is convected to the surface, often leading to the formation of a carbon star; ultimately, this carbon-enriched envelope is lost to the ISM through the process of stellar winds associated with planetary nebulae. The amount of $^{12}$C produced depends critically upon the $^{12}$C + $^4$He $\to$ $^{16}$O reaction.

2.2 Carbon-13

The $^{13}$C isotope is considered a secondary nucleus, produced not from the nuclear fusion of hydrogen and helium, but as a secondary process involving “seed” nuclei of $^{12}$C. It is thought to originate within stars not massive enough to become supernovae, in particular, AGB stars. At sufficient temperatures, $^{13}$C is produced via the capture of a proton by the $^{12}$C nucleus, to form $^{13}$N, which itself undergoes $\beta$-decay to form $^{13}$C. The relative abundance depends upon both the relevant reaction and destruction rates.

Having said that, there is also evidence to suggest that $^{13}$C nucleosynthesis also has a primary component (i.e., a production pathway exists which does not depend upon seed nuclei of $^{12}$C). For example, within AGB stars, periodic dredge-up episodes bring newly-formed $^{12}$C to the surface, converting AGB stars to carbon stars, as noted above. If the temperature at the base of the envelope is sufficient, this primary $^{12}$C can be partly converted to (primary) $^{13}$C and $^{14}$N by the first two reactions of the CN-cycle. However, if the star is massive enough ($M > 4M_\odot$) then hot bottom burning can occur, delaying or preventing the AGB star from turning into a carbon star, and therefore this process.

2.3 Sulphur-32

$^{32}$S is formed mostly through oxygen burning, two $^{16}$O nuclei colliding to form $^{30}$Si and $^4$He, with these products subsequently fusing to yield $^{32}$S. Almost all $^{32}$S is produced in Type II supernovae, which eject approximately ten times the quantity synthesised within Type Ia supernovae, and occur roughly five times as often.

2.4 Sulphur-34

$^{34}$S originates as a byproduct of oxygen-burning. $^{34}$S is partly a secondary isotope as it is formed from newly-made $^{32}$S and $^{33}$S by neutron captures, which itself is aided if the star that creates them also has carbon and oxygen in its composition. $^{18}$O and $^{22}$Ne created from this initial carbon and oxygen produce extra neutrons that are needed by heavier sulphur isotopes, but excess neutrons are also produced during oxygen burning by positron emissions, and as such, $^{34}$S is also partly a primary isotope. As far as $^{32}$S, $^{34}$S is produced primarily from supernovae.

2.5 Titanium-46

$^{46}$Ti originates from oxygen- and silicon-burning in massive stars. Two $^{16}$O nuclei collide and subsequent $\alpha$-captures produce $^{44}$Ti, while the capture of two free neutrons results in $^{46}$Ti. This can also be viewed as the addition of an $\alpha$-particle to $^{44}$Ca, so $^{46}$Ti becomes abundant in the same oxygen-burning zone that synthesises $^{44}$Ca. If the burning continues into that of silicon, then the $^{44}$Ti abundance erodes quickly. $^{46}$Ti cannot be labelled as a secondary nucleus as there are positive $\beta$-decays during the oxygen burning.

2.6 Titanium-47

$^{47}$Ti also originates from oxygen- and silicon-burning in massive stars, but in this case, three free neutrons are captured. This can be viewed as the addition of a neutron to $^{46}$Ti, so $^{47}$Ti becomes abundant in the same oxygen-burning zone that synthesises $^{46}$Ti. Some models of Type Ia supernovae also contribute to interstellar $^{47}$Ti. There does appear to be an apparent problem though, in the sense that models of both supernovae types have been claimed to be insufficient producers of $^{47}$Ti with respect to observations (Timmes et al. 1995).
2.7 Titanium-48

The production of $^{48}\text{Ti}$ is traced to the nucleosynthesis of $^{48}\text{Cr}$ in stellar explosions; two subsequent $\beta$-decays after its ejection leads to $^{48}\text{Ti}$. This occurs mostly in explosive silicon-burning and during helium fusion. The latter could occur either by the $\alpha$-rich freezout of shock-decomposed nuclei near the core of a Type II supernova, or as part of explosive helium burning associated with Type Ia supernovae.

