Chemical Evolution of Fluorine in the Milky Way

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ABSTRACT

Fluorine has many different potential sites and channels of production, making narrowing down a dominant site of fluorine production particularly challenging. In this work, we investigate which sources are the dominant contributors to the galactic fluorine by comparing chemical evolution models to observations of fluorine abundances in Milky Way stars covering a metallicity range -2 < [Fe/H] < 0.4 and upper limits in the range -3.4 < [Fe/H] < -2.3. In our models, we use a variety of stellar yield sets in order to explore the impact of varying both AGB and massive star yields on the chemical evolution of fluorine. In particular, we investigate different prescriptions for initial rotational velocity in massive stars as well as a metallicity dependent mix of rotational velocities. We find that the observed [F/O] and [F/Fe] abundance ratios at low metallicity and the increasing trend of [F/Ba] at [Fe/H] ≥ -1 can only be reproduced by chemical evolution models assuming, at all metallicities, a contribution from rapidly rotating massive stars with initial rotational velocities as high as 300 km s⁻¹. A mix of rotational velocities may provide a more physical solution than the sole use of massive stars with νrot = 300 km s⁻¹, which are predicted to overestimate the fluorine and average s-process elemental abundances at [Fe/H] ≥ -1. The contribution from AGB stars is predicted to start at [Fe/H] ≈ -1 and becomes increasingly important at high metallicity, being strictly coupled to the evolution of the nitrogen abundance. Finally, by using modern yield sets, we investigate the fluorine abundances of Wolf-Rayet winds, ruling them out as dominant contributors to the galactic fluorine.

Key words: Galaxy: abundances – Stars: abundances – Galaxy: evolution – Galaxy: disc

1 INTRODUCTION

For many years, understanding the origin and evolution of fluorine has posed a challenge for the scientific community. Fluorine has just one stable isotope, ¹⁹F, with many different channels of production depending on the conditions in stars. ¹⁹F is also fragile and can be easily destroyed by α captures (e.g. Meynet & Arnould 2000). This makes narrowing down a dominant site for fluorine production particularly difficult. There are five main sites that frequently appear in the literature as having the potential to contribute significantly to the chemical evolution of fluorine; these are the following.

(i) Asymptotic Giant Branch (AGB) stars: Fluorine is produced in AGB stars during thermal pulses (Forestini et al. 1992; Straniero et al. 2006). Secondary ¹⁹F is made from ¹⁴N seed nuclei via the following two chains of reactions: ¹⁴N(n,p)¹⁴C(α,γ)¹⁸O(p,α)¹⁵N(α,γ)¹⁹F and ¹⁴N(α,γ)¹⁸F(α*,¹⁸O(p,α)¹⁵N(α,γ)¹⁹F (Lugaro et al. 2004). In certain conditions, primary fluorine can also be made in AGB stars from the rapid burning of ¹³C at high temperatures, which produces ¹⁵N and allows for the nucleosynthesis of fluorine via ¹⁵N(α,γ)¹⁹F (Cristallo et al. 2014). For a more detailed review of the ¹⁹F production channels in AGB stars, see Lucatello et al. (2011). Kobayashi et al. (2011a) found that the dominant AGB mass range for fluorine production is 2-4 M☉, over which temperatures do not get hot enough for hot bottom burning to occur, preventing the destruction of fluorine via ¹⁹F(α,p)²²Ne. However, it should be noted that the yield set used in Kobayashi et al. (2011a) favours ¹⁹F production in this mass range (see fig. 8 of Karakas & Lattanzio 2007). There is observational evidence that AGB stars contribute to the galactic fluorine (see the pioneering works of Jorissen et al. 1992). However, it is still unclear if AGB stars can account for the total galactic abundance of fluorine.

(ii) Wolf-Rayet (WR) stars: Fluorine can be produced by WR stars during the helium burning phase. Again, the seed nuclei for

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Note that here and throughout this work we define AGB stars in the contribution to the galactic fluorine abundance.

Interestingly, Brinkman (2022) found negative net yields of fluorine, which will be addressed in later sections of this work.

The evolution of fluorine at low metallicity (e.g., $[\text{Fe/H}] < -1.5 \text{ dex}$) poses a particular challenge because of a large contamination from sodium. The majority of fluorine abundance determinations in the literature are obtained from the analysis of ro-vibrational HF lines at $2.3 \mu \text{m}$ (Abia et al. 2015). This spectral range is contaminated by lots of telluric lines, which prevent the use of many HF lines for fluorine abundance determinations. Recently, the first detection of an AIF line was obtained in 2 M-type AGB stars (Saberi et al. 2022). Danilovich et al. (2021) also detected the AlF line towards an S-type AGB star, measuring an abundance of AlF 40% greater than solar. Most fluorine observations for chemical evolution studies are available using HF lines as detected in both galactic and extra-galactic field stars, the previously listed observations in open and globular clusters will not be included in our analysis.

$^{19}$F production in these stars is $^{14}$N. If the $^{14}$N is of secondary origin, then the behavior of $^{19}$F is also secondary and is, therefore, metallicity dependent. It is thought that WR winds can eject some of the fluorine before it is destroyed by $\alpha$ captures; this process is the result of a delicate balance between the rate at which mass is lost via winds and the efficiency of the $^{19}$F$(\alpha, p) ^{22}$Ne reaction.

Note that here and throughout this work we define AGB stars in the contribution to the galactic fluorine abundance.

Aside from the uncertainties in the dominant production site of fluorine, we must also contend with difficulty in gathering observations of fluorine. The majority of fluorine abundance determinations in the literature are obtained from the analysis of ro-vibrational HF lines at $2.3 \mu \text{m}$ (Abia et al. 2015). This spectral range is contaminated by lots of telluric lines, which prevent the use of many HF lines for fluorine abundance determinations. Recently, the first detection of an AIF line was obtained in 2 M-type AGB stars (Saberi et al. 2022). Danilovich et al. (2021) also detected the AlF line towards an S-type AGB star, measuring an abundance of AlF 40% greater than solar. Most fluorine observations for chemical evolution studies are available using HF lines as detected in both galactic and extra-galactic AGB stars (Abia et al. 2011, 2015, 2019), field stars (Lucatello et al. 2011, Li et al. 2013) and in the Galactic center (Guerço et al. 2022). There are also a variety of observations of fluorine in open and globular clusters (e.g. Maiorca et al. 2014, Nault & Pilachowski 2013, de Laverny & Recio-Blanco 2013, Smith et al. 2005, Cunha et al. 2003; Cunha & Smith 2005, Yong et al. 2008). Since this work is mainly focused on the chemical evolution of fluorine in Milky Way field stars, the previously listed observations in open and globular clusters will not be included in our analysis.

