On the origin of fluorine in the Milky Way

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ABSTRACT
The main astrophysical factories of fluorine (\textsuperscript{19}F) are thought to be Type II supernovae, Wolf-Rayet stars, and the asymptotic giant branch (AGB) of intermediate mass stars. We present a model for the chemical evolution of fluorine in the Milky Way using a semi-analytic multi-zone chemical evolution model. For the first time, we demonstrate quantitatively the impact of fluorine nucleosynthesis in Wolf-Rayet and AGB stars. The inclusion of these latter two fluorine production sites provides a possible solution to the long-standing discrepancy between model predictions and the fluorine abundances observed in Milky Way giants. Finally, fluorine is discussed as a possible probe of the role of supernovae and intermediate mass stars in the chemical evolution history of the globular cluster \textomega Centauri.

Key words: galaxies: evolution – stars: abundances – stars: evolution

1 INTRODUCTION
The three primary astrophysical factories for fluorine (\textsuperscript{19}F) production have long been thought to be Type II supernovae (SNe II), Wolf-Rayet (WR) stars, and asymptotic giant branch (AGB) stars (e.g. Woosley \& Weaver 1995; Meynet \& Arnould 2000; Forestini et al. 1992; Mowlavi, Jorissen \& Arnould 1998, respectively). Previous attempts to model the Galactic production and evolution of \textsuperscript{19}F have been restricted to explore the role of SNe II alone (e.g. Timmes, Woosley \& Weaver 1995; Alibés, Labay \& Canal 2001).

The above problem has now been ameliorated by the release of the first detailed yield predictions for fluorine production from WR and AGB stars. We are now in a position to incorporate these yields into a Galactic chemical evolution framework, in order to assess the respective contributions of the three putative fluorine production sites. To do so, we will make use of \textsc{GeTool}, a semi-analytical multi-zone Galactic chemical evolution package which has been calibrated with extant observational data for the Milky Way (Fenner \& Gibson 2003; Gibson et al. 2003).

Specifically, in what follows, we compare the model fluorine distribution in the Milky Way with the abundances observed by Jorissen, Smith \& Lambert (1992) in near-solar metallicity giants. Further, our model predictions are contrasted with new fluorine determinations for giants in the Large Magellanic Cloud (LMC) and \omega Centauri (Cunha et al. 2003). In addition, new results for more \omega Centauri giants from Smith et al. (2004) are included. The latter two systems are likely to have had very different star formation and chemical evolution histories from those of the Milky Way, but despite these obvious differences, a comparison against these new data can be valuable. In Section 2, we provide a cursory overview of the three traditional \textsuperscript{19}F nucleosynthesis sites; the chemical evolution code in which the nucleosynthesis products from these factories have been implemented is described in Section 3. Our results are then presented and summarised in Sections 4 and 5, respectively.
2 NUCLEOSYNTHESIS OF $^{19}$F

2.1 Type II Supernovae

The massive star progenitors to SNe II produce fluorine primarily as the result of spallation of $^{20}$Ne by $\mu$ and $\tau$ neutrinos near the collapsed core (Woosley & Haxton 1988; Woosley et al. 1990). A fraction of the $^{19}$F thus created is destroyed by the subsequent shock but most is returned to the ambient Interstellar Medium (ISM). The fluorine yields by neutrino spallation are very sensitive to the assumed spectra of $\mu$ and $\tau$ neutrinos (Woosley et al. 2002), which could be nonthermal and deficient on their high-energy tails, lowering the equivalent temperature of the neutrinos in the supernova model (Myra & Burrows 1990). An additional source of $^{19}$F derives from pre-explosive CNO burning in helium shell. However, fluorine production by neutrino spallation is largely dominant, as evident by comparing the models in Woosley & Weaver (1995), the only ones to-date including neutrino process, and recent models which do not include neutrino nucleosynthesis of fluorine (Limongi & Chieffi 2003). Most recently, Heger et al. (2004) suggest that the relevant neutrino cross sections need to be revised downwards; if confirmed, the associated SNe II $^{19}$F yield would decrease by $\sim 50\%$. In light of the preliminary nature of the Heger et al. claim, we retain the conservative choice offered by the Woosley & Weaver (1995) compilation.

