

Synthesis of ^{19}F in Wolf-Rayet stars

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Received 19 March 1999 / Accepted 3 January 2000

Abstract. Meynet & Arnould (1993) have suggested that Wolf-Rayet (WR) stars could significantly contaminate the Galaxy with ^{19}F . In their scenario, ^{19}F is synthesized at the beginning of the He-burning phase from the ^{14}N left over by the previous CNO-burning core, and is ejected in the interstellar medium when the star enters its WC phase. Recourse to CNO seeds makes the ^{19}F yields metallicity-dependent.

These yields are calculated on grounds of detailed stellar evolutionary sequences for an extended range of initial masses (from 25 to 120 M_{\odot}) and metallicities ($Z = 0.008, 0.02$ and 0.04). The adopted mass loss rate prescription enables to account for the observed variations of WR populations in different environments.

The ^{19}F abundance in the WR winds of 60 M_{\odot} model stars is found to be about 10 to 70 times higher than its initial value, depending on the metallicity. This prediction is used in conjunction with a very simple model for the chemical evolution of the Galaxy to predict that WR stars could be significant (dominant?) contributors to the solar system fluorine content. We also briefly discuss the implications of our model on the possible detection of fluorine at high redshift.

Key words: nuclear reactions, nucleosynthesis, abundances – stars: Wolf-Rayet

1. Introduction

For long, the solar system has been the only location of the Galaxy with a known fluorine (^{19}F) abundance. At the same time, the production site(s) of this element has been a major nucleosynthetic puzzle, even if F is the least abundant (mass fraction of $4 \cdot 10^{-7}$, following Grevesse & Sauval 1998) of the elements ranging from carbon to calcium.

These last years, the situation has changed quite dramatically, both observationally and theoretically. Fluorine overabundances (with respect to solar) in MS, S and C stars have been reported (Jorissen et al. 1992), and correlate in particular with s-process enrichments. These observations demonstrate that ther-

mally pulsating Asymptotic Giant Branch (AGB) stars are fluorine producers, as predicted by Goriely et al. (1989), and confirmed by calculations conducted in the framework of detailed AGB models (Forestini et al. 1992, Mowlavi et al. 1996, 1998). It remains of course to determine the exact level of the contribution of these (mass losing) stars to the solar system and galactic F content.

In direct relation with this question, various calculations have been made in order to estimate the ^{19}F yields from massive stars. The neutrino process operating during supernova explosions has been envisioned as a possible producer of primary ^{19}F (e.g. Woosley & Weaver 1995). On the other hand, Meynet & Arnould (1993) have investigated on grounds of detailed stellar models the suggestion (Goriely et al. 1989) that the hydrostatically burning He-shell can synthesize ^{19}F of secondary nature. They find that the level of production is relatively modest in $M \lesssim 20 M_{\odot}$. In contrast, they show that stars which are massive enough to become Wolf-Rayet (WR) stars can eject through their winds substantial amounts of fluorine synthesized in the core at the beginning of the He-burning phase.

In the present work, we revisit the question of the galactic contribution of WR stars to ^{19}F with the help of new stellar models that better account for many important observable properties of WR stars. In addition, we extend the range of masses and metallicities considered in our previous study. The broadening of the explored metallicity range may take some additional importance in relation with the recent claim by Timmes et al. (1997) that “*positive detection of any fluorine at a sufficiently large redshift ($z \gtrsim 1.5$) would suggest strongly a positive detection of the neutrino process operating in massive stars*”. The possibility of a significant thermonuclear production of ^{19}F by WR stars of different metallicities might blur this picture, and might at least imply the necessity of establishing observationally the primary or secondary nature of the detected fluorine, if any.

The physical ingredients of the models are discussed in Sect. 2. Sect. 3 presents our predicted yields from individual WR stars, while Sect. 4 gives a rough estimate of the contribution of WR stars to the galactic ^{19}F content. Some conclusions are drawn in Sect. 5.

2. The physical ingredients of the stellar models

The evolutionary models are computed with the same physical ingredients as in Meynet et al. (1994). However, the adopted nuclear reaction network is extended, especially in order to include the reactions involved in the production and destruction of ^{19}F (see below).

