Galactic Chemical Evolution Redux: Atomic Numbers $6 \leq Z \leq 15$

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Motivated by the inability of Galactic chemical evolution models to reproduce some of the observed solar neighbourhood distribution of elements (and isotopes) with atomic numbers $6 \leq Z \leq 15$, we have revisited the relevant stellar and Galactic models as part of an ambitious new program aimed at resolving these long-standing discrepancies. Avoiding the use of (traditional) parametric models for low- and intermediate-mass stellar evolution, we have generated a new, physically self-consistent, suite of stellar models and integrated the nucleosynthetic outputs into GEtool, our semi-analytical galactic chemical evolution software package. The predicted temporal evolution of several light- and intermediate-mass elements (and their isotopes) in the solar neighbourhood - from carbon to phosphorus - demonstrate the efficacy of the new yields in reconciling theory and observation.

1. MOTIVATION

The role of asymptotic giant branch (AGB) stars in contributing to the chemical enrichment of the interstellar medium (ISM) has long been appreciated [1, 2]. Unfortunately, the dearth of self-consistent grids of non-parametric stellar models for low- and intermediate-mass stars (LIMS) ensured that that “appreciation” has remained more qualitative than quantitative. Nowhere has this been more problematic than in attempts to understand the origin and evolution of the light- and intermediate-mass metals – atomic numbers between 6 and 15 – where the discrepancy between supernovae yields and observed stellar abundances is most acute [3].

We have recently undertaken an ambitious program of coupled stellar and Galactic chemical evolution modeling, preliminary results for which are described here. Of order 50 stellar models were run using the Mount Stromlo Stellar Structure code; a nucleosynthesis post-processing with time-dependent diffusive mixing was then applied, in order to derive detailed yield information [4, 5]. The parameter space covered was extensive, with masses ranging from 1–7 $M_\odot$, metallicities ranging from zero to super-solar (for both scaled-solar and $\alpha$-enhanced abundance ratios), as well as varying treatments of mass-loss and reaction rates. Elements for which an initial mass function (IMF)-weighted abundance with respect to solar varied by more than 0.1 dex from that derived using the canonical LIMS yields of [1] include atomic numbers $6 \leq Z \leq 15$ (carbon through phosphorus).

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These new stellar yields have now been implemented within GEtool [6, 7], a semi-analytical galaxy evolution code which treats the formation of the Milky Way within a dual-phase infall framework – the first, a rapid infall phase leading to the formation of the stellar halo; the second, a more extended phase associated with the formation of the disk. Such dual-phase formation scenarios have proven success in reproducing the metallicity distribution of nearby stars [8, 9]. GEtool includes a sophisticated treatment of chemical enrichment in the interstellar medium, with the yields of Type Ia and II supernovae (SNe), Wolf-Rayet stars, and AGB stars, all incorporated. This powerful combination of GEtool and the new yields has been demonstrated recently by [10, 11, 12, 13].

2. RESULTS

In the following subsections, we highlight just a few specific examples for which the new LIMS yields have led to interesting new insights into the distribution of elemental and isotopic abundances for atomic numbers $6 \leq Z \leq 15$.

2.1. Carbon

Over the past 4.5 Gyr, the ratio of $^{12}\text{C}$-to-$^{13}\text{C}$ (by mass) in the local ISM has decreased $\sim 20\%$. Attempts at recovering this temporal behaviour in $^{12}\text{C}/^{13}\text{C}$ has led to the suggestion that significant pollution of the local ISM by novae ejecta must have occurred over the lifetime of the Milky Way’s disk [14]. This conclusion was driven in part by the failure of standard LIMS yields [2] to predict the observed decrease in the temporal evolution of $^{12}\text{C}/^{13}\text{C}$ over the disk’s lifetime - see Fig 1 of [14]. Conversely, after incorporating the new grid of LIMS yields into GEtool our standard solar neighbourhood model predicts an $\sim 15\%$ decrease in $^{12}\text{C}/^{13}\text{C}$ over the past 4.5 Gyr, in agreement with the aforementioned empirical data. Over the lifetime of the disk, the same ratio is predicted to have decreased by $\sim 40\%$. In other words, the new yields appear to obviate the need for a putative (significant) nova component to Galactic chemical evolution.3