2.8 Titanium-49

$^{49}\text{Ti}$ is produced mainly by the nucleosynthesis of radioactive $^{49}\text{Cr}$ in stellar explosions of both types of supernovae. The isotope $^{49}\text{Cr}$ is the result of the explosive fusion of helium as outlined above; $^{49}\text{Cr}$ is also synthesized during silicon-burning, as for the lighter titanium isotopes.

2.9 Titanium-50

It has been suggested that $^{50}\text{Ti}$ is produced primarily in sub-Chandrasekhar mass Type Ia supernovae (Timmes et al. 1995), during which electron capture turns the composition neutron-rich. Some fraction of the $^{50}\text{Ti}$ is likely also made by slow neutron capture within the the burning shells of pre-supernovae massive stars and AGB stars. It would appear that explosive burning in Type II supernovae does not produce significant quantities of $^{50}\text{Ti}$.

3 THE CHEMICAL EVOLUTION MODEL

Throughout our work, we have used the GEtool (Fenner & Gibson 2003; Fenner, Murphy & Gibson 2005) galactic chemical evolution package, employing its default “dual infall” (halo + disc) mode (similar in spirit to the seminal models of Chiappini, Matteucci & Gratton 1997).

Within this framework, the halo phase occurs on a rapid timescale and enriches the initially primordial gas to a metallicity of $\sim10\%$ solar. The second (disc) phase is delayed by $\approx1$ Gyr with respect to the first, and acts over a more prolonged timescale. We assume the infall of fresh material during this second phase to be somewhat metal-enriched (10% solar) and $\alpha$-enhanced (0.4 dex), consistent with patterns seen in metal-poor halo/thick disc stars (e.g. Ryan, Norris & Beers 1996) and present-day high-velocity infalling halo gas (e.g. Gibson et al. 2001).

The rate at which material is accreted is assumed to decline exponentially. The evolution of total surface mass density $\sigma_{tot}(r,t)$ is given by:

$$\frac{d\sigma_{tot}(r,t)}{dt} = A(r)e^{-t/\tau_H} + B(r)e^{-t-\tau_{\text{delay}}/\tau_D}$$  \hspace{1cm} (1)

where the infall rate coefficients $A(r)$ and $B(r)$ are chosen in order to reproduce the present-day surface mass density of the halo and disk components, which we take to be 10 and 45 $M_\odot$ pc$^{-2}$, respectively. The adopted timescales for the infall phases in the solar neighbourhood ($r_\odot=8.5$kpc) are $\tau_H = 0.05$ Gyr and $\tau_D = 10.5$ Gyr, with the functional form for the latter being $\tau_D(r)=1.38r - 1.27$, reflecting the “inside-out” formation framework in which the dual-infall model operates. These timescales and coefficients provide model predictions consistent with various local observational constraints such as the metallicity distribution function, age metallicity relation, and present-day gas surface density distribution, and are consistent with those employed by Fenner et al. (2005).

We adopt a fairly conservative star formation prescription based upon a “Schmidt Law” of the form:

$$\psi(r,t) = \nu\sigma_{gas}(r,t)^2$$  \hspace{1cm} (2)

where the value of the star formation efficiency $\nu$ is constrained by the present-day gas fraction (for this work, $\nu=0.06$ Gyr$^{-1}$).

3.1 Initial Mass Function

The shape of the initial mass function (IMF) controls the fraction of material locked-up in stellar generation, which in turn determines the rate at which different elements are released into the ISM. Our default assumption is that of the three-component IMF of Kroupa, Tout & Gilmore (1993; hereafter, KTG), with lower- and upper-mass limits of 0.08 and $60M_\odot$, respectively; the KTG IMF lies between those of Salpeter (1955) and Scalo (1986), in terms of mass fraction tied up in Type II supernovae progenitors (e.g. Table 7 of Gibson 1997). Unless otherwise stated, we assume that the mass fraction of the IMF which is tied up in SNe Ia progenitor binary systems (total binary masses in the range 3–16 $M_\odot$) is 4%; such an assumption yields, within our adopted model formalism, a disc-averaged present-day ratio between SNe II and SNe Ia rates of 4.1 (consistent with the disc-averaged empirical SNe II to SNe Ia ratio of 3.7 – van den Bergh 1988). We supplement this by exploring a range of single power-law IMF slopes to isolate the relative contributions of low- and high-mass stars.

