FLUORINE ABUNDANCES IN GALACTIC ASYMPTOTIC GIANT BRANCH STARS

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ABSTRACT

An analysis of the fluorine abundance in Galactic asymptotic giant branch (AGB) carbon stars (24 N-type, 5 SC-type, and 5 J-type) is presented. This study uses the state-of-the-art carbon-rich atmosphere models and improved atomic and molecular line lists in the 2.3 μm region. Significantly lower F abundances are obtained in comparison to previous studies in the literature. This difference is mainly due to molecular blends. In the case of carbon stars of SC-type, differences in the model atmospheres are also relevant. The new F enhancements are now in agreement with the most recent theoretical nucleosynthesis models in low-mass AGB stars, solving the long-standing problem of F in Galactic AGB stars. Nevertheless, some SC-type carbon stars still show larger F abundances than predicted by stellar models. The possibility that these stars are of larger mass is briefly discussed.

Key words: nuclear reactions, nucleosynthesis, abundances – stars: abundances – stars: AGB and post-AGB – stars: carbon

1. INTRODUCTION

The first observational evidence of ^{19}F stellar nucleosynthesis was reported by Jorissen et al. (1992, hereafter JSL). These authors derived F enhancements up to a factor of 50 solar in a sample of Galactic asymptotic giant branch (AGB) stars, and found a correlation between this enhancement and the C/O ratio. Since the C/O is expected to increase as a consequence of third dredge-up (TDU) episodes during the AGB phase (e.g., Busso et al. 1999), this was interpreted as a clear evidence of F production in these stars. Further observational evidence of such a production exists from studies of post-AGB stars (Werner et al. 2005) and planetary nebulae (Otsuka et al. 2008). Other sites for F production have also been proposed: Wolf–Rayet stars (Meynet & Arnould 2000) and neutrino spallation in core-collapse supernovae (Woosley & Haxton 1988). However, the role of these sources in the F budget is still uncertain (Cunha et al. 2003; Palacios et al. 2005). Nevertheless, from Galactic chemical evolution models, Renda et al. (2004) concluded that all three of these sources are required to explain the observed Galactic evolution of F, as deduced from abundance determinations in field stars (Cunha & Smith 2005; Cunha et al. 2008), although, only in AGB stars there exists an observational confirmation that F production is an ongoing process.

Fluorine can be produced in AGB stars from the nuclear chain ^{14}N$(\alpha, \gamma)^{18}$F$(\beta^+)^{18}$O$(p, \alpha)^{15}$N$(\alpha, \gamma)^{19}$F, where protons are mainly provided by ^{14}N$(n, p)^{14}$C and neutrons by ^{13}C$(\alpha, n)^{16}$O. However, the theoretical attempts made to explain the JSL results are unsatisfactory. The problem is that current AGB models fail to explain the highest F enhancements found in the C-rich objects of the JSL sample (Goriely & Mowlavi 2000; Lugaro et al. 2004). This discrepancy has led to a deep revision of the uncertainties in the nuclear reaction rates involved in the synthesis of F in AGB stars (Lugaro et al. 2004; Stancliffe et al. 2005), to argue for alternative nuclear chains and/or to propose the existence of non-standard mixing/burning processes, sim-

ilar to those commonly used to explain some of the isotopic anomalies found in dust grains formed in the envelopes of AGB stars (e.g., Nollett et al. 2003; Busso et al. 2007). However, no solution has been found to-date, leaving the subject of the origin of this element open.

Very recently, Abia et al. (2009, hereafter Paper I) derived F abundances from Very Large Telescope spectra in three Galactic AGB C stars in common with the JSL sample, namely AQ Sgr, TX Psc (N-type), and R Scl (J-type), by using mainly the HF R9 line at 2.3358 μm. In that work, we showed that this HF line is almost free of blends in AGB C stars and thus is probably the best tool for F abundance determinations in these stars (see also Uttenthaler et al. 2008). For these three stars, we derived F abundances $\sim$0.7 dex lower in average than those obtained by JSL. We ascribed this difference to molecular blends (mainly of C_2 and CN). These new F abundances are in better agreement with the most recent theoretical nucleosynthesis predictions in low-mass ($<$3 $M_\odot$) thermal pulsing (TP)-AGB models (Cristallo et al. 2009). Motivated by this result, we have reanalyzed the F abundances in the whole C-stars sample studied by JSL using the same tools as in Paper I. In this Letter, we confirm the results found in Paper I and show that the new F abundances nicely agree with the theoretical predictions of low-mass TP-AGB models. This apparently solves the long-standing problem of F enhancements in AGB stars without requiring the existence of any extra mixing/burning process.