2.2. Fluorine

The nucleosynthesis pathways for fluorine production in AGB stars involve both the helium and combined hydrogen-helium burning phases. The primary uncertainty in the net production rate can be traced to the adopted reaction rates of $^{14}\text{C}(\alpha,\gamma)^{18}\text{O}$ and $^{19}\text{F}(\alpha,p)^{22}\text{Ne}$, and from the inclusion of partial mixing of protons from the envelope in the top layers of the helium intershell region [13]. Models of Galactic chemical evolution which include only $^{19}\text{F}$ production from neutrino spallation of $^{20}\text{Ne}$ in Type II SNe underproduce the observed [F/O] in the Milky Way and LMC by a factor of $\sim 2$ [3, 13]. After including the new LIMS yields within GEtool, supplemented with the $^{19}\text{F}$ yields for Wolf-Rayet stars at super-solar metallicity [16], we ran our standard Milky Way chemical evolution model. The new yields resulted - for the first time - in the successful recovery

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2We note that the “single star” $^{12}\text{C}/^{13}\text{C}$ models of [14] were scaled upwards by 35% in order to ensure an a posteriori agreement with the Sun’s $^{12}\text{C}/^{13}\text{C}$.

3The present-day Galactic $^{12}\text{C}/^{13}\text{C}$ gradient is an additional constraint on novae pollution in the ISM. We note in passing that our Galactic models, with the new yields, result in a gradient in excellent agreement with the Galactic distribution of carbon monoxide [13]. The inclusion of novae (significant $^{13}\text{C}$ factories) does not impact significantly on the predicted gradient in $^{12}\text{C}/^{13}\text{C}$, but the resulting zeropoint is approximately a factor of two below that of the present-day Galactic ISM.
of the trend of [F/O] observed over ~1 dex in metallicity in the Milky Way and LMC [13].

2.3. Neon
The neon isotope $^{22}$Ne is produced with relative ease in the helium-burning shell of AGB stars via the capture of two $\alpha$-particles onto residual $^{14}$N remaining from the earlier operation of the CN-cycle; subsequent thermal dredge-up mixes this $^{22}$Ne into the envelope. This $^{22}$Ne nucleosynthetic pathway appears to operate independent of metallicity, but only over a limited mass range ($m\approx3.0\pm0.5$ M$_{\odot}$) [5]. The $^{22}$Ne/$^{20}$Ne ratio for this $^{22}$Ne-enriched ejecta (from stars with $m\approx3$ M$_{\odot}$ and $Z\lesssim Z_{\odot}$) is $\sim3$, comparable to the ratio expected in Wolf-Rayet stellar ejecta: $^{22}$Ne/$^{20}$Ne$\approx3$–$10$ for $m\gtrsim40$ M$_{\odot}$ and $Z\gtrsim Z_{\odot}$ [17]. The new yields, in combination with our standard Galactic model, result in a factor of $\sim2$ increase in $^{22}$Ne/$^{20}$Ne (with no discernible impact on $^{21}$Ne/$^{20}$Ne) over the past $\sim7$ Gyr history of the solar neighbourhood. In contrast, the isotopic ratio $^{22}$Ne/$^{20}$Ne in Galactic cosmic rays has been measured to be anomalously high - $\sim5\times$ that of the solar wind. This observation has been attributed to the cosmic rays having been accelerated from superbubbles of metallicity $\sim3Z_{\odot}$ with the accompanying Wolf-Rayet (and Type II SNe) ejecta accounting for $\sim20\%$ of the local ISM (by mass) [17]. It would be useful to revisit this latter conclusion in light of this previously unappreciated source of $^{22}$Ne - AGB stars of mass $\sim3$ M$_{\odot}$.

2.4. Sodium
It is a well-known fact that Galactic chemical evolution models which incorporate sodium yields from Type II SNe alone tend to underproduce [Na/Fe] by a factor of $\sim2$–$3$ over $\sim3$ dex in metallicity [3]. It has also been recognised for some time that the Ne–Na chain acting in AGB stars can lead to the production of $^{23}$Na via proton capture on $^{22}$Ne [4]. Using our new yields, we have constructed the first Milky Way chemical evolution model which includes self-consistently the sodium production from both Type II SNe and AGB stars. Regardless of the Type II SNe yields adopted, the inclusion of sodium from AGB stars results in fairly uniform 0.2–0.4 dex increase in the predicted [Na/Fe] in the ISM for $-2\lesssim[Fe/H]\lesssim+0$, in excellent agreement with observations from [18, 19].

2.5. Magnesium
While the bulk of magnesium in the Galaxy can be traced to Type II SNe, [4] have shown that sub-solar metallicity AGB stars can be important contributors of $^{25}$Mg and $^{26}$Mg isotopes to the ISM. Nucleosynthesis of these isotopes is believed to occur via $\alpha$-capture on $^{22}$Ne triggered by helium shell thermal pulsing. More massive AGB stars

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4Various nucleosynthesis pathways exist, including the hydrogen- and helium-burning shells, and hot bottom burning in massive AGB stars.