The evolution of fluorine at low metallicity (e.g., $[\text{Fe/H}] < -1.5 \text{ dex}$) poses a particular challenge because of a large contamination from telluric lines and blending of the HF lines with CO features (Lucatello et al. 2011). Despite these challenges, there are some measurements of fluorine abundances at low metallicities, which include a sample
of red giants from Lucatello et al. (2011) and two red giants in Carina dwarf spheroidal (dSph) galaxy from Abia et al. (2015) among others (e.g. Li et al. 2013, Mura-Guzmán et al. 2020). Both the stellar sample of Lucatello et al. (2011) and the Carina stars from Abia et al. (2015) are considered in our work.

The structure of the paper is as follows: Section 2 lays out the sample of fluorine abundance measurements that are used in this work for different metallicity ranges, Section 3 introduces the main hypothesis and working assumptions of our galactic chemical evolution model and summarizes the different combinations of yields that are included in the model, Section 4 presents the main chemical evolution trends of interest as predicted by our model to reproduce observational data, and Section 5 explains how these results can help us to probe the chemical evolution of fluorine. Finally, in Section 6, we present our conclusions.

2 OBSERVATIONS

The most recent set of fluorine abundance measurements are those of Ryde et al. (2020) who observed 66 red giants using the Immersion GRating INfrared Spectrometer (IRIS) and the Phoenix infrared high-resolution spectrograph at the Gemini South Observatory. The metallicity range of these observations is -1.1 < [Fe/H] < 0.4 which extends the metallicity range of fluorine abundances in the solar neighbourhood that were available previous to this study (e.g. Jónsson et al. 2017).

Due to telluric lines and blending, much of the data we have at low [Fe/H] are upper limits rather than absolute measurements. Though not as conclusive as absolute measurements, upper limits can still tell us about the range of fluorine abundances we might expect and can give us a preliminary idea of if our chemical evolution models can reproduce observations at low metallicity. The primary set of fluorine observations at low metallicity used in this work consists of a sample of eleven metal-poor red giant stars from Lucatello et al. (2011). The abundances were measured from the analysis of spectra obtained with the CRyogenic high-resolution InfraRed Echelle Spectrograph (CRIRES) on ESO’s VLT. Of the 11 stars in the metallicity range -3.4 < [Fe/H] < -1.3, two have abundance measurements of fluorine, while the remaining nine have upper limits provided.

Eight red giants in the sample of Lucatello et al. (2011) are classified as CEMP-s stars (carbon-enhanced metal poor stars that are also enriched in s-process elements), whereas two stars are classified as CEMP-no star (not enriched with s-process or r-process elements). There is also one star in this sample classified as carbon normal. While the physical origin of CEMP-no stars is still unclear and debated (Aoki et al. 2002; Yoon et al. 2016; Hansen, C. J. et al. 2016), the s-process and carbon enhancement as measured in the atmosphere of CEMP-s red giants likely results from binary mass transfer from an AGB companion that changed the initial surface abundances (e.g., Lucatello et al. 2005; Beers & Christlieb 2005; Bisterzo et al. 2010; Lugaro et al. 2012; Starkenburg et al. 2014; Hansen, T. T. et al. 2016; Hampel et al. 2016). Therefore, the predictions of our chemical evolution models at low [Fe/H] solely provide a baseline for the average fluorine abundances at birth in CEMP-s red giants before mass transfer took place. We also include fluorine measurements as obtained in two stars of the Carina dSph galaxy by Abia et al. (2015). These measurements were obtained from spectra taken using the Phoenix infrared high-resolution spectrograph by Abia et al. (2011) and reanalysed by using the spectral synthesis code Terbospectrum by Abia et al. (2015). The formation of Carina occurred with low star formation efficiencies and a short infall timescale (e.g. Lanfranchi et al. 2006, Vincenzo et al. 2014), as did the Milky Way halo. Therefore, observations in Carina dSph have been included in this work in order to further our understanding of how fluorine might behave at low metallicity in general. However, since these stars are not Milky Way stars we must be careful as they are not directly comparable with the chemical evolution models presented in this work or the other observations. The chemical evolution of fluorine in Carina will be the subject of future work.

3 GALACTIC CHEMICAL EVOLUTION MODEL

We have used the chemical evolution code OMEGA+ (Côté et al. 2018). This is a two-zone model where a central star forming region is modelled using the code OMEGA (Côté et al. 2017), which simulates the evolution of several physical and chemical properties within a cold gas reservoir, surrounded by a non-star forming hot gas reservoir. The latter is considered as the circumgalactic medium (CGM) in our model.

We can follow both the evolution of the CGM and the internal star forming galaxy. The evolution of the mass of the gas in the CGM ($M_{\text{CGM}}$) is as follows:

$$M_{\text{CGM}}(t) = M_{\text{CGM,in}}(t) + M_{\text{outflow}}(t) - M_{\text{inflow}}(t) - M_{\text{CGM, out}}(t)$$

where $M_{\text{CGM,in}}$ is the inflow rate from the external intergalactic medium into the CGM, $M_{\text{outflow}}$ is the mass removed from the central galaxy and added to the CGM via outflow, $M_{\text{inflow}}$ is the gas which flows into the galaxy from the CGM and $M_{\text{CGM, out}}$ is the outflow rate of gas from the CGM into the intergalactic medium. The intergalactic medium represents the space outside the CGM and is defined as a sphere with radius equal to the virial radius of the dark matter halo that hosts the central galaxy. The mass of the CGM tends to increase if the mass of the dark matter halo also increases, as $M_{\text{CGM,in}}$ can reach higher values due to a larger availability of gas in the environment; conversely, the CGM mass will decrease when the mass of the dark matter halo decreases, as gas can more efficiently leave the CGM, giving rise to higher values of $M_{\text{CGM, out}}$. We can also decrease the mass of the gas in the CGM, even if the dark matter mass stays constant, by allowing the CGM to have large scale outflows. Details of all of these terms can be found in Côté et al. (2018, 2019) and references therein (see fig. 7 of Côté et al. (2018) for a visual representation of the workings of OMEGA+).

The evolution of the galactic gas mass $M_{\text{gas}}$ is defined as (Tinsley 1980; Pagel 1997; Matteucci 2012):

$$M_{\text{gas}}(t) = M_{\text{inflow}}(t) + M_{\text{ej}}(t) - M_{\text{*}}(t) - M_{\text{outflow}}(t)$$

where $M_{\text{inflow}}$ is the mass added by galactic inflows from the CGM, $M_{\text{ej}}$ is the mass added by stellar ejecta, $M_{\text{*}}$ is the mass locked away by star formation and $M_{\text{outflow}}$ is the mass lost by outflows into the CGM. This equation is used at each timestep to track the evolution of the galaxy across 13 Gyr.