2. ANALYSIS AND RESULTS

Our data consist of high-resolution spectra from $\sim$1.5 to 2.5 μm obtained with the 4 m telescope at Kitt Peak Observatory and a Fourier transform spectrometer (FTS), which have been used in several abundance analysis of AGB stars (see Lambert et al. 1986 and JSL for details). Typical resolutions ranged from 0.05 to 0.14 cm^{-1} (R = 87,000–30,000). These spectra contain many HF lines of the vibrational 1–0 band although we
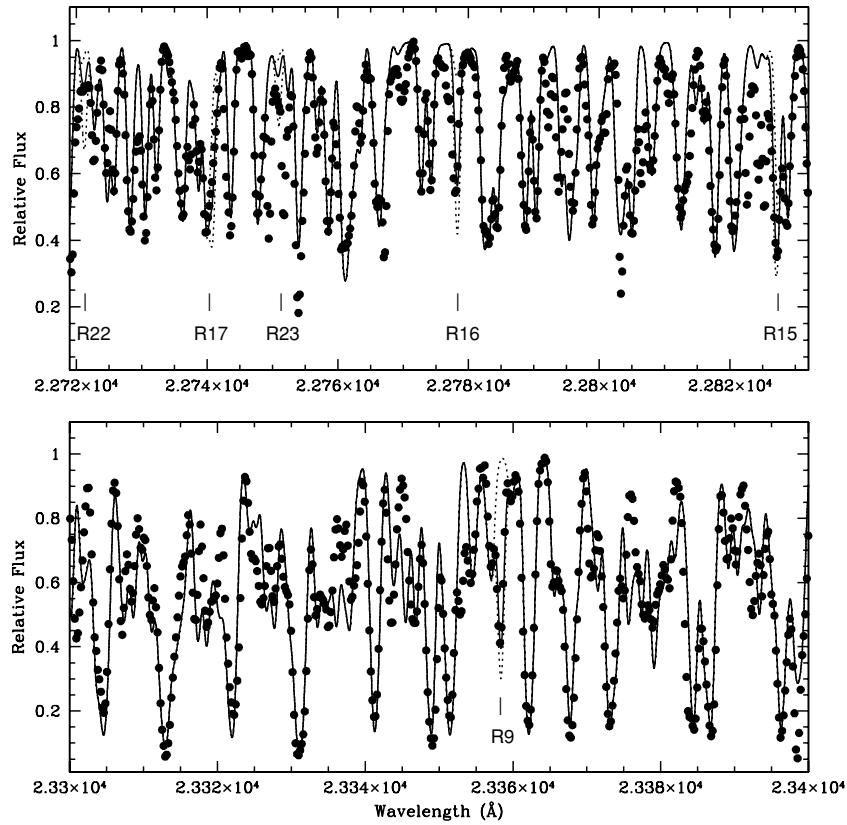
Figure 1. Comparison of the observed and synthetic spectra of UU Aur (dots) with an identification of the available HF lines. Dashed lines represent the synthetic spectra calculated with no F and with the abundance value obtained by JSL, respectively. The continuous line is the synthetic spectrum calculated with the abundance given in Table 1, $\log \epsilon(F) = 4.88$.

used only the lines R9 to R23. High-resolution optical spectra ($R \sim 160{,}000$) in the range 4600–8000 Å obtained at the 3.5 m TNG at La Palma Observatory with SARG echelle spectrograph were also analyzed. These spectra allowed us to derive the *s*-element content in the stars BL Ori, ST Cam, Y Tau, CY Cyg, RZ Peg, and GP Ori using the same procedure as in Abia et al. (2002). All program stars were ratioed with hot stars to remove telluric spectral features by using the task *telluric* within the IRAF package. The typical signal-to-noise ratio of the spectra is larger than 100. We adopted the stellar parameters ($T_{\rm eff}$, $\log g$, [Fe/H], ξ, CNO abundances, C/O, and $^{12}C/^{13}C$ ratios) derived by previous studies: Abia et al. (2002) and Lambert et al. (1986) for N-type stars, Abia & Isern (2000) for J-type stars, and Zamora (2009) for stars of SC-type (see these works for details). In addition, we also adopted the $^{16}O/^{17}O/^{18}O$ ratios from the literature when available (Harris et al. 1987), although this has a minimal impact on the derived F abundance. The method of analysis involves the comparison of theoretical local thermal equilibrium (LTE) spectra (computed with the *Turbospectrum* code) with the observed ones. We used the latest generation of C-rich atmosphere models for giant stars (Gustafsson et al. 2008) and up-to-date molecular and atomic line lists in the spectral ranges studied (see Paper I for details).