The differences with respect to the computations of Meynet & Arnould (1993) are twofold:

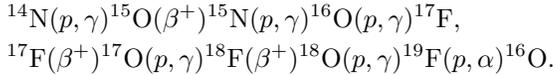
- 1) A more extended range of initial masses (from 25 to 120 M_{\odot}) and metallicities ($Z = 0.008, 0.02$ and 0.04) is explored;
- 2) The present grid of models is computed with the mass loss rates adopted by Meynet et al. (1994), which are twice as large as the values of \dot{M} recommended by de Jager et al. (1988) and Conti (1988) for the pre-WR and WNL phases. This mass loss rate prescription enables to account for the observed variations of WR populations in different environments (Maeder & Meynet 1994).

The metallicity dependence of the mass loss rates during the pre-WR phases is adopted from previous works (e.g. Meynet et al. 1994). More specifically, \dot{M} scales with metallicity Z according to $\dot{M}_Z/\dot{M}_{\odot} = (Z/Z_{\odot})^{0.5}$, where Z_{\odot} is the solar metallicity. This scaling is deduced from stellar wind models (cf. Kudritzki et al. 1987, 1991).

Let us finally add that the models are computed with a moderate core overshooting ($d/H_p = 0.20$, where d is the overshooting distance and H_p the pressure scale height at the boundary of the classical core).

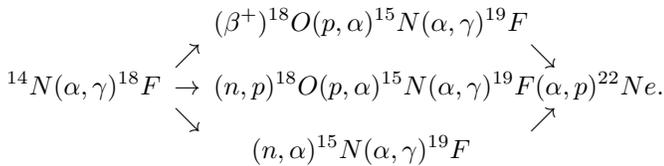
2.1. The thermonuclear ^{19}F production and destruction paths

The CNO mode of H-burning is responsible for the production and destruction of ^{19}F through the reaction chain



The adopted $^{19}\text{F}(p, \alpha)^{16}\text{O}$ rate is the geometrical mean of the lower and upper limits to that rate proposed by Kious (1990).

Fluorine can also be produced and destroyed during He-burning through the chains (see also Meynet & Arnould 1993)



The synthesis of ^{19}F thus requires the availability of neutrons and protons. They are mainly produced by the reactions $^{13}\text{C}(\alpha, n)^{16}\text{O}$ and $^{14}\text{N}(n, p)^{14}\text{C}$.

The first chain of transformation of ^{14}N into ^{19}F mentioned above is by far the most important in the conditions of relevance in this work, where the β^+ -decay lifetime $\tau_{\beta}(^{18}\text{F})$ of ^{18}F is much shorter than its lifetime $\tau_{n, \alpha}(^{18}\text{F})$ or $\tau_{n, p}(^{18}\text{F})$ against (n, α) or (n, p) reactions. For example, τ_{β} is a few hours only at the center of a 60 M_{\odot} model at the beginning of core He-burning, while the

corresponding $\tau_{n, \alpha}(^{18}\text{F})$ and $\tau_{n, p}(^{18}\text{F})$ amount to about 1 400 and 18 000 years, respectively.

The NACRE compilation of reaction rates (Angulo et al. 1999) was not available yet at the time of completion of the calculations reported here. This is why most of the necessary nuclear data are taken from Caughlan & Fowler (1988). There are some exceptions to this rule. In particular, the ^{13}C α -capture rate is taken from Descouvemont (1987), whose theoretical prediction of an increase of the astrophysical S-factor at low energies is confirmed experimentally (see NACRE). The $^{14}\text{N}(n, p)^{14}\text{C}$ rate is taken from Brehm et al. (1988). It is a factor of two lower than the one proposed by Koehler and O'Brien (1989), and leads consequently to a *lower limit* of the calculated ^{19}F yields.