3.2 Stellar Yields

In order to sample the range of uncertainties inherent to stellar evolution modelling, we explore the use of several sets of metallicity-dependent nucleosynthetic yields, in this work – those of Woosley & Weaver (1995), Chieffi & Limongi (2004), Kobayashi et al (2006)\footnote{Kobayashi et al. (2006) provide yields for both Type II supernovae and hypernovae, the latter represented by explosion energies $10\times$ those of their supernovae models.} for Type II supernovae\footnote{None of the Type II supernovae yield compilations employed here take into account the effects of rotationally-induced mixing; while this has little effect at moderate-to-high (e.g. Galactic disc) metallicities, it may have a significant impact at low (e.g. galactic halo) metallicities (Meynet et al. 2006; Hirschi 2007).} and those of Karakas & Lattanzio (2007), for low- and intermediate-mass single stars (hereafter, WW95, CL04, K06, and KL07, respectively). For Type Ia supernovae, the yields of Nomoto et al. (1997) have been assumed.

As these yields only have data for $M \leq 40 M_\odot$, and our GEtool models assumed an upper-limit mass of 60 $M_\odot$, a linear extrapolation was used, to extend the yields to the highest masses. We stress though that the results do not depend upon the assumption of linear, as opposed to logarithmic or, indeed, “flat” extrapolation.
A detailed isotope-by-isotope comparison between the compilations is beyond the scope of our work; indeed, as § 4, in Figs. 1 and 2 we show the $^{12}\text{C}/^{13}\text{C}$, $^{32}\text{S}/^{33}\text{S}$, and $^{46,47,49,50}\text{Ti}/^{48}\text{Ti}$ isotope ratios, as a function of stellar mass (at solar metallicity) for each of the yield compilations adopted here. We can see from Fig. 1, that, for carbon, there is little difference between supernovae and hypernovae (K06-SNe and K06-HNe, respectively), whereas for sulphur, the explosion energetics lead to a factor of $∼3$ variation in the predicted ejecta ratios. We will return to the issue of the impact of apparently “discrepant” individual stellar models in § 4, but we should note now, for example, the obvious “outlier” seen in the K06 M=25 M$_{\odot}$ solar metallicity model (upper panel of Fig. 1); this two-orders-of-magnitude outlier is also seen in the K06 M=18 M$_{\odot}$ Z=0.004 (not plotted) model. In both cases, this can be traced to the respective models producing $∼$100× the $^{13}\text{C}$ of the “flanking” models. In Fig. 2, it is also seen that there is a factor of $∼3$ variation in the predicted ejecta ratios of K06-SNe and K06-HNe.

Figures 3 and 4 show the variation of $^{12}\text{C}/^{13}\text{C}$ and $^{32}\text{S}/^{33}\text{S}$, with mass, for different metallicities. For clarity, only the WW95 and KL07 yields are shown, as the CL04 and K06 yields demonstrate a similar metallicity-dependence as that of WW95; the general trend of decreasing isotope ratio with increasing metallicity can be seen. In massive stars of decreasing metallicity, it is expected that the amounts of $^{12}\text{C}$ and $^{32}\text{S}$ would be similar, but the amounts of $^{13}\text{C}$ and $^{34}\text{S}$ would decrease (WW95).

### Table 1. Observational Constraints Used

| Isotope     | Meteoritic Grain$^a,1$ | ISM$^b,2$ | $z$=0.89$^{b,3}$ | $z$=1.15$^{c,4}$ |
|-------------|------------------------|-----------|------------------|------------------|
| $^{12}\text{C}/^{13}\text{C}$ | 82.83                  | 70 ± 10   | 27 ± 2           | >80              |
| $^{32}\text{S}/^{33}\text{S}$ | -                      | -         | 10 ± 1           | -                |

| Isotope     | Solar System$^d,1$ | Solar System$^e,1$ | ISM$^b,2$ | Z $\leq 10^{-3} f,5,*$ |
|-------------|-------------------|-------------------|-----------|----------------------|
| $^{12}\text{C}/^{13}\text{C}$ | 89                 | -                 | -         | 19.38                |
| $^{32}\text{S}/^{33}\text{S}$ | 22                 | 22.64             | 24.4 ± 5  | -                    |

$^a$RM03; $^b$M06; $^c$Levshakov et al. (2006); $^d$Anders & Grevesse (1989); $^e$Mauersberger et al. (2004); $^f$Spite et al. (2006).