Figure 1 shows an example of comparison between the observed and theoretical spectrum for the C-star UU Aur (N-type) in two different spectral ranges. In particular, top panel shows the fit to the R15 and R16 HF lines, the sole lines used by JSL to derive the F abundance in the C-rich objects. It can be seen that we can reproduce reasonably well the observed spectrum, and that the synthetic spectrum computed with the F abundance obtained by JSL (lower dashed line) would

overestimate the F abundance in this star. Our best estimation in this star ($\log \epsilon(F) = 4.88$, continuous line in Figure 1) fits quite well the six HF lines used, with a dispersion of only ± 0.04 dex (see also Table 1).[8] Similar quality fits were obtained for all the stars except for V Hya, which was excluded from the analysis since its effective temperature is outside the range covered by our grid of models. Table 1 lists the final F abundance derived in each star, assigning double weight to the R9 line when estimating the mean F abundance because this is the less blended among the available HF lines (see Paper I for a discussion). For most of the stars, more than three different HF lines were used. The agreement between the different lines is in general good with a typical mean dispersion of ± 0.08 dex. The formal error in the F abundance due to uncertainties in the stellar parameters ranges from 0.20 to 0.30 dex, depending on the particular HF line. Considering the abundance dispersion and the uncertainty in the continuum position as additional sources of error, we estimate a total uncertainty of ± 0.30–0.35 dex in the [F/H][9] ratio (see Paper I). However, the abundance ratio between F and any other element typically has a smaller error since some of the above uncertainties cancel out when deriving the abundance ratio: for the [F/Fe] ratio, we estimate a total uncertainty of ± 0.25 dex.

The third column in Table 1 shows the difference found between the F abundance derived by JSL and this work. The differences range from 0.3 dex up to more than 1 dex, the average value being $\Delta \log \epsilon(F) = +0.7$, confirming the

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[8]   We note that the F abundances derived in the stars AQ Sgr and R Scl by using both CRIRES and FTS spectra are in perfect agreement.
[9]   The solar F abundance adopted here is 4.56 (Grevesse et al. 2007).