The infall prescription of gas from the CGM into the galaxy we use here is a dual infall model based on Chiappini et al. (1997). It

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1 OMEGA+ is available online as part of the JINAPyCEE package https://github.com/becot85/JINAPyCEE
2 OMEGA is available online as part of the NuPyCEE package https://github.com/NuGrid/NUPYCEE
combines two episodes of exponential gas inflow and is described as follows:

\[
M_{\text{inflow}}(t) = A_1 \exp \left( \frac{-t}{\tau_1} \right) + A_2 \exp \left( \frac{t_{\text{max}} - t}{\tau_2} \right).
\]  

(3)

Where \( A_1 \), \( A_2 \), \( \tau_1 \), \( \tau_2 \), and \( t_{\text{max}} \) are free parameters, the values for which can be found in Table 1. \( A_1 \) and \( A_2 \) represent the normalisation of the first and second infall events, respectively, \( \tau_1 \) and \( \tau_2 \) are the timescales for mass accretion for the first and second infall, and \( t_{\text{max}} \) is the time of maximum contribution of the second gas accretion episode, which is zero for the first episode.

The star formation rate is defined as

\[
\dot{M}_* = \frac{\epsilon_* M_{\text{gas}}(t)}{\tau_*}
\]  

(4)

where \( \epsilon_* \) and \( \tau_* \) are the dimensionless star formation efficiency (sfe) and star formation timescale, respectively. The outflow rate is proportional to the star formation rate and is defined as

\[
\dot{M}_{\text{outflow}}(t) = \eta \dot{M}_*(t)
\]  

(5)

where \( \eta \) is the mass loading factor and controls the strength of the outflows. The values for \( \epsilon_* \), \( \tau_* \) and \( \eta \) can also be found in Table 1.

To calculate the mass of gas added by stellar ejecta, the contribution of every stellar population formed by time \( t \) is summed so that

\[
M_{\text{ej}}(t) = \sum_j M_{\text{ej}}^j (M_j, Z_j, t - t_j)
\]  

(6)

where \( M_{\text{ej}}^j \) is the mass ejected by the \( j \)th stellar population, \( M_j \) is the initial mass of the population, \( Z_j \) is the initial metallicity of the population and \( t - t_j \) is the age of the \( j \)th population at time \( t \). The simple stellar populations (SSPs) are created at every timestep using SYGMA (Stellar Yields for Galactic Modelling Applications) (Ritter et al. 2018a). An SSP is defined as a population of stars with the same age and chemical composition, with the number of each type of star in the different evolutionary stages being weighted by an initial mass function (IMF). In this work we adopt the IMF of Kroupa (2001). SYGMA includes ejecta from low and intermediate mass stars, massive stars, Type Ia Supernovae (SNe Ia), neutron star mergers and additional sources can also be added manually by the user. The ejecta from the SSPs are then instantaneously and uniformly mixed into the gas reservoir.

SNe Ia are modelled by assuming a power-law delay-time distribution (DTD) similar to that of Maoz & Manucci (2012, see also Freundlich & Maoz 2021; Wiseman et al. 2021) in the form \( t^{-\beta} \) with \( \beta = 1 \). The minimum delay time of SNe Ia is set by the lifetime of intermediate-mass stars used in the galactic chemical evolution (GCE) calculation. For every SSP, at any time \( t \), the DTD is multiplied by the fraction of progenitor white dwarfs \( \left( f_{\text{WD}}(t) \right) \) originating from stars in the mass range of 3 to 8 \( M_\odot \) (see Ritter et al. 2018a for more details). \( f_{\text{WD}}(t) \) smoothly evolves from 0 to 1 when the age of the SSP transits from the lifetime of a 8 \( M_\odot \) star to the lifetime of a 3 \( M_\odot \) star. The temporal evolution of the rate of SNe Ia is normalized such that \( 10^{-3} \) SN occurs per units of solar mass formed (see Table 5 in Côté et al. 2016 for references). We use the solar abundances of Asplund et al. (2009) throughout, where the \( ^{19}\text{F} \) solar abundance is \( \log(\epsilon(\text{F})) = 4.56 \pm 0.30 \).

3.1 Stellar Yields

Nine combinations of yields have been used throughout this work and are laid out in Table 2. We explore the following options for our AGB yields: (i) the FULL-Network Repository of Updated Isotopic Tables

| Parameter | Value |
|-----------|-------|
| \( A_1 \) [M\(_\odot\) yr\(^{-1}\)] | 46 |
| \( A_2 \) [M\(_\odot\) yr\(^{-1}\)] | 5.9 |
| \( \tau_1 \) [Gyr] | 0.8 |
| \( \tau_2 \) [Gyr] | 7.0 |
| \( t_{\text{max}} \) [Gyr] | 1.0 |
| \( \epsilon_* \) | 0.23 |
| \( \tau_* \) [Gyr] | 1.0 |
| \( \eta \) | 0.52 |

(iii) The yields of Nomoto et al. (2013, see also Kobayashi et al. 2006, 2011b, and Kobayashi et al. 2020) which do not include rotation; all of these options will be explored in this work. For each rotational velocity, Limongi & Chieffi (2018) developed models that varies as a function of [Fe/H] will also be explored in this work. For all models we use the W7 SNII yields of Iwamoto et al. (1999).

Of these yield sets, we mainly consider the FRUITY AGB yields because they cover a large range of masses and metallicities. The code used to calculate these yields is also coupled to a full nuclear network up to the termination point of the s-process, therefore it considers the full range of isotopes and reactions relevant to this work. For massive stars, we mainly use the yields of Limongi & Chieffi (2018) in order to investigate the impact of rotation. Finally, for all models we use the W7 SNII yields of Iwamoto et al. (1999).
The two models which include massive stars with no rotation (CLC000 and CNom) show an increasing trend in $[\text{F/Fe}]$ at higher metallicity observations in the red giant sample of Lucatello et al. (2011, brown square symbols represent stars classified as CEMP-s whereas brown crosses are CEMP-no stars, the carbon normal star is represented by a brown point) and Abia et al. (2015, pink squares with error bars). We remind the readers that our models predict the evolution of the chemical abundances in the interstellar medium (ISM), hence how the birth abundances of stars change with time throughout the evolution of the Galaxy.

The two models which include massive stars with no rotation (CLC000 and CNom) show an increasing trend in $[\text{F/Fe}]$ at higher metallicities that is in line with observations. However, these two models lie below the observed abundances. We note that, in the low metallicity regime from $-3.5 < [\text{Fe/H}] < -2$, the observational data are upper limits rather than absolute measurements, along with the high dispersion of the observational data in this metallicity range, which prevents us from drawing strong conclusions in this regime. The strongest constraint on our chemical evolution models is provided by observations in the metallicity range $-0.7 < [\text{Fe/H}] < 0.4$. We can still draw conclusions in the range $-2 < [\text{Fe/H}] < -0.7$ but we are limited by poor statistics. All models with rotating massive stars included cut through the middle of the upper limits, with the majority of the brown points sitting above the chemical evolution trend lines. This is important because we know that an upper limit means the value quoted has the potential to be lower than what is measured. We also see that the models including rotating massive stars are consistent with the bulk of the high-metallicity data. We note that models with higher $v_{\text{rot}}$ can reach increasingly higher $[\text{F/Fe}]$ ratios at high metallicity. Nonetheless, no model with high $v_{\text{rot}}$ reproduces the upward trend seen in observations at high $[\text{Fe/H}]$, which is only seen in the models with $v_{\text{rot}} = 0$.