1 $t$=8.5 Gyr; 2 $t$=13 Gyr; 3 $t$=5.7 Gyr; 4 $t$=4.8 Gyr; 5 $t$=1 Gyr; redshift-to-age conversion assuming ΛCDM concordant cosmology (H$_0$=71 km s$^{-1}$ Mpc$^{-1}$, Ω$_M$=0.27, Ω$_\Lambda$=0.73).

* The mean $^{12}\text{C}/^{13}\text{C}$ value for the unmixed stars from Spite (2006).

### 3.3 New Boundary Conditions

The observational data used in the models in this paper have been taken from RM03, M06, Levshakov et al. (2006), Anders & Grevesse (1989), Mauersberger et al. (2004), Spite et al (2006) and Chavez (2008). The data for the carbon and sulphur isotopes are summarised in Table 1. The ages used have been derived under the assumption of the concordant ΛCDM cosmology.

#### 3.3.1 Local Constraints

RM03 have used the solar system value of carbon from Cameron (1982), and derive a local ISM value based upon the average of a range of observational data; the local ISM value employed in our work is taken directly from RM03. Assuming a present-day age of 13 Gyr, the solar system is taken to have formed at $t$ = 8.5 Gyr (i.e., 4.5 Gyr ago). Wherever possible and relevant, we have used the solar values of Anders & Grevesse (1989).

For $^{32}\text{S}/^{33}\text{S}$, we use the data compilation from Mauersberger et al. (2004), itself based upon Ding et al. (2001) for the solar system value (derived using the Canyon Diablo troilite) and Chin et al. (1999) for the local ISM.

Finally, Chavez (2008) has recently measured, for the first time, titanium isotope ratios in nearby low-mass stars by studying isotopic shifts seen in TiO spectra of M-dwarfs of the halo, and thin and thick discs. This was done using the 2d-ccdé spectrograph at the 2.7m telescope at McDonald Observatory, with a nominal resolving power of $\sim$120k. In total, the isotopic ratios for 11 stars in the metallicity range $−1<[\text{Fe}/\text{H}]<0$ have been derived. The data is shown in Fig. 5 and tabulated (and fully described) in Chavez (2008).

#### 3.3.2 Higher Redshift Constraints

The values obtained recently by M06 for a spiral galaxy at redshift $z=0.89$ are listed in Table 1; the average value of the two spiral arm features seen in absorption towards a background radio-loud QSO is used. From M06 (figure 1), the mean galactocentric distance for these absorption features within the foreground galaxy’s spiral arms is $\sim$4.5 kpc.

In Levshakov et al (2006), C I features associated with
a damped Lyα system at $z=1.15$ seen in the spectrum of HE 0515−4414 were analysed to derive the $^{12}\text{C}/^{13}\text{C}$ ratio. The inferred lower limit of $^{12}\text{C}/^{13}\text{C} \geq 80$ suggested, for the first time, that the abundance of $^{13}\text{C}$ in extragalactic clouds was very low.

In order to infer the isotopic abundance patterns of the ISM at the time of formation of the Milky Way, we used a sample of extremely metal-poor giants ([Fe/H] $\leq -3$) from Spite et al. (2006). We employed the “unmixed” stars from their sample (i.e., stars which have not had their surface abundances affected by deep mixing), and taken the mean $^{12}\text{C}/^{13}\text{C}$ value (19.38) as representative of time $t\sim1$ Gyr (roughly the timescale of formation for the Galactic halo).

4 RESULTS

Figure 5 shows the time evolution of the $^{12}\text{C}/^{13}\text{C}$ and $^{32}\text{S}/^{34}\text{S}$ ratios in our default dual-infall model for the solar neighbourhood ($\S$ 3) using three different SNeII yield compilations. The observed values for the solar system (RM03), local halo stars (Spite et al. 2006), and the local interstellar medium (RM03; Mauersberger et al. 2004) are shown for comparison. The values from M06 are also plotted; as mentioned earlier, the mean galactocentric distance probed by the background QSO towards this high-redshift galaxy is $\sim4.5$ kpc; as such, besides the “solar neighbourhood” prediction, we have also plotted the results of our default model at a galactocentric radius of 4.5 kpc, using the WW95 yields.