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Table 1
Abundances

Star	$\log \epsilon(F)^a$	$\Delta \log \epsilon(F)^b$	C/O	[F/Fe]	$[\langle s \rangle/Fe]$
N stars					
AQ Sgr	4.63 ± 0.02 (4)	0.85	1.03	0.10	. . .
BL Ori	4.92 ± 0.17 (4)	0.57	1.04	0.37	1.00
R Lep	4.45 ± 0.20 (2)	0.47	1.03	0.34	. . .
RT Cap	4.95 ± 0.01 (5)	0.36	1.10	0.40	. . .
RV Cyg	4.70 ± 0.10 (4)	0.63	1.20	0.15	0.07
S Sct	4.62 ± 0.03 (4)	1.08	1.07	0.10	0.40
SS Vir	4.55 ± 0.07 (2)	. . .	1.05	0.00	0.30
ST Cam	4.72 ± 0.14 (4)	0.94	1.14	0.20	0.45
TU Gem	4.92 ± 0.07 (5)	0.88	1.12	0.36	. . .
TW Oph	4.61 ± 0.06 (3)	0.30	1.20	0.46	. . .
TX Psc	4.82 ± 0.10 (6)	0.73	1.03	0.65	1.10
U Cam	4.58 ± 0.07 (4)	0.54	1.30	0.12	0.55
U Hya	5.09 ± 0.08 (5)	. . .	1.05	0.61	1.10
UU Aur	4.88 ± 0.04 (5)	0.76	1.06	0.26	0.45
UX Dra	4.85 ± 0.15 (4)	0.64	1.05	0.45	0.65
V460 Cyg	4.65 ± 0.10 (4)	0.68	1.06	0.14	0.80
V Aql	4.62 ± 0.14 (5)	0.54	1.25	0.00	0.20
VY UMa	4.70 ± 0.08 (3)	1.02	1.06	0.24	0.90
W CMa	4.95 ± 0.08 (6)	0.56	1.05	0.20	0.60
W Ori	4.42 ± 0.05 (4)	0.65	1.16	-0.11	0.25
X Cnc	4.93 ± 0.10 (3)	0.76	1.14	0.67	. . .
Y Hya	4.90 ± 0.02 (5)	0.33	1.52	0.44	. . .
Y Tau	4.57 ± 0.09 (6)	0.49	1.04	0.01	0.05
Z Psc	4.90 ± 0.13 (4)	0.42	1.01	0.40	0.97
SC stars					
CY Cyg	5.05 ± 0.05 (4)	0.98	1.04	0.39	0.10
FU Mon	5.15 ± 0.10 (5)	1.35	1.00	0.59	0.40
GP Ori	5.26 ± 0.08 (6)	0.94	1.00	0.70	1.25
RZ Peg	5.00 ± 0.10 (6)	1.06	1.00	0.44	0.00
WZ Cas	5.80 ± 0.17 (6)	0.40	1.01	1.15	0.16
J stars					
R Scl	4.18 ± 0.03 (3)	1.22	1.34	0.09	. . .
RY Dra	4.48 ± 0.06 (3)	0.44	1.18	-0.08	< 0.20
T Lyr	4.35 ± 0.00 (2)	0.45	1.29	-0.21	. . .
VX And	4.35 (1)	. . .	1.76	-0.20	0.2
Y Cvn	4.40 (1)	0.50	1.09	-0.10	< 0.2

Notes. The abundances of fluorine are given using the definition $\log \epsilon(X) = 12 + \log(X/H)$, where (X/H) is the abundance of the element X by number.
^{a} The number in parenthesis indicates the number of HF lines used.
^{b} Abundance difference with respect to JSL.

main result of Paper I. As noted there, differences in the stellar parameters adopted in the analysis cannot explain this discrepancy. Actually, the major differences are found for the T_{eff} values, which for the N- and J-type stars in the sample do not exceed 150 K. In the case of SC-type stars, differences in adopted T_{eff} may reach up to 300 K, but in any case this cannot explain the differences of more than $\sim$1 dex in the F abundance found in some of these stars. Differences in the atomic data are also discarded since we used exactly the same HF line list than JSL. Finally, differences between the grid of model atmospheres might account up to a maximum of 0.15 dex, for the N- and J-type stars. For the SC-type stars, we found the largest abundance differences (see Table 1). For these stars, atmosphere models indeed play a significant role. JSL used, for the analysis of SC stars, Johnson (1982) models, while we use those from Gustafsson et al. (2008). For instance, considering the typical stellar parameters of an SC star in the sample (T_{eff}/$\log g$/[Fe/H] = 3500/0.0/0.0 and C/O = 1.0), we find differences in the F abundance from +0.4 dex (R9, R15, and R16 lines) to +0.02 dex (R23 line) when using Johnson models instead of Gustafsson et al. ones, but it may reach up to

Table 2
Main Blends Affecting the HF Lines

HF Line	Blend	$\Delta[C/H] = \pm 0.2^a$
R9	. . .	∓ 0.01
R15	$^{12}C^{14}N, \lambda22827.354$	∓ 0.25
R16	$^{12}C^{12}C, \lambda22778.775$	∓ 0.15
R17	$^{12}C^{14}N, \lambda22740.700$	∓ 0.03
R22	$^{13}C^{14}N, \lambda22721.294$	∓ 0.05
R23	$^{12}C^{14}N, \lambda22751.140$	∓ 0.02

Note. ^{a} Variation of the F abundance derived from each HF line due to changes in the carbon abundance for a representative case T_{eff}/$\log g$/[Fe/H] = 2800/0.0/0.0 and C/O = 1.06.