Fig. 1b shows the abundance trend of $[\text{F/O}]$ versus $[\text{O/H}]$ for the same set of models as in Fig. 1a. These ratios are commonly plotted together when studying the chemical evolution of fluorine to trace the impact of the chemical enrichment from massive stars with minimal connection to the choice of the location of the mass cut in the massive star models. Looking at chemical evolution trends relative to oxygen is also useful because they do not include the uncertainties associated with SN1a models. In Fig. 1b the trajectories are again compared with observations from Ryde et al. (2020) and Lucatello et al. (2011). Again, some observations provide better constraints for our GCE models than others, with those at $[\text{O/H}] > 0.4$ providing the strongest constraint. We can see that all models which include any sort of prescription for rotation in massive stars cut through the low metallicity observations, including VenLCmix. Further discussion of this model can be found later in the section. Of the two models that do not include rotating massive stars (CLC000 and CNom), only CLC000 reproduces the abundance trends of the high metallicity observations.

In Figs 1a and 1b we also investigate the impact of different AGB stellar yields on the chemical enrichment of fluorine. Our model with the FRUITY stellar yields for AGB stars (CLCmix) predicts similar abundance trends as the models with the Monash stellar yields (Mon18LCmix and MonLCmix). The model with the AGB stellar yields of Ventura et al. (2013, 2014, 2018) (VenLCmix) predict higher final fluorine abundances in both Figs 1a and 1b compared to the FRUITY and Monash yields but they still lie within the high metallicity observations.

The AGB stellar yields of Ventura et al. (2013, 2014, 2018) were the reference set adopted by Grisoni et al. (2020) in their ‘parallel’ chemical evolution model for the Solar Neighbourhood. However, when comparing our results with those in fig. 1 of Grisoni et al. (2020), we caution the readers that we assume a different IMF and DTD for SNe Ia. In particular, Grisoni et al. (2020) assumed the IMF of Kroupa et al. (1993), which hosts much lower numbers of massive stars than the IMF of Kroupa (2001) which we use in our models (see also Vincenzo et al. 2016 for more details); secondly, while Grisoni et al. (2020) assumed the SN Ia single-degenerate model of Matteucci & Recchi (2001), here we assume a power-law DTD which is motivated by recent observational surveys (Maoz & Mannucci 2012, see also Wiseman et al. 2021 for an observational perspective, and Vincenzo et al. 2017 for the impact of those two different DTDs on elemental abundance trends).

When we consider the $[\text{F/Fe}]$ versus $[\text{Fe/H}]$ abundance diagram (Fig. 2a), our models with $v_{\text{rot}} = 0$ (VenLC000) predicts $[\text{F/Fe}]$ ratios that are always $\approx 0.5$ dex higher than model Thin-V000 of Grisoni et al. (2020). Our models with $v_{\text{rot}} = 150$ and $300 \text{ km s}^{-1}$ (VenLC150 and VenLC300, respectively), instead, always lie below models Thin-V150 and Thin-V300 of Grisoni et al. (2020) for iron abundances between $-1.5 < [\text{Fe/H}] < -0.5$ but then move above them as metallicity increases. It is difficult to compare models with variable $v_{\text{rot}}$ because we follow different prescriptions. We recall that Grisoni et al. (2020) chose the prescription of Romano et al. (2019) with a sharp transition from $v_{\text{rot}} = 300 \text{ km s}^{-1}$ to $v_{\text{rot}} = 0 \text{ km s}^{-1}$ at $[\text{Fe/H}] = -1$ dex, whereas our model uses a prescription from Prantzos et al. (2018) which employs a more gradual change to lower rotational velocities as the metallicity increases. The mix of rotational velocities adopted in the present work (VenLCmix) follows the observational trends much more closely than Thin-Viar of Grisoni et al. (2020).
When we consider the [F/O] versus [O/H] abundance diagram (Fig. 2b), our models with \(v_{\text{rot}} = 0 \text{ km s}^{-1}\) always lie above model Thin-V000 of Grisoni et al. (2020), being separated by a constant offset of \(\approx 0.2\) dex. Our model Thin-LC150 appears to sit lower than Thin-V150 of Grisoni et al. (2020) for [Fe/H] \(\leq 0\) dex. Interestingly, the models with \(v_{\text{rot}} \approx 300 \text{ km s}^{-1}\) follow a very similar shape in both this work and Grisoni et al. (2020). However, our model always lies below Thin-V300 of Grisoni et al. (2020), being separated by an offset of \(\approx 0.3\) dex. Our model with a rotational mix (Thin-LCmix) can reproduce the observations at high metallicity more closely than the Thin-VV4 of Grisoni et al. (2020). However, we remind the reader once again that each of our models employs a different prescription for rotational mixing.

In summary, this discussion shows how careful we must be when we make chemical evolution models, and it further highlights the uncertainties we have in trying to best model the Milky Way.

4.1 Fluorine and s-process elements

The interplay between fluorine and s-process elements has been previously commented on in the literature (e.g. Lucatello et al. 2011, Abia et al. 2011, 2015, 2019). Fluorine and s-process elements can be made together both in AGB stars and massive stars, especially when mixing is enhanced by rotation.

In massive stars, fluorine nucleosynthesis takes place in the helium convective shell via a series of reactions involving \(\alpha\)-captures and proton captures. s-process elements in massive stars are synthesised via neutron captures, with the neutrons primarily coming from the \(^{22}\text{Ne} (\alpha, n) ^{25}\text{Mg}\) reaction. \(^{22}\text{Ne}\) is synthesised from \(^{14}\text{N}\) produced in the convective H-burning shell and brought into the He-burning core. Once in the core, two convective \(\alpha\)-captures starting from \(^{14}\text{N}\) produce \(^{22}\text{Ne}\). This process continues into the carbon burning phase (see Pignatari et al. 2010; Prantzos et al. 2018 for more details).

In massive star models without rotation, we might expect to see s-process production up to the so-called ‘first-peak’ i.e. Sr, Y, Zr (e.g. Limongi & Chieffi 2003). However, Frischknecht et al. (2012) showed that the efficiency of the mixing processes described above can be greatly enhanced within rapidly rotating massive stars, leading to s-process production beyond the first peak.

In AGB stars, both fluorine and s-process elements are made during thermal pulses. Fluorine is made via a series of neutron, proton and \(\alpha\) captures that use \(^{14}\text{N}\) as the seed nucleus. s-process elements are made via neutron captures in the intershell region of the star (e.g. Busso et al. 1999). The primary neutron source here is the \(^{13}\text{C} (\alpha, n) ^{16}\text{O}\) reaction. Given the similar production sites of fluorine and s-process elements, it seems likely that where we find one we would likely find the other. This means there is a potential correlation between fluorine and s-process elements that needs to be explored.