3. Predicted ^{19}F yields from individual WR stars

As discussed by Arnould et al. (1999) on grounds of the NACRE rates, ^{19}F could be overproduced (with respect to solar) by the CNO cycle only at temperatures around 15×10^6 K, the exact level of this overproduction remaining poorly predictable, however, in view of remaining rate uncertainties. This conclusion contradicts the one derived from the use of the rates recommended by Caughlan & Fowler (1988), in which case fluorine can never emerge in significant amounts from the CNO burning. As the latter rates are adopted in our calculations, the CNO zones of the computed model stars are depleted in ^{19}F . This translates directly into a decrease of the ^{19}F mass fraction X_{19}^s at the stellar surfaces when the ^{19}F -depleted CNO ashes are uncovered by mass loss (with the choice of the ordinate scales, the changes of fluorine abundance at the center and at the surface during the H-burning phase are not visible on Fig. 1). With the NACRE rates, it is expected that more ^{19}F would be present at the surface. However, it is also likely that this change is not able to affect drastically the predicted final yields, as these are dominated by the ^{19}F made during the He-burning phase.

In fact, as seen in Fig. 1, fluorine builds up through $^{14}\text{N}(\alpha, \gamma)^{18}\text{F}(\beta^+)^{18}\text{O}(p, \alpha)^{15}\text{N}(\alpha, \gamma)^{19}\text{F}$ during the early phase of core He-burning. However, at the end of He-burning, $^{19}\text{F}(\alpha, p)^{22}\text{Ne}$ is responsible for a significant ^{19}F destruction. Thus, material experiencing the whole He-burning episode cannot be ^{19}F -enriched. *In contrast, in massive stars going through the WR stage* (initial mass $M_i \gtrsim 25 M_{\odot}$ for $Z = 0.02$, $M_i \gtrsim 35 M_{\odot}$ for $Z = 0.008$; see Maeder & Meynet 1994), *some ^{19}F synthesized early during the core He-burning phase is ejected into the interstellar medium by stellar winds before its destruction*. Indeed, Fig. 1 exhibits an increase of X_{19}^s when the He-burning products appear at the surface during the WC phase. As a result, the ratio $\langle X_{19}^s(\text{WC}) \rangle / X_{19}^{\odot}$ of the average ^{19}F surface mass fraction during the whole WC phase to the solar system ^{19}F mass fraction takes values as high as about 55, 95 and 60 in the case of the 60 M_{\odot} model stars with $Z = 0.008, 0.02$ and 0.04 , respectively.

Fig. 2 shows the ^{19}F “wind” yields for the computed stars (M_i, Z) with initial mass M_i and metallicity Z . These yields, noted $p_{19}^{\text{wind}}(M_i, Z)$, are equal to