+0.6 dex for lower T_{eff}. In any case, for the N- and J-type stars, we conclude (as in Paper I) that the difference between the molecular line list used is the main cause of the discrepancy with respect to the analysis of JSL (see Table 2). For the SC-type stars, it is a combination of that, the use of a different grid of model atmospheres and, in the case of CY Cyg and GP Ori, the adoption here of a $T_{eff} \sim$ 300 K cooler. It should be mentioned that the structure of the C-rich atmosphere models change dramatically with a tiny variation of the C/O ratio when it is very close to 1, as it is the case for SC stars. Therefore, the abundance analyses in these stars are affected by systematic differences between the model atmosphere and the real star and/ or the treatment of the molecular equilibrium in the computation of the atmosphere models. In consequence, for SC-type stars the uncertainty in [F/H] is certainly larger than ± 0.3 dex.

3. DISCUSSION

The main consequence of the new F abundances is that the large [F/Fe] (or [F/O]) ratios (up to 1.8 dex) found by JSL in Galactic AGB C stars are systematically reduced. The largest F enhancements are now close to $\sim$1 dex. These enhancements can be accounted for by current low-mass TP-AGB nucleosynthesis models of solar metallicity, as we will show below. As noted in Section 1, during the ascension along the AGB, fresh carbon is mixed within the envelope due to TDU episodes. Eventually, an O-rich AGB star becomes a C star when the C/O ratio in the envelope exceeds 1. Similarly, F is also expected to increase in the envelope during the AGB phase, thus a fluorine versus carbon correlation should exist. Figure 2 shows the observed relationship derived in this study. We have also included in this figure the intrinsic[10] O-rich AGB stars studied by JSL (not analyzed here, open circles). Excluding the J-type[11] stars (triangles), a clear increase of the F abundance with the C abundance can be seen. This behavior is well reproduced by theoretical AGB models. Lines in Figure 2 show the predicted F and C content in the envelope (S. Cristallo et al. 2010, in preparation) for a 1.5 $M_\odot$ model with different metallicities (continuous lines) and a 2 $M_\odot$ model (dashed line) with solar metallicity. These metallicities match those of

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[10] Intrinsic AGB stars have their envelopes polluted by nucleosynthesis products made in situ. Extrinsic stars, in contrast, own their chemical peculiarities to a mass-transfer episode in a binary system. All the O-rich stars shown in Figure 2 show ^{99}Tc ($\tau_{1/2} \sim 2 \times 10^5$ yr) in their envelopes (Smith & Lambert 1990), revealing their intrinsic nature.
[11] The origin of J-type C stars is still unknown. They are slightly less luminous than N-type C stars and show chemical peculiarities rather different with respect to these stars (e.g., Abia & Isern 2000). It has been suggested that they might be the descendants of the early R-type stars, however, this has been questioned recently (Zamora 2009).

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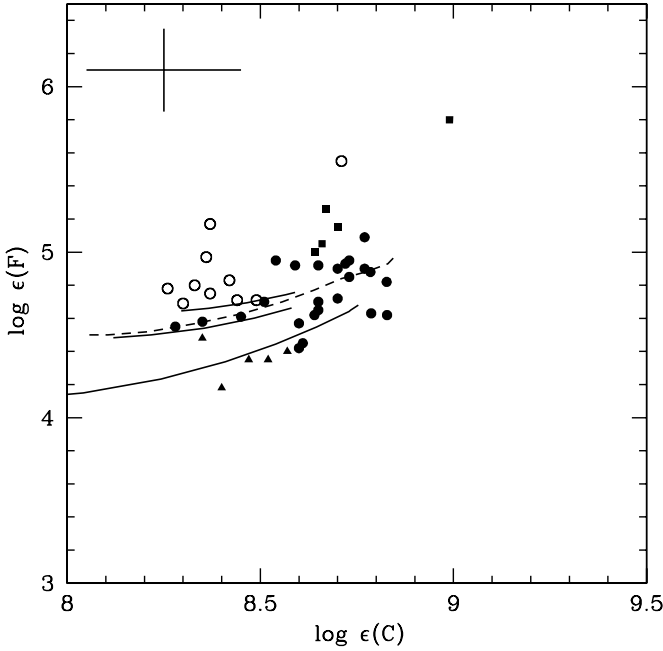
Figure 2. Logarithmic abundances of fluorine vs. carbon. Symbols: filled circles, N-stars; triangles, J-type; squares, SC-type; open circles, intrinsic O-rich AGB stars from JSL. Lines are theoretical predictions for a 1.5 $M_\odot$, TP-AGB model with metallicities $Z = 0.02$, $Z_\odot$, and 0.006 (continuous lines from up to down), and a 2 $M_\odot$, $Z = Z_\odot$ model (dashed line), respectively.