5It should be noted that a “numerical” (coincidental!) pseudo-degeneracy exists between sodium from AGB stars and sodium from stars of mass $m=40$–$100$ M$_{\odot}$. For example, as the most massive model generated by [20] is 40 M$_{\odot}$, if one decides to adopt an upper mass limit of, say, 100 M$_{\odot}$ for the IMF, one is forced to extrapolate the sodium production from the lower mass models. Because this sodium production is a steeply increasing function of stellar mass, linearly extrapolating to 100 M$_{\odot}$ can actually lead to a predicted [Na/Fe] vs [Fe/H] behaviour which mimics (again, coincidentally) that encountered when using the new AGB sodium yields. A careful consideration of very massive star sodium yields must be undertaken before we can make any further quantitative statements.
($m=4–6 \ M_\odot$) may actually burn magnesium via hot bottom burning at the base of the convective envelope. Models of Galactic chemical evolution which include only the heavy magnesium isotopes returned to the ISM via Type II SNe are significantly discrepant with observational data \cite{3}. Incorporating the Mg isotopic contribution from AGB stars into GEtool leads to a factor of 2–3 increase in $^{25,26}$Mg/$^{24}$Mg over $\sim 2$ dex in metallicity, in agreement with the distribution observed in the solar neighbourhood \cite{10}.

2.6. Phosphorus

Our new stellar models produce $^{31}$P efficiently; when coupled with the phosphorus associated with Type II SNe \cite{20, 21}, an $\sim 0.2$ dex enhancement in the predicted solar neighbourhood [P/Fe] is seen across $\sim 2$ dex in metallicity ($-2 \lesssim [\text{Fe/H}] \lesssim +0$). While empirical stellar phosphorus abundances are difficult to determine, a firm upper limit of [P/S]$<+0$ has been placed on the intergalactic medium $^6 \sim 2$ Gyr after the Big Bang \cite{12}. Such an empirical limit was already only 0.3–0.5 dex outside the predictions of chemical evolution models generated without an AGB phosphorus component \cite{12}; Fig 6); the inclusion of our new $^{31}$P AGB yields into the same damped Lyman-$\alpha$ model means the current empirical limit is less than a factor of two outside the model predictions. Future, more sensitive, observations of such high-$z$ clouds can therefore, in principle, support or refute this specific prediction of our new LIMS models.

REFERENCES

1. A. Renzini and M. Voli, A&A 94 (1981) 175.
2. L.B. van den Hoek and M.A.T. Groenewegen, A&AS 123 (1997) 305.
3. F.X. Timmes, S.E. Woosley and T.A. Weaver, ApJS 98 (1995) 617.
4. A.I. Karakas and J.C. Lattanzio, PASP 20 (2003) 279.
5. A.I. Karakas and J.C. Lattanzio, PASP 20 (2003) 393.
6. Y. Fenner and B.K. Gibson, PASA 20 (2003) 189.
7. B.K. Gibson, Y. Fenner, A. Renda, D. Kawata and H.-c. Lee, PASA 20 (2003) 401.
8. Chiappini, C., Matteucci, F. & Gratton, R., ApJ 477 (1997) 765
9. Chiappini, C., Matteucci, F. & Romano, D., ApJ 554 (2001) 1044
10. Y. Fenner, B.K. Gibson, H.-c. Lee, A.I. Karakas, et al., PASA 20 (2003) 340.
11. Y. Fenner, S. Campbell, A.I. Karakas, et al. MNRAS 353 (2004) 789.
12. Y. Fenner, J.X. Prochaska and B.K. Gibson, ApJ 606 (2004) 116.
13. A. Renda, Y. Fenner, B.K. Gibson, A.I. Karakas, et al., MNRAS 355 (2004) 575.
14. D. Romano and F. Matteucci, MNRAS 342 (2003) 185.
15. T.L. Wilson and R.T. Rood, ARAA 32 (1994) 191.
16. G. Meynet and M. Arnould, A&A 355 (2000) 176.
17. J.C. Higdon and R.E. Lingenfelter, ApJ 590 (2003) 822.
18. Edvardsson, B., Andersen, J., Gustafsson, B., et al. A&A 275 (1993) 101
19. Gratton, R. G., Carretta, E., Desidera, S., Lucatello, S., et al. A&A 406 (2003) 131
20. S.E. Woosley and T.A. Weaver, ApJS 101 (1995) 181.
21. M. Limongi and A. Chieffi, ApJ 592 (2003) 404.

\footnote{Or at least one damped Lyman-$\alpha$ system.}