The evolution of $^{12}\text{C}/^{13}\text{C}$, employing the WW95 and CL04 yields, is essentially indistinguishable after $\sim5$ Gyr, while the discrepant nature of the models employing the K06 yields is self-evident. We have not shown the models using the K06 hypernovae yields, as their impact for the evolution of $^{12}\text{C}/^{13}\text{C}$ is negligible. In the case of $^{32}\text{S}/^{34}\text{S}$, each of the yield compilations results in fairly self-consistent evolutionary trends, although the hypernovae do reduce the predicted ratio by a factor of two relative to models neglecting them.

From Fig. 5 we also note the existence of predicted positive radial gradients in both $^{12}\text{C}/^{13}\text{C}$ and $^{32}\text{S}/^{34}\text{S}$, reflecting both the inside-out galaxy formation framework and the consequent increased importance of the secondary production of $^{13}\text{C}$ in the inner regions of the galactic model (e.g. RM03). From the lower panel of Fig. 5, we can see that our template dual-infall model is consistent with the extant galactic $^{32}\text{S}/^{34}\text{S}$ data (solar system and local ISM); the lower value observed at $z=0.89$ (M06) can be partially reconciled with it being nearer its respective galaxy’s centre than the solar neighbourhood, a point to which we return in § 4.2.

4.1 The Need For Novae

Previous galactic models for $^{12}\text{C}/^{13}\text{C}$ (e.g. RM03), while consistent with the local ISM, predicted an increase in $^{12}\text{C}/^{13}\text{C}$ over the past 5-10 Gyrs, driven in part by the use of the older van den Hoek & Groenewegen (1997) yields. To ameliorate that apparent discrepancy, RM03 introduced an important additional source of $^{13}\text{C}$, in the form of novae. While successful in recovering the decline in $^{12}\text{C}/^{13}\text{C}$ with time, the overproduction of $^{13}\text{C}$ resulted in a significant mismatch between the model and the observations, as shown in Fig. 5 which required an a posteriori re-scaling of the model to the solar system value.

Conversely, the predicted decline in $^{12}\text{C}/^{13}\text{C}$ over the past 5-10 Gyrs in our model is naturally consistent with the observed solar value and that of the local ISM. This behaviour is driven by the new KL07 yields (which obviously RM03 did not have access to) without the need of recourse to any additional $^{12}\text{C}$ novae contribution. The putative need for novae might even be exacerbated if one were to include, for example, “born again” (i.e., re-ignited) stars such as Sakurai’s Object; it has been suggested recently that such objects might be the dominant source of $^{13}\text{C}$ in the Universe (Hajduk et al. 2005). In the future, a phenomenological treatment of both novae and such born-again objects will be implemented within GEtool.

4.2 Isotopes At High-Redshift

As alluded to earlier, it can be seen in Fig. 5 that it is difficult for our template model to reproduce the isotopic ratios observed in the spiral galaxy at $z=0.89$. Admittedly, the K06 yields appear to provide a better fit to $^{12}\text{C}/^{13}\text{C}$ at $t=5.7$ Gyr (upper panel) although, at the same time, they are less successful for $^{32}\text{S}/^{34}\text{S}$. We have examined two possible alternatives to our template solar neighbourhood model which could explain the lower values observed at high-redshift: (i) varying the galactocentric distance of the model; (ii) varying the IMF.

First, as noted earlier, the data of M06 probes a galactocentric distance closer to 4.5 kpc, rather than the solar galactocentric distance of 8.5 kpc; our template Milky Way model for this radial “bin” would predict a $^{12}\text{C}/^{13}\text{C}$ evolution offset by $\sim20\%$ from the solar neighbourhood value, as shown in Fig. 5. This is, however, insufficient to reproduce the observed values.