Figure 3. Fluorine vs. average s-element enhancements in Galactic AGB stars. Symbols as in Figure 2. Lines are theoretical predictions for 1.5, 2, and 3 $M_\odot$, $Z = 0.008$ TP-AGB models (solid, dashed, and dotted lines, respectively) from S. Cristallo et al. (2010, in preparation). The number of TPs achieved by each model is also indicated.

the stellar sample ($-0.5 \leqslant$ [Fe/H] $\leqslant 0.1$). The theoretical curves start with an envelope composition as determined by the first dredge-up and end at the last TDU episode. On the other hand, Figure 2 seems to indicate that O-rich stars and SC stars (squares) have F abundances systematically larger than N-type stars (dots) for a given C abundance. Similarly to the intrinsic C stars, also in the case of the O-rich stars this may be simply due to a systematic error affecting the analysis: in fact, for stars of spectral types K and M (with [Fe/H] ~ 0.0), JSL derived an average F abundance ~ 0.13 dex higher (4.69) than the solar F abundance adopted here (4.56). These K and M stars are sub-giants or RGB stars, thus they are not expected to present F enhancements. Excluding the possibility that the Sun might be anomalous with respect to nearby stars of similar metallicity (F determinations in unevolved dwarf stars are needed in this sense), blends may also play a role in the analysis of F lines in O-rich AGB stars. Decreasing the F abundances by 0.13 dex in them, the agreement with theoretical predictions would be definitely better. However, it does not apply to the case of the star BD+48°1187 (at log ϵ(F) ~ 5.5 in Figure 2); the large F enhancement in this star can be only obtained in metal-poor AGB models, but this star has [Fe/H] = 0.07. Something similar seems to occur with SC-type stars. SC stars are AGB stars with C/O ≈ 1. According to the accepted chemical (spectral) evolution along the AGB (M→MS→S→SC→N), these stars should present equal-or-slightly lower F enhancements than N-type stars. However, some of the studied SC stars clearly deviate from this sequence, showing larger F abundances with respect to N stars. This is reinforced by WZ Cas[12] ([Fe/H] $\sim$ 0.0, at the upper right corner of Figure 2), which shows a huge F enhancement. We recall, however, that this star is indeed peculiar: it is one of the few super Li-rich C stars known, also presenting very low $^{12}C/^{13}C$ (4.5) and $^{16}O/^{17}O$ (400) ratios.
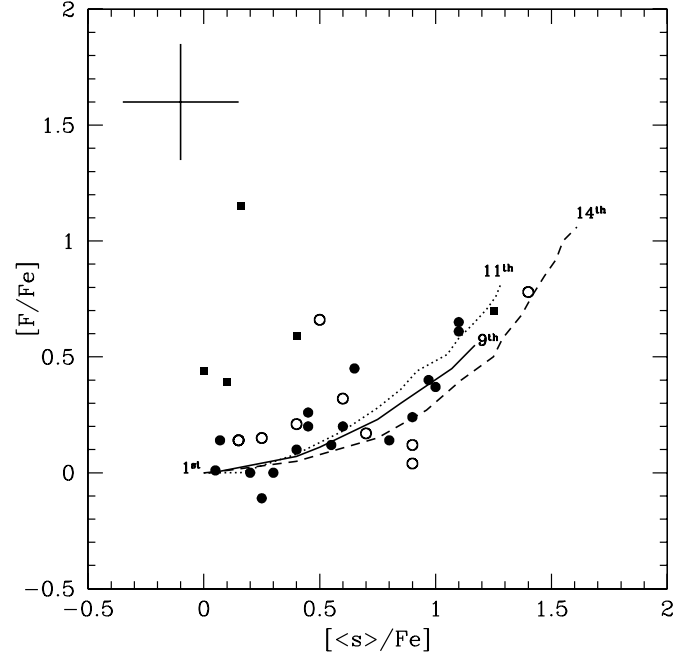
The fact that most of the SC stars studied here show low or no s-element enhancements (see below) makes the evolutionary status of these stars very uncertain.