Fig. 3 shows the [s/Fe] versus [Fe/H] abundance trend for the models CLCmix, CLC000, CLC150, CLC300, CNom, Mon18LCmix and MonLCmix, that are specified in Table 2. The models with the AGB yields of Ventura et al. (2013), the first set of Monash AGB yields (Mon.1), and the massive star yields of Nomoto et al. (2013) are not shown because they do not include heavy element abundances. In Figs 3 and 4, ‘s’ denotes the average s-process abundance for each of the models, where [s/Fe] is defined as follows (Abia et al. 2002):

\[
[s/Fe] = ([\text{Sr}/\text{Fe}] + [\text{Y}/\text{Fe}] + [\text{Zr}/\text{Fe}] + [\text{Nb}/\text{Fe}] + [\text{Ba}/\text{Fe}] + [\text{La}/\text{Fe}] + [\text{Ce}/\text{Fe}] + [\text{Pr}/\text{Fe}])/8.
\]

If we focus on the very low-metallicity regime, the only models that can reproduce the high upper limits on [s/Fe] are those which include massive stars with \(v_{\text{rot}} = 300 \text{ km s}^{-1}\). In the domain -2.5 < [Fe/H] < -1 the models CLC300 and MonLC300 underestimate the observations. These models also severely overestimate [s/Fe] at high metallicity, disagreeing with the observations of Ryde et al. (2020). We note that a similar mismatch was also seen by Vincenzo et al. (2021) when comparing their models with the Limongi & Chieffi (2018) rotating massive star yields to the stellar abundance measurements of neutron-capture elements from the second data release of the GALactic Archaeology with HERMES (GALAH) survey (Buder et al. 2018). The rest of the models (those with a minor or absent contribution from stars with \(v_{\text{rot}} = 300 \text{ km s}^{-1}\)) provide a better explanation for the high metallicity observations, with CLCmix and CLC150 reproducing the plateau in the data up to solar metallicity.
Fig. 2. Panel a: [F/Fe] versus [Fe/H] for the Ventura et al. (2013, 2014, 2018) AGB yields in combination with each rotational prescription of the Limongi & Chieffi (2018) massive stars, compared with the same observational data as Fig. 1a. Panel b: same as the Fig. 2a but for [F/O] versus [O/H].

Fig. 3. [s/Fe] versus [Fe/H] for models CLCmix, CLC000, CLC150, CLC300, MonLCmix and MonLC300. The observational data is the same as Fig. 1a.

Fig. 4. [F/s] versus [Fe/H] for models CLCmix, CLC000, CLC150, CLC300, MonLCmix and MonLC300. The observational data is the same as Fig. 1a.

Fig. 4 shows [F/s] versus [Fe/H] for the same models as Fig. 3. By investigating this ratio we can continue to probe the chemical evolution of fluorine. For comparison, Fig. 5 shows [F/Ba] versus [Fe/H] for the same set of models. Since there is minimal change in the trajectory of the chemical evolution trends between [F/s] in Fig. 4 and [F/Ba] in Fig. 5, we can safely use the average s-process abundances for comparison with stellar observations by including a variety of s-process elements without loss of important information from tracking elements individually.

In the low metallicity regime (-3.4 < [Fe/H] < -2.3), the abundance of F and s-process elements for the CEMP stars in the figure has likely arisen due to accretion of material from an AGB companion (e.g. Busso et al. 2001, Sneden et al. 2008, Lucatello et al. 2011, Mura-Guzmán et al. 2020). Coupled with the fact that most of the observations in this region are upper limits, we cannot use these observations to constrain the GCE models. That being said, it is noteworthy that two scenarios seem to provide similar predictions for [F/s] in Fig. 4: (i) AGB + massive stars with $v_{\text{rot}} = 0$ (CLC000), and (ii) AGB + massive stars with $v_{\text{rot}} = 300$ km s$^{-1}$ (CLC300 and MonLC300). These two scenarios are potentially very different. For stars rotating as quickly as 300 km s$^{-1}$, the fluorine present on the surface will likely have been transported from the interior layers onto the surface due to the strong mixing from rotation. However, internal mixing is not as strong for non-rotating massive stars so there may not be as much fluorine transported from the interior layers to the surface. This could mean some of the surface fluorine is present due to accretion from a companion.

There are two key details in the figures presented in this work that can separate the two potentially different scenarios mentioned above.

(i) In Fig. 4, the solar and super-solar metallicity observations from Ryde et al. (2020) show an upturn in their [F/s] that is only predicted by the models with $v_{\text{rot}} = 300$ km s$^{-1}$.

(ii) In Fig. 1a, model CLC000 is below all the observations, which means that solely including non-rotating massive stars is not enough to reproduce the observed fluorine abundance pattern.
Therefore, even though models this range in more detail. when AGB stars kick in between -1.

Overall, this suggests that we need a contribution from rotating massive stars throughout the evolution of the Galaxy in order to reproduce the observations; in particular, Fig. 4 shows that massive stars with \( v_{\text{rot}} = 300 \text{ km s}^{-1} \) might play a crucial role in the chemical evolution of fluorine, especially when considering the simultaneous production of s-process elements.

Figs. 6 and 7 disentangle the contributions from massive stars, AGB stars and Type Ia SNe to \( ^{19}\text{F}, ^{56}\text{Fe}, ^{16}\text{O}, \) and \( ^{140}\text{Ce} \) as predicted by the model with \( v_{\text{rot}} = 300 \text{ km s}^{-1} \) (CLC300). Here cerium is used as a proxy for the s-process elements. We can see that the massive star model with \( v_{\text{rot}} = 300 \text{ km s}^{-1} \) dominates both \( ^{19}\text{F} \) and \( ^{140}\text{Ce} \) even when AGB stars kick in between -1 < [Fe/H] < 0. Fig. 7 highlights this range in more detail.

By looking at the predictions of model CLC300 in Figs. 6 and 7, both \( ^{19}\text{F} \) and \( ^{140}\text{Ce} \) abundances at [Fe/H] = 0 are higher than solar by a factor of \( \approx 4 \) and \( \approx 6 \), respectively (the black dashed line on each panel corresponds to the solar fluorine and cerium abundances). Therefore, even though models CLC300 and MonLC300 are best at reproducing the observational trends of Fig. 4, the fluorine and average s-process abundances that they generate at solar metallicity are not physical, suggesting that a mix of massive star models with different \( v_{\text{rot}} \) should be assumed. The mix of rotational velocity we might expect will be discussed in the following section.

