EVALUATION OF FLUORINE IN THE GALAXY WITH THE $\nu$-PROCESS

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We calculate the evolution of fluorine in the solar neighborhood with the $\nu$-process of core-collapse supernovae, the results of which are in good agreement with the observations of field stars. The $\nu$-process operating in supernovae causes the [F/O] ratio to plateau at [O/H] $\lesssim$ −1.2, followed by a rapid increase toward [O/H] $\sim$ −0.5 from the contribution of Asymptotic Giant Branch stars. The plateau value of [F/O] depends on the neutrino luminosity released by core-collapse supernovae and may be constrained by using future observations of field stars at low metallicities. For globular clusters, the handful of [F/O] measurements suggest that the relative contribution from low-mass supernovae is smaller in these systems than in the field.

Subject headings: Galaxy: abundances — Galaxy: evolution — stars: abundances — stars: AGB and post-AGB — supernovae: general

1. INTRODUCTION

Most of the energy from core-collapse supernovae is released as neutrinos and anti-neutrinos (\(\gtrsim 10^{53}\) erg). However, the interaction of the neutrinos with matter and the effects on the nucleosynthesis have only been discussed for a few models (e.g., Woosley et al. 1990, Woosley & Weaver 1995, Yoshida et al. 2004, Heger et al. 2005, Yoshida et al. 2008, Nakamura et al. 2010). The $\nu$-process does not affect the yields of major elements such as Fe and $\alpha$ elements, but it will increase those of some elements such as B, F, K, Sc, V, Mn, and Ti.

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the cases of supernovae (SNe, the explosion energy of \( E = 10^{51} \) erg) and hypernovae (HNe, \( E > 10^{51} \) erg). The neutrino luminosity is assumed to be uniformly partitioned among the neutrino flavors, and is assumed to decrease exponentially in time with a timescale of 3 sec (Woosley et al. 1990). The total neutrino energy is given by a free parameter and in this paper we present two cases with \( E_\nu = 3 \times 10^{53} \) erg, which corresponds to the gravitational binding energy of a 1.4\( M_\odot \) neutron star (Lattimer & Prakash 2001), and \( 9 \times 10^{53} \) erg as the maximum possible effect of the \( \nu \)-process. The neutrino energy spectra are assumed to be Fermi-Dirac distributions with zero chemical potentials. The temperatures of \( \nu_\mu, \nu_\tau \) and \( \bar{\nu}_e, \bar{\nu}_\mu \) are set to be \( T_\nu = 6 \) MeV/k and \( 4 \) MeV/k, respectively (Rauscher et al. 2002). Note that the \( \nu \)-cross sections contain some uncertainties (Heger et al. 2003).

In a supernova, neutrinos interact with heavy elements through neutral-current reactions, and scatter off nuclei in or near their ground state, which lead to the excitation of particle unbound states that decay by neutron, proton, or \( \alpha \) emission:

\[
(Z, A) + \nu \rightarrow (Z, A)^* + \nu' \rightarrow (Z, A - 1) + n + \nu' \quad (1)
\]

\[
\rightarrow (Z - 1, A - 1) + p + \nu'(2)
\]

\[
\rightarrow (Z - 2, A - 4) + \alpha + \nu'(3)
\]

Charged-current reactions of \( \nu_e \) or \( \bar{\nu}_e \) with heavy nuclei also play a role in producing new elements. These reactions correspond to the inverse processes of electron or positron captures. The new products in excited states emit \( \gamma \)-rays, neutron, proton, or \( \alpha \) particles to decay to the ground state. The capture reactions of the protons and neutrons produced though these neutrino reactions also enhance the abundances of some elements. For most nuclei, neutral-current reactions are dominant because of the contribution from all flavors of neutrinos and higher temperature of \( \nu_\mu, \tau \) and \( \bar{\nu}_e \) than that of \( \nu_e \) and \( \bar{\nu}_e \).

We calculate the nucleosynthesis of core-collapse supernovae with progenitor masses of \( M = 15, 25 \), and \( 50 M_\odot \) and initial metallicities of \( Z = 0, 0.004, \) and \( 0.02 \) for SNe and HNe. The nuclear network includes 809 species up to \( ^{121} \)Pd (Izutani et al. 2009; Izutani & Umeda 2010). The yields are calculated with the same assumptions as in Kobayashi et al. (2006): for SNe, the mass-cut is set to meet the observed iron mass of \( 0.07 M_\odot \). For HNe, the explosion energy is set to be \( 10 \times 10^{51} \) and \( 40 \times 10^{51} \) erg for \( 25 \) and \( 50 M_\odot \), respectively, and the parameters of mixing fallback models are determined to get \( [O/Fe] = 0.5 \). Although there may be diversity in the mixing-fallback process (as in the case of faint supernovae, e.g., Kobayashi et al. 2011a), in this paper we focus on “typical” supernovae that are dominant in the Galactic chemical evolution.