2.2 Asymptotic giant branch stars

The nucleosynthesis pathways for fluorine production within AGB stars involve both helium burning and combined hydrogen-helium burning phases (e.g. Forestini et al. 1992; Jorissen et al. 1992; Mowlavi et al. 1998) and are companions for the nucleosynthesis by slow neutron accretion (s-process) (Mowlavi et al. 1998). Provided a suitable source of protons is available, fluorine can be synthesised via $^{14}$N($\alpha$, $\gamma$)$^{19}$F ($\beta^+$) $^{19}$F($p$, $\alpha$)$^{14}$N($\alpha$, $\gamma$)$^{19}$F. Primary sources of uncertainty in predicting fluorine nucleosynthesis in AGB stars relate to the adopted reaction rates, especially $^{14}$C($\alpha$, $\gamma$)$^{18}$O and $^{17}$F($\alpha$, $p$)$^{22}$Ne, and the treatment of the nucleosynthesis occurring during the convective thermal pulses. Nucleosynthesis during the interpulse periods can also be important if protons from the envelope are partially mixed in the top layers of the He intershell (partial mixing zone), as Lugaro et al. (2004) have recently demonstrated. Nucleosynthesis in this zone may result in a significant increase in the predicted $^{19}$F yields. The magnitude of these systematic uncertainties for stellar models with mass $\sim 3$ $M_\odot$ and metallicities $Z = 0.004 - 0.02$ are $\sim 50\%$, while for stellar models with mass $M = 5$ $M_\odot$ and metallicity $Z = 0.02$ the uncertainty is a factor of $\sim 5$, due to the uncertain $^{17}$F($\alpha$, $p$)$^{22}$Ne reaction rate. Characterising the mass- and metallicity-dependence of the partial mixing zone $^{19}$F relationship needs to be completed before we can assess its behaviour self-consistently within our chemical evolution model of the Milky Way. For the present study, we have adopted the yields presented in Appendix, based upon the Karakas & Lattanzio (2003, and references therein) models, which themselves do not include $^{19}$F nucleosynthesis via partial mixing. This choice is a conservative one, and thus should be considered as a lower limit to the production of $^{19}$F from AGB stars.

For stars more massive than $\approx 4$ $M_\odot$, the convective envelope is so deep that it penetrates into the top of the hydrogen-burning shell so that nucleosynthesis actually occurs in the envelope of the star. Such “hot-bottom-burning” acts to destroy $^{19}$F, and should be treated self-consistently within the AGB models considered.

2.3 Wolf-Rayet stars

Fluorine production in WR stars is tied to its nucleosynthesis during the helium-burning phase. At the end of this phase though, significant fluorine destruction occurs via $^{19}$F($\alpha$, $p$)$^{22}$Ne. Any earlier synthesised $^{19}$F must be removed from the stellar interior in order to avoid destruction. For massive stars to be significant contributors to net fluorine production, they must experience mass loss on a timescale that allows the removal of $^{19}$F before its destruction. This requirement is met by WR stars.

Recently, Meynet & Arnould (2000) studied the role that such stars can play in the chemical evolution of fluorine by adopting updated reaction rates coupled with extreme mass-loss rates in not-rotating stellar models. They pointed out that WR mass-loss is strongly metallicity-dependent, and that the number of WR stars at low metallicities is very small. Their WR yields reflect such metallicity-dependence, with minimal fluorine returned to the ISM at low metallicities, but significant $^{19}$F returned at solar and super-solar metallicities. The WR yields are sensitive to the adopted reaction and mass-loss rates, while rotating models could favour an early entrance into the WR phase for a given mass, decrease the minimum initial mass for a star to go through a WR phase at a given metallicity, and open more nucleosynthetic channels because of the mixing induced by rotation. Therefore, after Meynet & Arnould (2000), we consider the aforementioned WR yields as lower limits.