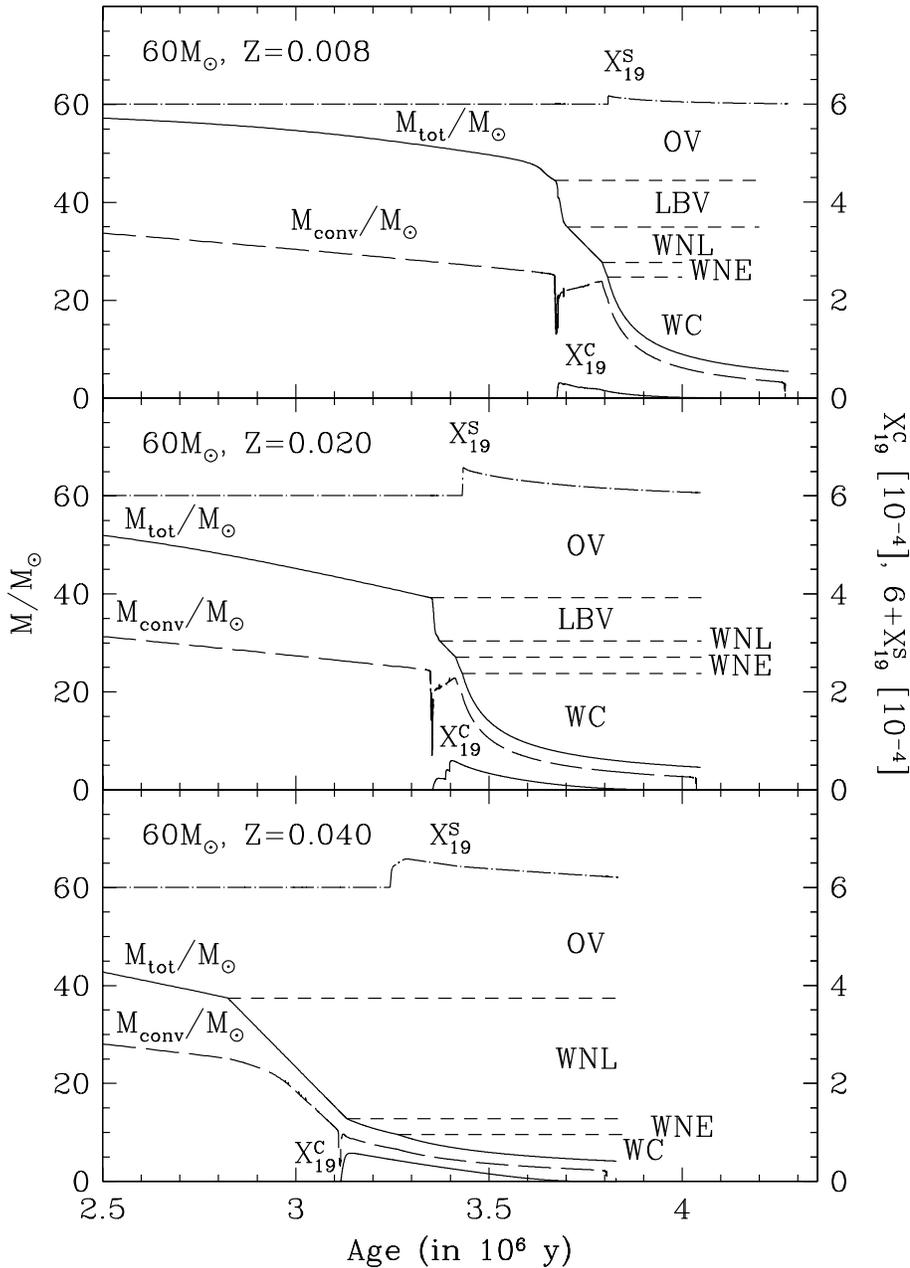


Fig. 1. Evolution of the total mass M_{tot} , of the mass of the convective core M_{conv} , and of the central (X_{19}^c) and surface (X_{19}^s) ^{19}F mass fractions for the $60 M_{\odot}$ model stars with metallicities $Z = 0.008, 0.020$ and 0.040 during the end of the H-burning stage and the whole He-burning phase. The initial ^{19}F mass fraction is assumed to relate to the solar value X_{19}^{\odot} by $X_{19}^{\odot}(Z) = (Z/Z_{\odot})X_{19}^{\odot}$. The spectroscopic types encountered during the evolution are indicated on the right of the figure: OV for O-type main sequence stars, LBV for Luminous Blue Variables, WNL, WNE and WC for the different classes of WR stars. Note the different ordinate scales on the left and on the right of the figure.

$$p_{19}^{\text{wind}}(M_i, Z) = \int_0^{\tau(M_i, Z)} \dot{M}(M_i, Z, t) [X_{19}^s(M_i, Z, t) - X_{19}^{\odot}(Z)] dt, \quad (1)$$

where $\tau(M_i, Z)$ is the total lifetime of the star (M_i, Z), $\dot{M}(M_i, Z, t)$ its mass loss rate at age t , $X_{19}^s(M_i, Z, t)$ its ^{19}F surface mass fraction at age t , and $X_{19}^{\odot}(Z)$ its initial ^{19}F mass fraction, assumed to relate to X_{19}^{\odot} by $X_{19}^{\odot}(Z) = (Z/Z_{\odot})X_{19}^{\odot}$. These yields may be negative if most of the ejected material has been depleted in fluorine.

Fig. 2 demonstrates that the highest yields are obtained for stars with $Z = Z_{\odot}$ and $40 \lesssim M_i \lesssim 85 M_{\odot}$. At lower metallicities, the winds are indeed weaker, and thus uncover the He-

burning core only for the most massive stars and when the ^{19}F has already been burnt. On the other hand, at higher metallicities and for $M_i \gtrsim 85 M_{\odot}$, the H-burning core mass decreases so rapidly during the main sequence as a consequence of very strong stellar winds that the He-burning core becomes too small for being uncovered by the stellar winds.