5 DISCUSSION

At low metallicity, most red giants in the sample of Lucatello et al. (2011) are classified as CEMP-s, hence they likely had their surface fluorine abundances altered by binary mass transfer from an AGB companion. In Figs. 1a - 5 we also show CEMP-no stars, whose origin in the Milky Way halo is less clear. Our model predictions at low metallicity can solely be used as a baseline for the average ISM abundances at the point of birth of the stars, before any binary accretion has occurred, providing an empirical constraint on the degree of fluorine-enhancement for AGB stellar models. There is also a larger spread in the observed chemical abundance patterns at [Fe/H] < -2.5, which indicates a more inhomogeneous ISM at low metallicity, as stars formed out of gas enriched by a smaller number of CCSNe, whereas our models assume that the ISM is well mixed at all times, with the IMF being fully sampled starting from the turn-off mass. An additional source of scatter in the chemical abundances at [Fe/H] < -2.5, which is not included in our models, might be due to the fact that the Milky Way halo comprises several populations of stars that were born in different substructures and were later accreted by our Galaxy. We also note again that the observations in the metallicity range -3.4 < [Fe/H] < -2.3 are upper limits with a lot of dispersion. All this leads to uncertainty in our conclusions at [Fe/H] < -2.

At super-solar metallicity, there is a secondary behaviour of fluorine (Ryde et al. 2020). However, we must be careful about comparing our models to observations at this metallicity for a number of reasons. The first being that we do not have fluorine yields at super-solar metallicity, instead at [Fe/H] > 0 the model copies the yields from the final metallicity until the end of the simulation (when the age of the galaxy is 13 Gyr). Secondly, stars with super-solar metallicity are known to have formed in the inner disk and migrated so their composition is different to that of the local gas (see fig. 10 of Vincenzo & Kobayashi 2020 for an illustration of this). Therefore, the abundances of super-solar metallicity stars cannot be compared with a one-zone model. Though we do not make strong conclusions about the evolution of fluorine above [Fe/H] = 0, these considerations should be kept in mind.

The models using massive stars with initial rotational velocities of 300 km s\(^{-1}\) are the only ones to reproduce both the slight downward trend of [F/s] at low metallicity and upward trend of [F/s] at high metallicities. Therefore, we need a contribution from rapidly rotating massive stars with initial rotational velocities of 300 km s\(^{-1}\) throughout the evolution of the Galaxy in order to match the full abundance pattern. Though models CLC300 and MonLC300 do not match the full abundance trend of the observations in the [F/Fe] versus [Fe/H] space (Fig. 1a), there are many considerations to be made including the fact that the low metallicity observations are upper limits so there is a chance that those observations could sit lower than where they are placed, and we expect fewer massive stars rotating that quickly at higher metallicities (see Meynet & Maeder 1997, Prantzos et al. 2018). Therefore, we should explore the possibility of a mix of initial rotational velocities, where stars with \( v_{\text{rot}} \) in the range 150-300 km s\(^{-1}\) contribute throughout the evolution of the Galaxy. Romano et al. (2019) assumed a sharp transition for massive star rotation where massive stars have \( v_{\text{rot}} \approx 300 \text{ km s}^{-1} \) for [Fe/H] < -1 and, suddenly, \( v_{\text{rot}} = 0 \) for [Fe/H] ≥ -1. This strategy is not appropriate for the situation we have here, as a contribution from models with \( v_{\text{rot}} \) in the range 150-300 km s\(^{-1}\) needs to be assumed even above [Fe/H] = -1. Given we know that at higher metallicities massive stars should rotate more slowly, perhaps a combination of rotational velocities are present at higher metallicities, much like the approach employed by Prantzos et al. (2018).

The mixed-rotation scenario of Prantzos et al. (2018) assumes that rotating massive stars with \( v_{\text{rot}} = 300 \text{ km s}^{-1} \) cease to contribute to the yields at around [Fe/H] ≈ -2, failing to reproduce the observed trend of [F/s] as a function of [Fe/H] (see model CLCmix in Fig. 4). Therefore, a different combination of rotating massive star models needs to be employed, by including a metallicity-dependent contribution from models with \( v_{\text{rot}} = 150 \text{ km s}^{-1} \) and 300 km s\(^{-1}\) up to solar metallicity. Fig. 8 shows the contributions of each rotational velocity to the isotopes \( ^{19}\text{F}, ^{56}\text{Fe}, ^{16}\text{O} \) and \( ^{140}\text{Ce} \) relative to solar for models CLC000, CLC150 and CLC300 at [Fe/H] = 0. Model CLC000 predicts \( X(^{19}\text{F})/X(^{16}\text{O})(^{19}\text{F}) = 0.2 \) and \( X(^{140}\text{Ce})/X(^{16}\text{O})(^{140}\text{Ce}) = 1.5 \), model CLC150 predicts \( X(^{19}\text{F})/X(^{16}\text{O})(^{19}\text{F}) = 1.4 \) and \( X(^{140}\text{Ce})/X(^{16}\text{O})(^{140}\text{Ce}) = 1.2 \) and model CLC300 predicts \( X(^{19}\text{F})/X(^{16}\text{O})(^{19}\text{F}) = 3.7 \) and \( X(^{140}\text{Ce})/X(^{16}\text{O})(^{140}\text{Ce}) = 5.8 \), at [Fe/H] = 0. In order to re-
produce the fluorine solar abundance, we need to achieve \( \frac{X(^{19}F)}{X_\odot(^{19}F)} = 1.0 \). This can be done with a 45% contribution from \( v_{\text{rot}} = 0 \text{ km s}^{-1} \), a 50% contribution from \( v_{\text{rot}} = 150 \text{ km s}^{-1} \) and a 5% contribution from \( v_{\text{rot}} = 300 \text{ km s}^{-1} \). When employing these contributions, we achieve \([F/Fe] = 0.08\), \([F/O] = -0.033\) and \([F/s] = -0.45\). These percentage contributions are our suggestion for a mix of rotational velocities that are successful at reproducing fluorine abundances at solar metallicity. It is difficult to make a suggestion for combinations at other metallicities as we do not have a constraint for the abundances. We must be careful when suggesting a combination of rotational velocities as there are uncertainties in the yields that we must be aware of. Firstly, a change in the implementation of rotation may change the yields of elements affected by rotation. As discussed by Prantzos et al. (2018), another uncertainty associated with the Limongi & Chieffi (2018) yields in particular is the enhancement of fluorine in the 15 M_\odot and 20 M_\odot models with \( v_{\text{rot}} = 150 \text{ km s}^{-1} \). In these models, a smaller He convective shell forms separately to the main He convective shell. When these two shells merge, the base of the new shell is deeper and thus, is exposed to higher temperatures which causes an enhancement in fluorine production. It is pointed out by Prantzos et al. (2018) that is is difficult to know if this scenario is ‘realistic’ given it only affects two of the stellar models. Other uncertainties such as reaction rates and nuclear networks will be discussed later in this work.