3 THE MODEL

In this study we employ GEtool, our semi-analytical multi-zone chemical evolution package to model a sample Milky Way-like disk galaxy (Fenner & Gibson 2003; Gibson et al. 2003). A dual-infall framework is constructed in which the first infall episode corresponds to the formation of the halo, and the second to the inside-out formation of the disk.

A Kroupa, Tout & Gilmore (1993) initial mass function (IMF) has been assumed, with lower and upper mass limits of 0.08 $M_\odot$ and 120 $M_\odot$, respectively. Stellar yields are one of the most important features in galactic chemical evolution models, yet questions remain concerning the precise composition of stellar ejecta, due to the uncertain role played by processes including mass loss, rotation, fallback, and the location of the mass cut, which separates the remnant from the ejected material in SNe. The SNe II yields are from Woosley & Weaver (1995); the yields for stars more massive than 60 $M_\odot$ are assumed to be mass-independent. Such assumption is made to avoid extreme extrapolation from the most massive star in the Woosley & Weaver models (40 $M_\odot$) to the upper end of the IMF (120 $M_\odot$), and has negligible effect on the results, given the shape of the adopted IMF.

We have halved the iron yields shown in Woosley &
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3) MWc includes all three sources of fluorine contributions (both in density and metallicity), abundance ratio SNe II, WR, and AGB stars.

patterns, age-metallicity relation, and G-dwarf distribution (Gibson et al. 2003). While the modification of any individual ingredient within model framework will have an impact, to some degree, upon the predicted chemical evolution, this can only eventuate at the expense of one or more of the aforementioned boundary conditions that we require our model to adhere to. Within our framework, yield uncertainties will dominate the systematic uncertainties for the predicted evolution of $^{19}$F.

3.1 Fluorine yields

We now summarise the $^{19}$F yields employed in our three "Milky Way" models.

1) SNe II $^{19}$F yields are taken from Woosley & Weaver (1995) and assumed to be mass-independent for stellar masses in excess of 60 $M_\odot$.

2) WR $^{19}$F yields are taken from Meynet & Arnould (2000) for stellar masses in the range 25 – 120 $M_\odot$: each star within this range is assumed to evolve through the WR stage. Such simplifying assumption could overestimate the WR contribution to fluorine, even though the adopted WR yields are themselves lower limits (Section 2.3). The WR fluorine contribution has been added to the corresponding SNe II contribution (which comes from a different stage of the stellar evolution).

3) AGB $^{19}$F and oxygen yields in the 1 – 6.5 $M_\odot$ mass range have been derived from stellar models constructed with the Mount Stromlo Stellar Structure Code (Frost & Lattanzio 1996; Karakas et al. 2002), and are presented in Appendix. The post-processing nucleosynthesis models with 74 species and time-dependent diffusive convective mixing are described in detail in Frost et al. (1998) and Karakas & Lattanzio (2003).

To ensure internal consistency, we have also employed the AGB oxygen yields in lieu of those of Renzini & Voli (1981), within this mass range.

The above fluorine yields are shown in Figure 1. In Figure 2, the yields are expressed as $[F/O]_I^\text{SFR}$ and $[F/O]_I^\text{IMF}$, the latter corresponding to the mean $[F/O]$ yields for SNe II and AGB stars, weighted by the IMF over the SNe II and AGB mass range, respectively. We have not shown a comparable entry for the WR stars as a self-consistent treatment of the oxygen production was not included in Meynet & Arnould (2000). Here, oxygen has been used as the normalisation to make easier the comparison with the observations, especially in $\omega$ Centauri, though oxygen can be synthesised in various stellar sites, and its yields can be affected by different reaction rates and modeling of helium cores, semi-convection, convective boundary layers, and mass-loss (e.g. Woosley et al. 2002; Dray et al. 2003).