The above discussion shows that the most important physical ingredient influencing the WR ^{19}F yields is the metallicity-dependent mass loss rates, quantities like convective core masses being less crucial in this respect. As a numerical example, the value for $\langle X_{19}^s(\text{WC}) \rangle / X_{19}^{\odot}$ rises from about 18 in the $60 M_{\odot}$ low mass loss rate model of Meynet & Arnould (1993) to about 95 in the same model star computed in this paper with an increased \dot{M} value. This high sensitivity to \dot{M} might cast doubts on the reliability of the predicted ^{19}F yields.

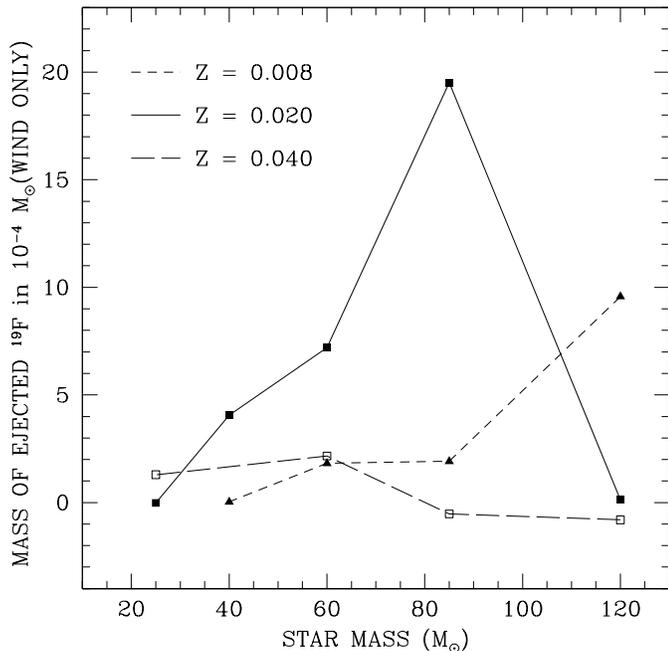


Fig. 2. Mass of ^{19}F ejected by the stellar winds (p_{19}^{wind} in Eq. (1)) as a function of the initial mass and metallicity.

In fact, some confidence in the results presented in this paper may be gained by noting that our present choice of the mass loss rates allows to account for the variation with metallicity of the number ratio of WR to O-type stars in regions of constant star formation rate (Maeder & Meynet 1994).

4. Estimate of the contribution of WR stars to the galactic fluorine

In order to evaluate the level of ^{19}F contamination by the winds of WR stars on a galactic scale, we use the p_{19}^{wind} yields [Eq. (1)] in a very simple model of galactic chemical evolution making use of the closed box and instantaneous recycling approximations. We also suppose that only WR stars are able to affect the galactic ^{19}F budget through their winds, all other possible production or destruction sites being neglected.

In such conditions, the ^{19}F mass fraction $X_{19}(t)$ in the galactic gas at time t is equal to (e.g. Tinsley 1980)

$$X_{19}(t) = \widetilde{y}_{19} \ln[1/\sigma(t)], \quad (2)$$

where $\sigma(t)$ is the mass fraction of the gas in the Galaxy at time t , and \widetilde{y}_{19} is a representative time-independent approximation of the net yield of a stellar generation defined by

$$y_{19}(t) = \frac{1}{1-R} \int_{M_1}^{M_2} p_{19}^{\text{wind}}(M_i, Z(t)) \Phi(M_i) dM_i, \quad (3)$$

where R is the “returned fraction”, M_1 and M_2 the lowest and highest mass of the stars going through the WR phase, and $\Phi(M_i)$ the initial mass function (IMF). It has to be noted that Eq. (2) would break down if the true time- (or Z -) dependent $y_{19}(t)$ yields were used instead of \widetilde{y}_{19} . In order to evaluate

the latter quantity, we notice that $y_{19}(Z(t))$ values of about 10^{-7} , $5.7 \cdot 10^{-7}$ and $2.2 \cdot 10^{-7}$ are obtained for $Z = 0.008$, 0.02 and 0.04 if use is made of the p_{19}^{wind} values reported in Sect. 3 and of the (properly normalized) IMF derived by Kroupa et al. (1993). On such grounds, we just adopt the rough estimate $\widetilde{y}_{19} \approx 3 \cdot 10^{-7}$.

