Fluorine in AGB Carbon Stars Revisited

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ABSTRACT

A reanalysis of the fluorine abundance in three Galactic AGB carbon stars (TX Psc, AQ Sgr and R Scl) has been performed from the molecular HF (1-0) R9 line at 2.3358 µm. High-resolution (R ∼ 50000) and high signal to noise spectra obtained with the CRIRES spectrograph and the VLT telescope or from the NOAO archive (for TX Psc) have been used. Our abundance analysis uses the latest generation of MARCS model atmospheres for cool carbon rich stars. Using spectral synthesis in LTE we derive for these stars fluorine abundances that are systematically lower by ∼ 0.8 dex in average with respect to the sole previous estimates by Jorissen, Smith & Lambert (1992). The possible reasons of this discrepancy are explored. We conclude that the difference may rely on the blending with C-bearing molecules (CN and C2) that were not properly taken into account in the former study. The new F abundances are in better agreement with the prediction of full network stellar models of low mass AGB stars. These models also reproduce the s-process elements distribution in the sampled stars. This result, if confirmed in a larger sample of AGB stars, might alleviate the current difficulty to explain the largest [F/O] ratios found by Jorissen et al. In particular, it may not be necessary to search for alternative nuclear chains affecting the production of F in AGB stars.

Subject headings: stars: abundances — stars: carbon — stars: AGB and post-AGB — nuclear reactions, nucleosynthesis, abundances
1. Introduction

The origin of the sole stable isotope of fluorine, $^{19}$F, is not well known. It is easily destroyed by proton and alpha capture reactions in the stellar interiors so that, its abundance is the lowest among the light elements with atomic number $6 \leq Z \leq 20$. Fluorine has only a few accessible atomic and molecular lines suitable for abundance studies, detected whether in hot gaseous nebulae in the ultra-violet spectral region or in a rather crowded region at $\sim 2.3\mu m$ in cool objects. Three are the proposed sites of $^{19}$F production: neutrino spallation on $^{20}$Ne in gravitational supernovae (SNII) (Woosley & Haxton 1988), hydrostatic nucleosynthesis in the He-burning core of heavily mass-losing Wolf-Rayet (WR) stars (Meynet & Arnould 2000), and hydrostatic nucleosynthesis in the He-rich intershell of thermally pulsing (TP) Asymptotic Giant Branch (AGB) stars (Forestini et al. 1992). Up to date, the contribution of each source to the fluorine content in the Universe is still controversial. Renda et al. (2004) concluded that the inclusion of all the three components is necessary to explain the observed fluorine Galactic evolution as inferred from abundance determinations in a small sample of field red giants (Cunha & Smith 2005; Cunha et al. 2008). However, recent measurements of fluorine in the interstellar medium (Federman et al. 2005) yield no evidence of F over-abundances caused by the neutrino process in SNII. In addition, Palacios et al. (2005) revisited the F production in rotating WR star models concluding that the F yields from WR stars are significantly lower than previously predicted by Meynet & Arnould (2000), so that their contribution to the Galactic F budget would be negligible. This leaves AGB stars as the only significant producers.

The first evidence of F production in AGB stars was provided by the study of Jorissen, Smith & Lambert (1992; hereafter JSL) who determined F abundances from rotational HF lines in extrinsic (binary) and intrinsic stars of near solar metallicity along the AGB spectral sequence ($M\rightarrow MS\rightarrow S\rightarrow C$). JSL found [F/Fe] ratios up to $\sim 100$ times solar and
a clear correlation between the F enhancement and the C/O ratio. Because the C/O ratio is expected to increase along the AGB evolution due to the third dredge-up (TDU), this occurrence has been interpreted as an evidence of the F production in AGB stars. This result has been later supported by the large F enhancements found in post-AGB stars (Werner et al. 2005) and planetary nebulae (Zhang & Liu 2005; Otsuka et al. 2008, and references therein), the progeny of AGB stars. Nevertheless, up to now, nucleosynthetic models in AGB stars (e.g. Forestini et al. 1992; Lugaro et al. 2004; Cristallo et al. 2008) have failed to quantitatively reproduce the largest [F/Fe,O] ratios found in the JSL’s sample. Such a discrepancy has led to a deep revision of the uncertainties associated with the major nuclear reactions affecting the production/destruction of F in AGB stars, to a search for alternative nuclear chains (e.g. Lugaro et al. 2004), or to invoke non-standard mixing processes capable to increase the F production below the convective envelope (e.g. the cool bottom process, see Wasserburg, Boothroyd, & Sackmann 1995 and Busso et al. 2007). However, no satisfactory solution has been found, making this large fluorine enhancement a major challenge for stellar nucleosynthesis.