4 RESULTS

In Figure 3, the evolution of $[F/O]$, $A(O)$, the gas infall rate $\dot{\Sigma}_\text{infall}$, the star formation rate (SFR), the SNe II rate and the gas-phase global metallicity $Z$ of the three models at the solar neighbourhood are summarised. The empirical SFR history derived by Bertelli & Nasi (2001) is shown as a thick solid line in Figure 3d, while the shaded region corresponds to the range of values suggested by Rana (1991). A conservative range of estimated SNe II rates is also shown in Figure 3e (Cappellaro, Evans & Turatto 1999).$^2$ Figure 4

$^1$ Hereafter, $[X/Y]=\log_{10}(X/Y) - \log_{10}(X/Y)_\odot$ and $A(X)=12 + \log_{10}(n_X/n_H)$. An accurate determination of photospheric solar abundances requires detailed modeling of the solar granulation and accounting for departures from local thermodynamical equilibrium (e.g. Allende Prieto, Lambert & Asplund 2001). We adopt the solar fluorine abundance suggested by Cunha et al. (2003), and the solar iron and oxygen abundances from Holweger (2001).

$^2$ The range of values shown in Figure 3e is derived from the sample of 50a – 5b galaxies in Cappellaro et al. (1999) - 0.42 ± 0.19 SNeu, where 1 SNeu = 1 SN(100 yr)$^{-1}$(10$^{10}$ L$\odot$/yr)$^{-1}$, assuming $L^B_{MW} = 2 \times 10^{10}$ L$\odot$ and a galactic radial extent of 15 kpc.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Fluorine yields from a) SNe II (Woosley & Weaver 1995), b) WR (Meynet & Arnould 2000), and c) AGB stars (Appendix).}
\end{figure}
Given these assumptions, the estimated SNe II rate at the solar neighbourhood is necessarily uncertain.

Figure 2. [F/O] and ([F/O]_{IMF} for SNe II and AGB yields (upper and lower panels, respectively). Here, A^{[19F]}_\odot = 4.55 (see discussion in Cunha et al. 2003) and A(O)\odot = 8.736 (e.g., Holweger 2001). The shaded regions in Figures 2a and 2b show the observed [F/O] in ω Cen giants (Cunha et al. 2003). The ([F/O]_{IMF} are weighted by the IMF over the SNe II (11–40 M_\odot) and AGB (1–6.5 M_\odot) mass range, respectively. In Figure 2d, both ([F/O]_{AGB}_{IMF} and ([F/O]_{SNe II}_{IMF} are shown (closed boxes and open triangles, respectively).

Figure 3. Predicted evolution in the solar neighbourhood of a) the gas infall rate \dot{\rho}_{\text{infall}}, b) A(O), c) [F/O], d) star formation rate (SFR), e) SNe II rate, and f) metallicity Z (MWa, solid line; MWb, dotted; MWc, short-dashed). The SFR history at the solar neighbourhood obtained by Bertelli & Nasi (2001) is also shown as a thick solid line in panel ‘d’, while the shaded region shows the range of values suggested by Rana (1991). A range of values corresponding to the estimated SNe II rate is shown in panel ‘e’ (Cappellaro et al. 1999).

5 DISCUSSION

We have studied the Galactic chemical evolution of fluorine, for the first time using new grids of stellar models which provide self-consistent predictions of fluorine nucleosynthesis for stars in both the WR and AGB phases of stellar evolution. We have shown that the WR contribution is significant at solar and super-solar metallicities because of the adopted metallicity-dependent mass-loss prescription employed in the stellar models. In contrast, the contribution of AGB stars to fluorine production peaks during the early epochs of the Galaxy’s evolution (again due to the metallicity-dependent behaviour of the AGB models). In combination, the addition of the WR and AGB contributions allows for a significant improvement in the comparison between galactic models incorporating fluorine evolution and the observational data.