Second, we explored the dependence of the predicted isotope ratios upon the relative proportion of massive stars in the IMF by flattening (significantly) the high-mass end of the IMF (representing the IMF by a single power-law of slope 0.9). Figure 6 shows the time evolution of the $^{12}\text{C}/^{13}\text{C}$ and $^{32}\text{S}/^{34}\text{S}$ isotope ratios using both this massive-star biased IMF and the default KTG IMF. The immediate conclusion to be drawn is that both ratios decrease dramatically (by a factor of approximately four) when adopting the massive star-biased IMF. Having said that, it is important to be aware that in large part, this dramatic decrease is a consequence of the accelerated global chemical enrichment produced by the flatter IMF, as these isotopic ratios decrease rapidly with increasing metallicity (recall the earlier discussion surrounding Figures 5 and 6), as opposed to any mass-dependency in the yields. While an IMF slope of 0.9 appears to be a viable solution to the low ratios seen at $z=0.89$, the predicted global metallicity would be $\sim4\times$ so-
Figure 1. Top panel: Carbon isotope ratios as a function of stellar mass at solar metallicity for the sets of yields indicated in the inset. Bottom panel: As above, but sulphur isotopes. In both panels, the Type Ia supernova (SNe Ia) values were derived from Nomoto et al. (1997). The grey horizontal lines correspond to the various observational constraints described in § 3.3.

Figure 2. Titanium isotope ratios as a function of stellar mass at solar metallicity for the sets of yields indicated in the inset. In all panels, the Type Ia supernova (SNe Ia) values were derived from Nomoto et al. (1997).
Figure 3. Top panel: Carbon (top panel) and sulphur (bottom panel) isotope ratios as a function of stellar mass for each of the metallicities used by WW95.

Figure 4. Top panel: Carbon (top panel) and sulphur (bottom panel) isotope ratios as a function of stellar mass for each of the metallicities used by KL07.
Figure 5. Evolution of carbon and sulphur isotope ratios in the solar neighbourhood (r = 8.5 kpc) using the KTG IMF for the Type II supernovae (SNeII) models of WW95, CL04, and K06. For the carbon isotopes: The asterisk, arrow, and plus sign represent the solar value from RM03, the high-redshift Levshakov et al (2006) lower limit, and the Spite et al (2004) halo star data, respectively; the error bar at 5.7 Gyr represents the M06 data, and the error bar at 13 Gyr correspond to the local ISM values, as reported by RM03. For the sulphur isotopes: The asterisk represents the solar system value of Mauersberger et al. (2004), while the error bars at 5.7 and 13 Gyr correspond to the high-redshift data of M06 and the local ISM (Mauersberger et al. 2004), respectively.

We note that neither scenario appears consistent with the low $^{12}\text{C}/^{13}\text{C}$ seen in the local halo stars within the Milky Way (i.e., the t=1 Gyr datum in Fig. 7). To try and reach such low values, we examined a range of halo infall timescales and disk infall “delays”, for example, having a 5 Gyr delay between the first and second infall phase. All of these attempts to reach the low values seen in halo stars were to no avail, however, and the models could not be made to reproduce the observational data. This is not completely surprising, as none of the yields used in this work have ratios as low as 20, as shown in Fig. 1 other than the $5M_\odot$ value of KL07. Therefore, there is no combination of parameters in this work that would lead to such low values, and the answer must lie in additional physics. One such solution, and perhaps the most likely, is the idea of rotationally-induced mixing at low-metallicity, as demonstrated by Chiappini et al (2008), to which we refer the reader.

4.3 Titanium Isotopes
Until recently, the chemical evolution of titanium isotopes has been more of an academic exercise than an experimentally-driven one, in the sense that observational constraints outside the pre-solar nebula did not exist (e.g. see the lack of data in TWW95; figure 28). The classical TWW95 models suggested that all of the titanium isotopes

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4 Indeed, the problem is compounded by having to extrapolate the WW95 and CL04 yields to such high global metallicities, which exacerbates the rapid decrease in the isotopic ratios.
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Figure 6. Comparison between the evolution of carbon isotope ratios using the WW95 yields (without novae: solid curve), for the template model described here, alongside the RM03 models both with (dashed curve) and without (dotted curve) the inclusion of a novae contribution. An important difference between the RM03 curves shown here, and those in the corresponding figure 1a of RM03, is that the models have not been re-scaled \textit{a posteriori} to match the solar neighbourhood data. Contemporary low- and intermediate-mass stellar yields, such as those of KL07, obviate the need for any such “re-calibration”. Symbols are as in Fig. 5.