The connection between the F and the s-process is less straightforward. There are two different contributions to the F production in low-mass AGB stars. The first comes from the ^{15}N production in the radiative ^{13}C pocket, the site where the s-process main component is built up: when, during the interpulse period, the $^{13}C(\alpha, n)^{16}O$ is activated within the pocket, some protons are released by the main poisoning reaction, $^{14}N(n, p)^{14}C$, thus producing ^{15}N via $^{18}O(p, \alpha)^{15}N$. The second contribution involves the same reaction chain, but it is activated when the ^{13}C left by the advancing H-burning shell is engulfed into the convective zone generated by a thermal pulse. In the latter case, the correlation with the s-process is less stringent, because the resulting neutron flux is not enough to give rise to a sizable production of elements beyond iron. At nearly solar metallicity, the latter contribution accounts for $\sim 70\%$ of the total F production (e.g., Cristallo 2006). Nevertheless, a correlation between the F and the s-element overabundance is in any case expected if a large enough ^{13}C pocket forms after each dredge-up episode. Figure 3 shows the new [F/Fe] ratios in C stars versus the observed average s-element enhancement (from Abia et al. 2002; Zamora 2009; or derived in this work, see Section 1). J-type stars are not shown in this figure as they do not have s-element enhancements (see Table 1; Abia & Isern 2000). Similarly to Figure 2, we have included the intrinsic O-rich stars analyzed by JSL taken their s-element content from Smith & Lambert (1990). It is clear that the F and s-nuclei overabundances correlate and that this correlation is nicely reproduced by theoretical TP-AGB stellar models (S. Cristallo et al. 2010, in preparation). The theoretical predictions in Figure 3 correspond to 1.5, 2, and 3 $M_\odot$ TP-AGB models with $Z = 0.008$ ([Fe/H] ~ -0.25, the average metallicity of the stars analyzed here) starting from the first TP pulse.

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[12] This star has also been classified as J-type.

The number of TPs calculated until the occurrence of the last TDU is indicated in the figure for each model. Models with metallicity within $\sim \pm 0.2$ dex of this value do not significantly differ from those in Figure 3. In addition, with the combination of models with different stellar mass and metallicity, it is possible not only to reproduce the new observed [F/Fe] versus s-element relationship, but also the detailed F and s-element abundance pattern observed in a particular star (see, e.g., Figure 3 in Paper I). Note that this is not possible for most of the stars when adopting the F determinations of JSL.

As already noted, SC-type stars (except GP Ori) show larger F abundances than predicted by low-mass AGB models with the same s-element enhancement. A possible explanation could be that the SC stars are more massive (in average) than the bulk of the N-type C stars. From AGB models with mass of about 3–5 $M_\odot$, we expect smaller ^{13}C pockets and weaker s-element surface enrichments, even if the number of TPs and TDU episodes is larger. It occurs because the larger the core mass is, the smaller the He-rich intershell is with a steeper pressure gradient. Notwithstanding, the ^{13}C left in the ashes of the H-shell still provide a substantial contribution to the fluorine production. Recent studies of the luminosity function of Galactic C stars (Guandalini 2008) support such a hypothesis. They indicate that the SC-type stars are among the most luminous AGB C stars. Once again, the case of WZ Cas is particularly extreme. This star shows a huge F abundance ([F/Fe] = +1.15) with almost no s-element enhancement. Its large Li abundance might be interpreted as a consequence of the hot bottom burning (HBB) mechanism which operates only for $M \geqslant 5\,M_\odot$. However, the operation of the HBB would be at odds with the presence of F in the envelope since ^{19}F$(p, \alpha)^{16}$O might destroy ^{19}F. Detailed abundance studies (including F) in a larger sample of SC stars are needed to confirm this hypothesis.

4. SUMMARY

Fluorine abundances in Galactic AGB carbon stars are determined from high-resolution infrared spectra using state-of-the-art C-rich spherical model atmospheres, updated atomic and molecular line lists, and LTE spectral synthesis. We derive F abundances that are in average $\sim$0.7 dex lower than those derived in previous studies. A clear correlation between the F and s-element enhancements is found. The new fluorine enhancements can be explained by standard low-mass AGB stellar models. F abundance determinations appear as a valuable tool to test theoretical AGB models. Studies of the F abundance in metal-poor unevolved and AGB stars are mandatory to understand the Galactic abundance evolution of this element and to evaluate the role of AGB stars in its origin, respectively.

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