In massive stars \( ^{19} \)F is mainly produced in a convective He shell as a secondary product through \( ^{15} \)N\((\alpha, \gamma)^{19} \)F, where the \( F \) yields are highly dependent on the metallicity. With the \( \nu \)-process \( ^{19} \)F is produced in the O- and Ne-enriched region through \( ^{20} \)Ne\((\nu, \nu'p)^{19} \)F, and the \( F \) yield is increased by a factor of \( \sim 10 \) and 1000 for \( Z = 0.02 \) and \( Z = 0 \), respectively. In the yields, the \( F/O \) ratio is smaller for more massive progenitors because of the larger mantle mass and larger O production, although the mass dependence of \( F/Fe \) is not so large. The \( F/O \) ratio does not strongly depend on the explosion energy, but \( F/Fe \) is smaller for HNe than SNe II because of the larger Fe production of HNe.

3. GALACTIC CHEMICAL EVOLUTION

We adopt the \( \nu \)-process nucleosynthesis yields in the Galactic chemical evolution models. The nucleosynthesis yields of AGB stars (1 – 7\( M_\odot \)) from Karakas (2010) are also included. We adopt the Kroupa initial mass function (IMF) and the same infall and star formation history as in Kobayashi et al. (2011b), which reproduces the observed metallicity distribution function (MDF) in the solar neighborhood.

Figure 1 shows the evolution of [F/O] against [O/H]. Without the AGB yields and the \( \nu \)-process (short-dashed line), the predicted F abundance is too low to meet the observational data at all metallicities. With the AGB yields (long-dashed line), [F/O] shows a rapid increase from \( [O/H] \geq -1.2 \) toward higher metallicities, which corresponds to the timescale of 2 – 4\( M_\odot \) stars in the solar neighborhood. At \( [O/H] \sim 0 \), [F/O] reaches \(-0.14 \), which is 0.26 dex larger than the case without the AGB yields. However, the present [F/O] ratio is still significantly lower than the observations at \( [O/H] \sim 0.0 \). Note that compared to the yields from Karakas & Lattanzio (2007), the F yields from AGB stars in Karakas (2010) were increased by applying the slower \( ^{19} \)F\((\alpha, p)^{22} \)Ne reaction rate (Ugalde et al. 2008). AGB stars may have polluted some Carbon-Enhanced Metal Poor (CEMP) stars with F at low metallicity via binary interactions (Lugaro et al. 2008; Lucatello et al. 2011), or through inhomogeneous enrichment. However, the overall contribution from AGB stars to the chemical evolution of the Galaxy is minimal at \( [Fe/H] \geq -1.5 \).

The timescale of supernovae is much shorter than AGB stars, which means that the [F/O] ratio at low metallicities can be strongly enhanced by the \( \nu \)-process occurring in core-collapse supernovae. With the standard case of \( E_\nu = 3 \times 10^{53} \) erg (solid line), the [F/O] ratio shows a plateau of \( [F/O] \sim -0.4 \) at \( [O/H] \leq -1.2 \), and reaches \( [F/O] +0.19 \) at \( [O/H] > 0.0 \). This is consistent with the observational data of field stars at \( [O/H] < 0 \) (Cunha et al. 2003; Cunha & Smith 2005; Cunha et al. 2008). If we adopt a larger neutrino luminosity of \( E_\nu = 9 \times 10^{53} \) erg (dot-dashed line), [F/O] can be as large as \( +0.37 \) at \( [O/H] \sim 0 \).

In the bulge the star formation timescale is shorter and the average metallicity is higher than the solar neighborhood, but the [F/O] ratio is not so different at \( [O/H] \sim 0 \) (see Fig. 16 in Kobayashi et al. 2011b). The observations for the bulge stars (filled circles) might suggest that the IMF is also different, although the number of observations is too small to make a conclusion.

At \( -1 \lesssim [F/O] \lesssim -0.5 \) the observational data are for stars in globular clusters (GCs), where the star formation and chemical enrichment histories are likely to be different to the solar neighborhood. These GC data seem to be more consistent with the models with the AGB yields only than with the \( \nu \)-process. However, it is unlikely that the existence of the \( \nu \)-process depends on the environment. With the \( \nu \)-process the [F/O] ratio does not vary strongly with metallicity. Thus the differences ob-
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4. CONCLUSIONS AND DISCUSSION

Both the $\nu$-process of core-collapse supernovae and AGB stars play an important role in the production of fluorine. We succeed in reproducing the observed F abundances with our chemical evolution model that includes the $\nu$-process of $E_V = 3 \times 10^{53}$ erg. At low metallicities ($\langle [O/H] \rangle \lesssim -1.2$) F production is dominated by supernovae, and thus future observations of field stars at low-metallicities are important for constraining the neutrino luminosity released from a core-collapse supernova. If the neutrino luminosity is specified, the F abundance along with C could be a good clock in the study of galactic archaeology to distinguish the contribution from AGB stars and supernovae. The F observations of stars in GCs suggest that the star formation and chemical enrichment histories of GCs are different from those of field stars and that low-mass supernova played a smaller role in shaping the chemical evolution of these systems.

The $\nu$-process is also expected to be the producer of other elements such as K, Sc, and V. With $E_V = 9 \times 10^{53}$ erg, $\langle [K,Sc,V] / [Fe] \rangle$ ratios are increased to be closer to the observational data, but such a large improvement is not seen with the standard value of the neutrino luminosity. There are several uncertainties that should be discussed; for K, the NLTE correction in the observations is significant [Kobayashi et al. 2006]. The Sc yields could also be increased by the low-density models that mimic 2D calculations [Umeda & Nomoto 2003]. There are also uncertainties in the reaction rates for V that may affect the nucleosynthesis calculations.

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