Figure 7. The evolution of carbon and sulphur isotope ratios in the solar neighbourhood using a single power-law IMF slope of 0.9 (cf. slope of 1.35 for Salpeter 1955) for the SNeII models of WW95 and CL04. The metallicities compared to the solar value for each of the WW95 models used are also shown. Symbols are as in Fig. 5.
Figure 8. The evolution of titanium isotope ratios in the solar neighbourhood using the default dual-infall model with the KTG IMF. For $^{50}\text{Ti}/^{48}\text{Ti}$, an older single-infall model (akin to that of TWW95) is shown for comparison. In the bottom panel, the 11 local disc + halo stars observed by Chavez (2008) are labelled accordingly. Representative uncertainties are shown in the lower left corner of the bottom panel; exact star-by-star uncertainties are tabulated in Chavez (2008).

The primary difference between the single- and dual-infall models is manifest in the behaviour of $^{50}\text{Ti}/^{48}\text{Ti}$, with the others differing by less than a factor of two; as such, we only show the former in Fig. 8.

5 The primary difference between the single- and dual-infall models is manifest in the behaviour of $^{50}\text{Ti}/^{48}\text{Ti}$, with the others differing by less than a factor of two; as such, we only show the former in Fig. 8.

were underproduced with respect to the solar values, with $^{47}\text{Ti}$ and $^{50}\text{Ti}$ being particularly problematic. Two developments over the past decade make it timely to revisit this issue: (1) dual-infall models such as RM03 and our own have supplanted the simpler monolithic-like collapse models of TWW95, and (2) recent observational data from Chavez (2008) have, for the first time, provided stellar values (outside the pre-solar nebula) against which to confront models.

In Fig. 8 (top panel) we show the predicted behaviour of $[^{46,47,49,50}\text{Ti}/^{48}\text{Ti}]$ vs $[\text{Fe/H}]$ for our template dual-infall model, compared with the single-infall model used to replicate the results found by TWW95.

Figure 8 (bottom panel) again shows the dual-infall model predictions as well as the ratios observed in the 11 disc and halo stars from Chavez (2008). We can identify three interesting conclusions from our preliminary analysis of this dataset:

(i) the underproduction of $^{50}\text{Ti}$ claimed by TWW95 appears to be, in large part, an artifact of the single-infall model;

(ii) $^{47}\text{Ti}$ remains problematic; whether this reflects an important missing nucleosynthetic source from our chemical evolution models, such as helium detonation in sub-Chandrasekhar mass Type Ia supernovae, remains unclear;

(iii) most importantly, our models predict a positive correlation between metallicity and $[^{46,47,49,50}\text{Ti}/^{48}\text{Ti}]$ over the range of metallicity sampled by the observations, while the data are more suggestive of a lack of correlation (or even a slight anti-correlation). If confirmed, this would be very difficult to understand within the context of existing galactic chemical evolution models.
5 SUMMARY

We have explored the evolution of carbon, sulphur, and titanium isotopes in both the local- (Milky Way) and high-redshift Universe, using a suite of chemical evolution models generated with GEtool. We examined the need for a novae contribution to explain the carbon isolette patterns in the Milky Way, the evidence for a massive star-biased IMF at high-redshift based upon sulphur isotope ratios, and the impact of new observations of titanium isotope patterns in nearby stars upon our picture of galactic chemical evolution. We have found:

- In contrast to earlier studies, the necessity for a significant contribution of $^{13}$C from novae is ameliorated when employing contemporary models of asymptotic giant branch stars.

- A massive star-biased IMF at high-redshift results in a significant decrease in the predicted $^{12}$C/$^{13}$C and $^{32}$S/$^{34}$S, consistent with those observed, but at the expense of predicting highly super-solar metallicity in otherwise normal-looking spiral galaxies.

- Earlier studies which suggested that $^{50}$Ti was significantly underproduced were, in part, led to this conclusion by the adoption of older monolithic-style collapse models of galactic evolution. Our dual-infall model eliminates these apparent problems, although it remains true that $^{46}$Ti is problematic (i.e., underproduced).