The comparison between our MW models and the fluorine abundances in LMC and ω Cen giants (Cunha et al. 2003) is not straightforward, as the latter two have star for-
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Figure 4. (a): [F/O] as a function of A(O) for the MW models (MWA, solid line; MWb, dotted; MWc, short-dashed). Also shown are the values observed in Milky Way, LMC, and giants (crosses, boxes and hexagons, respectively). (b): [F/O] as a function of [O/Fe], compared with the IMF-weighted [O/Fe] yields for SNe II (open triangles). Within the open triangles, `0' corresponds to Z=0; `1', to Z=1.9; `2', to Z=1.9x10^{-4}; `3', to Z=1.9x10^{-3}; `4', to Z=1.9x10^{-2}. The upper panels represent enlargements of the framed regions delineated in the corresponding bottom panels.

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References

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APPENDIX A: ASYMPTOTIC GIANT BRANCH $^{19}$F AND $^{16,17,18}$O YIELDS

The yields employed here have been derived via the following:

$$Y_{19F, O}(Z) = Y_{net19F, O} + X_{19F, O}(Z) \times [m_* - m_{* rem}(Z)]. \quad (A1)$$

Here, $Y_{19F, O}(Z)$ is the overall yield, $X_{19F, O}(Z)$ is the initial mass fraction of the element within a star of mass $m_*$ and metallicity $Z$, $[m_* - m_{* rem}(Z)]$ is the total mass ejected during the stellar lifetime, and $Y_{net19F, O}$ is the net yield. We calculate $X_{iO}$ and $Y_{netiO}$ as, respectively:

$$X_{iO} = X_{16iO} + X_{17iO} + X_{18iO}; \quad (A2)$$

$$Y_{netiO} = Y_{net16iO} + Y_{net17iO} + Y_{net18iO}. \quad (A3)$$

The yields are the result of full evolutionary calculations using the Mount Stromlo Stellar Structure Code (e.g. Karakas & Lattanzio 2003). We use the standard Reimers mass-loss formula on the first giant branch and the Vassiliadis & Wood (1993) formula during the AGB evolution. Opacities are from OPAL (Iglesias & Rogers 1996). The models with $Z = 0.02$ and 0.0001 used scaled solar abundances, whereas those for $Z = 0.004$ and 0.008 are appropriate to the Small and Large Magellanic Clouds, respectively, and are taken from Russell & Dopita (1992). Numerical problems during the third dredge-up are handled in the way described in Frost & Lattanzio (1996). A mixing length of 1.75 pressure scale-heights has been used. A main uncertainty in the predicted yields for fluorine is the occurrence and dimension of the partial mixing zone. Note that this partial mixing zone was ignored in the models presented here. Primary sources of uncertainty in predicting fluorine nucleosynthesis in AGB stars relate to the adopted reaction rates, especially $^{14}C(\alpha, \gamma)^{18}O$ and $^{19}F(\alpha, p)^{22}Ne$, and the treatment of the nucleosynthesis occurring during the convective thermal pulses and the interpulse periods (Lugaro et al. 2004; see also Section 2.2).
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Table A1. AGB $^{19}$F and $^{16,17,18}$O yields (M$_\odot$).

<table>
<thead>
<tr>
<th>Z</th>
<th>$X_{^{19}F}$</th>
<th>$X_{^{16}O}$</th>
<th>$X_{^{17}O}$</th>
<th>$X_{^{18}O}$</th>
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<td>4.4478e-05</td>
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<table>
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<tr>
<th>$m_*$</th>
<th>$m_{*\text{ rem}}$</th>
<th>$Y_{^{19}F,AGB}^{\text{net}}$</th>
<th>$Y_{^{16}O,AGB}^{\text{net}}$</th>
<th>$Y_{^{17}O,AGB}^{\text{net}}$</th>
<th>$Y_{^{18}O,AGB}^{\text{net}}$</th>
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<td>1.0</td>
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<td>0.51379E-08</td>
<td>0.22865E-05</td>
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<td>-0.57154E-05</td>
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<td>-0.41576E-06</td>
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