If this approximation is used in conjunction with the value $\sigma \approx 0.2$ considered to characterize the solar neighbourhood at the time of the solar system formation 4.5 billion years ago (see Prantzos & Aubert 1995, and references therein), Eq. (2) leads to $X_{19} \approx 5 \cdot 10^{-7}$ in the local $Z = Z_{\odot}$ interstellar medium (to be compared with the solar system abundance of $4 \cdot 10^{-7}$). Thus, our simple estimate predicts that *WR stars might account for most of the solar system ^{19}F content*. Even larger ^{19}F quantities would be predicted with the use of the $^{14}\text{N}(\text{n}, \text{p})^{14}\text{C}$ rate of Koehler & O’Brien (1989)! After having faced for long the problem of the underproduction of ^{19}F , the theory of nucleosynthesis might now live with the danger of its predicted overabundance. If this is confirmed by further studies, constraints will obviously have to be put on one model or another.

5. Implications of ^{19}F detection at high redshift

Any ^{19}F present at high redshifts has to have been synthesized in massive stars only. Timmes et al. (1997) have argued further that its detection at redshifts $z \gtrsim 1.5$ would in fact be a signature of the ν -process in massive star explosions. The possibility of ^{19}F production by non-exploding WR stars might in fact weaken this statement, and blur the picture substantially.

Of course, one has to acknowledge that the contribution from WR stars at high redshifts may be reduced as a direct result of the lower metallicities that appear to characterize such regions. According to observations of Damped Lyman α systems (Pettini et al. 1997), the metallicity at redshifts between 1.5 and 2 indeed lies around $0.1 Z_{\odot}$. Such a reduced metallicity lowers the WR ^{19}F yields for two reasons. First, the number of WR stars predicted by non-rotating single star models is considerably reduced as a result of lower mass losses (Maeder & Meynet 1994). Second, the abundances of the CNO seeds that are needed for the secondary WR ^{19}F production are reduced as well.

Even so, it would certainly be premature at this point to completely forget about the role of WR stars in a possible enrichment of high- z material with ^{19}F , and to relate it strictly with the ν -process. This is even more true as the predictions reported in this paper are based on single, non-rotating stellar models only. How binarity and/or rotation would change these results remains to be checked. At present, the published rotating evolutionary models leading to WR stars (Fliegner & Langer 1994, Meynet 1998, 1999) make no predictions concerning the synthesis of fluorine. However they show that rotation favours an early entrance into the WR phase for a given mass, and decreases the minimum initial mass for a star to go through a WR phase at a given metallicity. Moreover, the mixing induced by rotation opens up new nucleosynthetic channels (see Heger 1998) whose importance for the scenario of fluorine production presented in

this paper remains to be quantitatively assessed. Finally, let us note that the effects of rotation might be more important at low Z if, as suggested by Maeder et al. (1999), the average rotation is faster at low metallicities. In such conditions, and in absence of quantitative calculations, one has to remain alert to the possibility of a significant contamination of low metallicity high redshift regions by the ^{19}F -loaded wind of WR stars.

Clearly, observations of ^{19}F at high redshift, if possible at all, would be decisive in order to answer the question of the very production mechanism of this element. An important distinguishing feature would be the primary nature of the observed ^{19}F , as predicted by the ν -process, or its secondary behaviour, as expected from the thermonuclear model discussed in this paper.

6. Conclusion

Detailed stellar model predictions made in the framework of a very rough model for the chemical evolution of the solar neighbourhood leads to the conclusion that non-exploding non-rotating single WR stars alone could account for the solar ^{19}F content. This conclusion remains to be ascertained by the adoption of a more realistic galactic evolution model. Still, it appears likely that the considered WR stars might be significant, and even possibly dominant, galactic ^{19}F contributors. In addition, they might well be responsible for a ^{19}F enrichment, if any, of high-redshift ($z \gtrsim 1.5$) low-metallicity regions ($\sim 0.1 Z_{\odot}$). Further predictions are eagerly awaited for rotating, as well as binary, WR stars.

Finally, let us stress that the most direct test of the present model would be the measurement of the abundance of fluorine in the wind of WC stars. It remains to be seen if such observations are really feasible.

Acknowledgements. We thank N. Prantzos for comments on the galactic chemistry aspects of this work. This research has been supported in part by the HCM Programme of the European Union under contract ERBCHRXCT 930339.

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