It has been proposed that a contribution from novae is needed in order to match the observed behaviour of \([F/O]\) versus \([O/H]\) (e.g. Timmes et al. 1995, Spitoni et al. 2018). The majority of the models in this work (CLCmix, CLC150, CLC300, Mon18 LCmix, and MonLCmix) can reproduce the trends of \([F/O]\) versus \([O/H]\) without including any chemical enrichment of fluorine from novae (see Fig. 1b). Therefore, it could be argued that we no longer need a contribution from novae to understand the chemical evolution of fluorine. That being said, it is important to understand the fluorine yields we might expect from novae and the consequences that could have on our results. It is unclear from the literature both how frequent the occurrence of novae are and the fluorine yields we might get from them. Kawash et al. (2021) suggests a nova rate of \( 30 \text{ yr}^{-1} \) while Shafer (2017) suggests a nova rate of \( 50 \text{ yr}^{-1} \) and recent results from Rector et al. (2022) suggest a rate of \( 40 \text{ yr}^{-1} \), however this result is for M31 rather than the Milky Way. Both Spitoni et al. (2018) and Grisoni et al. (2020) used the nova yields as predicted by Jose & Hernanz (1998), who found that fluorine is only significantly synthesised in their 1.35 M_\odot model, with a maximum yield of \( 5.4 \times 10^{-5} \) M_\odot and a minimum yield of \( 9.9 \times 10^{-7} \) M_\odot. This gives a range of potential \(^{19}F\) nova production rate that varies between \( 2.97 \times 10^{-3} \) M_\odot yr\(^{-1}\) and \( 2.7 \times 10^{-3} \) M_\odot yr\(^{-1}\). The upper bound here is so high due to the significant yield from the 1.35 M_\odot model. This wide range makes the contribution of novae to the galactic fluorine very uncertain. However, we can compare the potential nova yields to the yields we might expect from CCSNe. The CCSNe rate is variable with time in our model with an average rate of \( 0.025 \text{ yr}^{-1} \). The minimum \(^{19}F\) yield from the Limongi & Chieffi (2018) massive star yields with \( v_{\text{rot}} = 300 \text{ km s}^{-1} \) is \( 1.027 \times 10^{-5} \) M_\odot and the maximum is \( 1.025 \times 10^{-5} \) M_\odot.

Figure 6. The contribution of each stellar source relative to solar for model CLC300 at metallicities \([Fe/H] = -2\) (top left), \([Fe/H] = -1\) (top right), \([Fe/H] = 0\) (bottom left) and \([Fe/H] = 0.3\) (bottom right - present). The contribution from massive stars is show in orange, AGB stars in blue and SNe 1a in grey.
10$^{-3}$ M$_\odot$. This yields a potential range of $^{19}$F production rate from CCSNe between $2.57\times10^{-7}$ M$_\odot$ yr$^{-1}$ and $2.56\times10^{-5}$ M$_\odot$ yr$^{-1}$. This range is lower than that of the potential nova yields. However, we must be aware that only the 1.35 M$_\odot$ nova model is enhanced in fluorine, so there is the potential for the range of fluorine yield from novae to be lowered given that the enhancement only occurs at this one particular mass. Starrfield et al. (2020) looked at $^{19}$F ejecta from novae for a 1.35 M$_\odot$ star and found a range of $6.3\times10^{-11}$ M$_\odot$ to $1.0\times10^{-6}$ M$_\odot$, again demonstrating how uncertain fluorine yields from novae can be. Overall, we recognise that novae may indeed contribute to the galactic fluorine, though the yields are highly uncertain and several critical assumptions need to be made to include them in chemical evolution models, however, they are not required to reproduce the observational abundance patterns in this work.

5.1 Wolf-Rayet stars as a significant source of fluorine?

When massive stars rotate, they can, even if only for a brief period, enter into a Wolf-Rayet phase. Given that WR winds have been suggested as a dominant contributor to the chemical evolution of fluorine (Meynet & Arnould 2000, Renda et al. 2004), it is important to disentangle what portion of the rotating massive star yields comes from WR winds and what portion comes from the CCSN at the end of their evolution.

Meynet & Arnould (2000) found that WR stars could contribute significantly to the galactic fluorine content by calculating a series of WR yields and incorporating them in a chemical evolution model for the Milky Way. They found that the $^{19}$F wind yield of a 60 M$_\odot$ model could be a factor of 10-70 times higher than the initial stellar content of $^{19}$F. These fluorine yields were subsequently used in the chemical evolution study of Renda et al. (2004), who explored three different scenarios for the nucleosynthesis of fluorine by using the chemical evolution code GEtool (Fenner & Gibson 2003, Gibson et al. 2003). The first scenario explored by Renda et al. (2004) used solely yields from CCSNe, the second CCSNe and WR stars, and the third used CCSNe, WR and AGB stars. Renda et al. (2004) concluded that, while AGB stars dominate fluorine production at low metallicity, WR stars are the dominant source of fluorine at solar and super-solar metallicities (see their fig. 4). In the years since, many more massive star models have been created which include WR yields. This begs the question, do any of these studies find $^{19}$F yields as high as those found by Meynet & Arnould (2000)?

Fig. 9 shows a comparison of massive star wind yields from a variety of studies over the last couple of decades. The yields that are compared in the figure are from Limongi & Chieffi (2018), Ritter et al. (2018b), Brinkman et al. (2021); Brinkman (2022), Meynet & Arnould (2000), Ekström et al. (2012) and Sukhbold et al. (2016). Here, we look at non-rotating stars at solar metallicity in order to gain the widest comparison and to be able to compare with the non-rotating yields of Meynet & Arnould (2000). We can see that all considered wind yields sit at least 1 dex below the the Meynet & Arnould (2000) yields. This suggests that perhaps the Meynet & Arnould model is overestimating the fluorine production from WR stars.

**Figure 7.** The contribution to each isotope from each stellar source relative to solar for model CLC300 at metallicities [Fe/H] = -0.8 (top left), [Fe/H] = -0.6 (top right), [Fe/H] = -0.4 (bottom left) and [Fe/H] = -0.2 (bottom right - present). The contribution from massive stars is show in orange, AGB stars in blue and SNe Ia in grey.
Figure 8. The contribution to each isotope from each stellar source relative to solar at [Fe/H] = 0 for models CLC000 (top left), CLC150 (top right) and CLC300 (bottom). The contribution from massive stars is show in orange, AGB stars in blue and SNe 1a in grey.

Figure 9. Non-rotating, solar metallicity wind yields from a range of studies over the last two decades. LC = Limongi & Chieffi (2018), Ritter = Ritter et al. (2018b), Brinkman = Brinkman et al. (2021); Brinkman (2022), M&A = Meynet & Arnould (2000), Ekström = Ekström et al. (2012), Sukhbold = Sukhbold et al. (2016).

Arnould (2000). $^{19}$F wind yields are unusually high compared to subsequent models. Therefore, there is potential that we may be able...

Figure 10. IMF weighted fluorine yield as a function of metallicity ([Fe/H]) for each rotational velocity prescription. The total yields are shown by a full line and darker colour while the wind yields are represented by dotted lines and lighter colours.

to rule out WR stars as a dominant contributor to the galactic fluorine budget.

