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Nuclear Physics A 758 (2005) 324c–327c

NUCLEAR
PHYSICS A

The Evolution of Fluorine in Galactic Systems

A. Renda^{a*}, Y. Fenner^a, B.K. Gibson^a, A.I. Karakas^b, J.C. Lattanzio^c, S. Campbell^c,
A. Chieffi^{a,c,d,e}, K. Cunha^f, V.V. Smith^g

^aCentre for Astrophysics & Supercomputing, Swinburne University,
Hawthorn, Victoria, 3122, Australia

^bInstitute for Computational Astrophysics, Department of Astronomy & Physics,
Saint Mary's University, Halifax, Nova Scotia B3H 3C3, Canada

^cCentre for Stellar & Planetary Astrophysics, School of Mathematical Sciences,
Monash University, Clayton, Victoria 3800, Australia

^dIstituto di Astrofisica Spaziale e Fisica Cosmica (CNR),
Via Fosso del Cavaliere, 00133 Roma, Italia

^eINAF Osservatorio Astronomico di Roma,
Via Frascati 33, 00040 Monteporzio Catone, Italia

^fObservatório Nacional,
Rua General José Cristino 77, 20921 400 São Cristovão, Rio de Janeiro, Brazil

^gDepartment of Physics, University of Texas at El Paso, El Paso, TX 79968, U.S.A.

The main astrophysical factories of fluorine (^{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 ω Centauri.

1. Introduction

The three primary astrophysical factories for fluorine (^{19}F) production have long been thought to be Type II Supernovae (SNe II), Wolf–Rayet (WR) stars, and asymptotic

*We acknowledge the financial support of the Australian Research Council through its Discovery Project and Linkage International schemes, and the Victorian Partnership for Advanced Computing through its Expertise Grant program.

giant branch (AGB) stars (e.g. [18]; [12]; [4], respectively). Previous attempts to model the Galactic production and evolution of ^{19}F have been restricted to the exploration of the role of SNe II alone (e.g. [16]). This limitation has 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.

2. Nucleosynthesis of ^{19}F

The massive star progenitors to SNe II produce fluorine primarily as the result of spallation of ^{20}Ne by μ and τ neutrinos near the collapsed core (e.g. [17]). A fraction of the ^{19}F thus created is destroyed by the subsequent shock but most is returned to the ambient Interstellar Medium (ISM). An additional source of ^{19}F derives from pre-explosive CNO burning in the helium shell. However, fluorine production by neutrino spallation appears the dominant pathway in SNe II, as witnessed by a comparison of the [18] models (which include the neutrino process) with those of [10] (which do not include spallation).

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 $^{19}\text{F}(\alpha, p)^{22}\text{Ne}$. Any earlier synthesised ^{19}F must be removed from the stellar interior in order to avoid destruction. For massive stars to be significant fluorine contributors, 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 [12].

The nucleosynthesis pathways for fluorine production within AGB stars involve both helium burning and combined hydrogen–helium burning phases (e.g. [4]). Uncertainties in the fluorine production in AGB stars come from the adopted reaction rates, especially $^{14}\text{C}(\alpha, \gamma)^{18}\text{O}$ 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 He intershell [11].

3. Model and Yields

In this study we employ **GETool**, our semi-analytical multi-zone chemical evolution package to model a sample Milky Way-like disk galaxy. 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. Within the established dual-infall picture for the chemical evolution of the Milky Way [2], our model is constrained to self-consistently adhere to the observational constraints [5]. We have constructed three Milky Way (MW) model variants that differ only in their respective treatments of ^{19}F production: 1) MWa assumes that SNe II are the only source of ^{19}F (using the [18] yields); 2) MWb adopts yields from massive stars *including* the contribution from their WR phase, the latter from [12]; 3) MWc includes all three sources of fluorine - SNe II, WR, and AGB stars, the latter from [9]. In Figure 1, the AGB and SNe II yields are expressed as $[\text{F}/\text{O}]$. We have not shown a comparable entry for the WR stars as a self-consistent treatment of the oxygen production was not included in [12].

Figure 1. $[F/O]$ for SNe II and AGB yields at Pop II and Pop I metallicities (solid and dotted lines, $Z \sim 10^{-2} Z_{\odot}$ and $Z \sim Z_{\odot}$ respectively). The shaded regions show the observed $[F/O]$ in ω Cen giants [3].

Figure 2. (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 ω Cen giants (crosses, boxes and hexagons, respectively). (b): $[F/O]$ as a function of $[O/Fe]$.

4. Results and Discussion

The MWa model, whose only fluorine source is SNe II, underproduces fluorine with respect to the abundances measured in Milky Way giants ([8]; [3]), as shown in Figure 2. The results of the MWa and MWb models show that the additional contribution from WR stars increases $[F/O]$ by up to factor of ~ 2 by the present-day, but that it is also negligible at low metallicities. The addition of both WR *and* AGB sources within the MWc model leads to a present-day $[F/O]$ that is ~ 3 times greater than for the MWa case. Further, and perhaps more important, AGB stars are now shown to deliver significant amounts of fluorine to the ISM during the early epochs of the Milky Way's evolution. Such a result is entirely consistent given the metallicity-dependence of the AGB yields; said yields possess $[F/O]$ ratios which are greater at lower metallicities (recall Figure 1; see also [13]). We can conclude that it is only the addition of *both* the WR and AGB contributions which allow 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 [3] is not straightforward, as the latter two have star formation (and therefore chemical evolution) histories different from that of the MW. However, it is interesting to speculate on the possible origin of fluorine in ω Cen, given the unique nature of this “globular cluster” [14]. Specifically, ω Cen is the most massive Galactic cluster, and

unlike most globulars, possesses a significant spread in metallicity (~ 1.5 dex) amongst its stellar population. It has been suggested that ω Cen is actually the remnant core of a tidally-disrupted dwarf galaxy [1]. Such a scenario could naturally drive radial gas inflows to the dwarf nucleus, potentially triggering starbursts. Interestingly, SNe II ejecta are characterised by low $\langle [F/O] \rangle_{IMF}$ and high $\langle [O/Fe] \rangle_{IMF}$, whereas AGB ejecta have higher $\langle [F/O] \rangle_{IMF}$ [13]. The observed ω Cen giants have primarily low $[F/O]$ and high $[O/Fe]$ values (Figure 2), consistent with a picture in which their interiors have been polluted by the ejecta of an earlier generation of SNe II, but not that from a comparable generation of AGB. Given that the observed oxygen abundance in such ω Cen giants is similar to that seen in comparable LMC and MW giants, this would suggest that the chemical enrichment of ω Cen proceeded on a short timescale (to avoid pollution from the lower mass progenitors to the AGB stars) and in an inhomogeneous manner (given the significant scatter in observed fluorine abundances), as discussed previously by [3]. A possible significant decrease of SNe II ^{19}F production, due to updated cross-sections [6], would improve the agreement of the model with $[F/O]$ observed in ω Cen giants, strengthening our conclusions which support the picture whereby those giants had been polluted by earlier generations of SNe II ejecta.

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