- Our chemical evolution models predict a positive correlation between trace-to-dominant titanium isotope ratios and metallicity, while the data is more suggestive of a lack of correlation.

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REFERENCES

Anders E. and Grevesse N., 1989, GeCoA, 53, 197
Arnett D., 1996, Supernovae And Nucleosynthesis, Princeton University Press
Cameron A. G. W., 1982, in Barnes C. A., Clayton D. D., Schramm N. D. eds, Essays In Nuclear Astrophysics, Cambridge Univ. Press, Cambridge, p. 23
Carigi L., Peimbert M., Esteban C. and García-Rojas J., 2005, ApJ, 623, 213
Chavez J.M., 2008, PhD Thesis, Univ of Texas
Chiappini C., Matteucci F. and Gratton R., 1997, ApJ, 477, 765
Chiappini C., Ekström S., Meynet G., Hirschi R., Maeder A. and Charbonnel C., 2008, A&A, 479, L9
Chin Y. -N., Henkel C., Whiteoak J. B., Langer N., and Churchwell E. B., 1996, A&A, 305, 960
Chieffi A. and Limongi M., 2004, ApJ, 608, 405 (CL04)
Clayton D., 2007, Handbook Of Isotopes In The Cosmos, Cambridge University Press
Ding T., Valkiers S., Kipphardt H., de Bièvre P., Taylor P. D. P., Gonfiantini R. and Krouse R., 2001, GeCoA, 65, 2433
Fenner Y. and Gibson B. K., 2003, PASA, 20, 189
Fenner Y., Murphy M. T. and Gibson, B. K., 2005, MNras, 358, 468
Gibson, B. K., 1997, MNRAS, 290, 471
Gibson B. K., Giroux M. L., Penton S. V., Stocke J. T., Shull J. M. and Tumlinson J., 2001, AJ, 122, 3280
Hajduk M., et al., 2005, Science, 308, 231
Hirschi R., 2007, A&A, 461, 571
Karakas A. and Lattanzio J. C., 2007, PASA, 24, 103 (KL07)
Kobayashi C., Umeda H., Nomoto K., Tominaga N. and Ohkubo T., 2006, ApJ, 653, 1145 (K06)
Kroupa P., Tout, C. A. and Gilmore G., 1993, MNRAS, 262, 545 (KTG)
Levhakov S. A., Centurion M., Molaro P. and Kostina M. V., 2006, A&A, 447, L21
Limongi M. and Chieffi A., 2003, ApJ, 592, 404
Matteucci F., 2001, The Chemical Evolution Of The Galaxy, Kluwer Academic Publishers
Mauersberger R., Ott U., Henkel C., Cernicharo J. and Gallino R., 2004, A&A, 426, 219
Meynet G., Hirschi R., Ekström S. and Maeder A., 2006, ASPC, 353, 49
Muller S., Guelin M., Dumke M., Lucas R. and Combes F., 2006, A&A, 458, 417 (M06)
Nomoto K., Iwamoto K., Nakasato N., Thielemann F.-K., Brachwitz F., Tsujimoto T., Kubo Y. and Kishimoto N., 1997, Nucl. Phys. A, A621, 467
Pagel B. E. J., 1997, Nucleosynthesis And Chemical Evolution Of Galaxies, Cambridge University Press
Prantzos N., Aubert O. and Audouze J., A&A, 309, 760
Ryan S. G., Norris J. E. and Beers T. C., 1996, ApJ, 471, 254
Salpeter E. E., 1955, ApJ, 121, 161
Scalo J. M., 1986, Fund. Cosm. Phys., 11, 1
Spite M. et al, 2006, A&A, 455, 291
Timmes F. X., Woosley S. E. and Weaver T. A., 1995, ApJS, 98, 617 (TWW95)
van den Bergh S., 1988, Comments Astrophys., 12, 131
van den Hoek L. B. and Groenewegen M. A. T., 1997, A&A, 305, 328
Woosley S. E. and Weaver T. A., 1995, ApJS, 101, 181 (WW95)

6 It should be noted that novae, or some additional source, will be required though to explain isotopic ratios such as $^{14}$N/$^{15}$N and $^{16}$O/$^{18}$O; the KL07 yields do not assist in this regard.