To investigate this further, Fig. 10 shows the IMF-weighted yield versus metallicity for the Limongi & Chieffi (2018) massive star yields used in this work. Here we see a comparison between the...
wind yield and the total ejecta for each rotational velocity. At low metallicity, the wind yields sit 4.6 dex lower than the total ejecta for the rotating models and around 2 dex lower for the non-rotating model. At higher metallicities, the gap between wind contribution and total ejecta reduces due to enhanced mass loss, with the wind yields being around 2 dex lower than the total ejecta for the model rotating at 300 km s\(^{-1}\) and 1 dex lower for the model rotating at 150 km s\(^{-1}\). For the non-rotating model, the yields are almost identical at high metallicity.

We conclude that we need a large contribution from rapidly rotating massive stars in order to reproduce observations of fluorine in the Milky Way across the whole metallicity range. For \(v_{\text{rot}} = 300\) km s\(^{-1}\), wind yields contribute a factor of around \(10^{-2}\) less fluorine at high metallicities ([Fe/H] \(\geq 0\)) and a factor of around \(10^{-5}\) less fluorine at the lowest metallicity ([Fe/H] = -3) than the explosive yield, for \(v_{\text{rot}} = 150\) km s\(^{-1}\) wind yields contribute a factor of around \(10^{-3}\) less fluorine at high metallicities and a factor of around \(10^{-6}\) less fluorine at the lowest metallicity. We can, therefore, rule out Wolf-Rayet stars as a dominant source of fluorine. Being able to draw such conclusions is vital in untangling the web of possibilities for the origin and chemical evolution of fluorine.

### 5.2 Sources of Uncertainty in GCE

Like for any physical model, it is important to consider that there can be significant uncertainties concerning galactic chemical evolution (GCE) studies (e.g., Romano et al. 2005, 2010). For example, each choice for the parameters in Table 1 can affect the behaviour of the chemical evolution models. Côté et al. (2016) explored some sources of GCE uncertainty, including: the IMF, DTD and number of SNe Ia, current stellar mass and star formation history.

We briefly explored the effect of changing both the IMF and the star formation efficiency of the models on our results. We found that:

(i) using a Kroupa et al. (1993) IMF rather than Kroupa (2001) does not drastically change the results of the chemical evolution trends. Using the Kroupa et al. (1993) IMF produces more fluorine at lower metallicities which can produce a slightly better fit for [F/Fe] versus [Fe/H] trends but provides an overproduction of [F/O] as a function of [O/H] for the models which use the Limongi & Chieffi (2018) yields. However, a better fit to the observations is achieved by the model including the massive star yields of Nomoto et al. (2013).

(ii) using a higher star formation efficiency naturally exhausts the available gas more quickly, and thus does not produce as much fluorine at higher metallicities whereas a lower star formation efficiency sees a late increase in [F/Fe]. However, the shape of the chemical evolution trend is not significantly affected.

Another major source of uncertainty in GCE studies are the yield sets used (see, e.g., Gibson 1997; Mollá et al. 2015). Each author will use a different code for stellar modelling which will in turn use a different reaction network. A reaction network specifies the reactions that will occur in a model and the rates at which such reactions will occur. Different modelling choices made by each author produce a layered effect when it comes to the uncertainty provided by stellar yields in chemical evolution modelling.

To better understand reaction rate uncertainties in the context of this work, we will look at the two reactions that can destroy fluorine: \(^{19}\text{F}(\alpha, p)^{22}\text{Ne}\) and \(^{19}\text{F}(p, \alpha)^{16}\text{O}\).

(i) The most recent work on \(^{19}\text{F}(p, \alpha)^{16}\text{O}\) was performed by Zhang et al. (2021b). By reanalysing experimental data, they found drastically different \(^{19}\text{F}(p, \alpha)^{16}\text{O}\) rates than those recommended by the Nuclear Astrophysics Compilation of Reaction Rate (NACRE) (Angulo et al. 1999). They found rates larger by factors of 36.4, 2.3 and 1.7 for temperatures 0.01, 0.05 and 0.1 GK respectively. This increased rate naturally leads to the destruction of \(^{19}\text{F}\) on a scale larger than previously thought. By performing a network calculation at solar metallicity with their recommended new rate for the reaction, the value of \(^{19}\text{F}\) decreased by an order of magnitude. This reaction was directly measured by Zhang et al. (2021a) using the Jinping Underground Nuclear Astrophysics (IUNA) experimental facility. Though the rate they found was 0.2-1.3 times lower than that of their theoretical prediction (Zhang et al. 2021b), it is still significantly higher than the accepted rate of Spyrou et al. (2000). Therefore, we will still expect a larger depletion of fluorine at solar metallicity using this reaction rate.

(ii) The most recent work to study \(^{19}\text{F}(\alpha, p)^{22}\text{Ne}\) is Palmieri et al. (2019), who focused on the role that this reaction takes in AGN stars in particular. They found that during thermal pulses, \(^{19}\text{F}\) can be easily destroyed by \(\alpha\)-captures; in particular for a 5 M\(_\odot\) AGN star \(^{19}\text{F}\) can be destroyed by a factor of 4.

These new discoveries related to the reactions that destroy fluorine could have implications for this work. If indeed, the destruction of fluorine is more enhanced in AGN stars than previously thought, the chemical evolution of fluorine at higher metallicities could be affected. The point at which AGN stars begins to be significant is model dependent. For model CLC300, Fig. 6 shows us that AGN stars begin to be significant in the production of fluorine around solar metallicity. Therefore, we might expect that the [F/Fe], [F/O] and [F/O] ratios studied in this work decrease from [Fe/H] = 0. Whether these reaction rates will also have a significant impact in the destruction of fluorine in rotating massive stars remains to be seen.

Uncertainties around reaction rates are a large source of uncertainty in stellar modelling and the yields we retrieve from those models. All this must be kept in mind when studying galactic chemical evolution. Especially given how uncertain each source’s contribution to the galactic fluorine is, uncertainties around reaction rates add another piece to this complex puzzle.

### 6 CONCLUSIONS

We have studied the chemical evolution of fluorine in the Milky Way. We have used a range of yield sets to try to understand the dominant contributor to the galactic fluorine budget. In order to do this we compared our chemical evolution models to abundance determinations across a wide range of metallicities. The main conclusions of this work are as follows:

(i) We investigated many combinations of yields with different prescriptions for the rotation of massive stars. Though we are limited by upper limits and poor statistics in the low metallicity regime, we found that in order to reproduce fluorine abundances across the whole metallicity range (-3.4 < [Fe/H] < 0.4), we need a contribution from rapidly rotating massive stars with initial rotational velocities as high as 300 kms\(^{-1}\). We agree with the results of Prantzos et al. (2018) and Grisoni et al. (2020) that rotating massive stars play a crucial role in the fluorine production up to solar metallicities. We also suggest a combination of initial rotational velocities which can reproduce solar abundances.

(ii) We have investigated the contribution of massive star and WR winds to the galactic fluorine budget. We compared the winds of more recent massive star models to the winds of Meynet & Arnold.
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**DATA AVAILABILITY**

The data generated for this article will be shared on reasonable request to the corresponding author.

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