Extant theoretical models show that the nuclear chain allowing the fluorine production in the He-rich and H-exhausted intershell zone of a TP-AGB star is $^{14}\text{N}(\alpha, \gamma)^{18}\text{F}(\beta^+)^{18}\text{O}(p, \alpha)^{15}\text{N}(\alpha, \gamma)^{19}\text{F}$. Note that the $^{15}\text{N}$ production requires the existence of a few protons, which can eventually be produced by the $^{14}\text{N}(n, p)^{14}\text{C}$ reaction, but only when neutrons are released by the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction. The latter is the main neutron source in AGB stars, giving rise to the $s$-process nucleosynthesis (e.g. Gallino et al. 1998; Cristallo et al. 2008). Therefore, F and $s$-elements are expected to correlate in TP-AGB stars undergoing TDU. Nevertheless, some of the stars with the largest F abundances among those in the JSL sample are J-type carbon stars, which do not present $s$-element enhancements (Abia & Isern 2000).
As a part of a more extended work focused on the study of the F production in AGB stars and its dependence with the stellar metallicity, we present here new F abundance determinations in three galactic AGB carbon stars included in the JSL’sample. Based on the analysis of the R9 (1-0) HF line at $\lambda_{\text{air}} = 2.33583 \ \mu m$, we found F abundances on average $\sim 0.8$ dex lower than those in JSL. We discuss the possible reasons of this discrepancy and show that the new F values nicely agree with the state of the art of AGB nucleosynthesis models.

2. Observations and Analysis

Echelle spectra in the 2.3 $\mu$m K-band of two well known galactic AGB carbon stars namely, AQ Sgr (N-type) and R Scl (J-type), were obtained with the 8.2 m Antu telescope of ESO’s VLT on Cerro Paranal observatory using the CRIRES spectrograph. The spectral range covered was $\lambda \sim 2.290 - 2.450 \ \mu m$, with some gaps between the four detectors, including the R9 (1-0) line of HF at $\lambda \sim 2.3358 \ \mu m$. This line, in our opinion, is the best one for F abundances analysis in cool stars as we will show below. The selected spectral domains also contain several CO, C$_2$ and CN lines (and their respective isotopic variations) that allowed the determination of the CNO content, the C/O and $^{12}$C/$^{13}$C ratios in the stars. The resolving power of the spectra was $R \sim 50000$ and the exposure times were chosen to achieve a S/N ratio larger than 100 at the position of the R9 HF line. The reduction and calibration of the spectra were done with the standard CRIRES pipeline procedures. Hot standard stars at similar air mass were observed immediately after each target object to properly remove telluric lines using the task *telluric* within the IRAF software package.

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1In the following, all the wavelengths will be given in air.

2Observing programs 080.D-0310(A) and 081.D-0276(A), respectively.
Additionally, and for comparison purposes, we also analysed the $\sim 2.3 \, \mu m$ spectrum of the AGB carbon star TX Psc (N-type) and of the normal (O-rich) giant $\alpha$ Boo (Arcturus), both stars also included in the JSL’s sample. The spectra of these stars were obtained from the NOAO digital public archive of high resolution infrared spectra\(^3\) and have a resolving power $R > 45000$. More details on these spectra (telescopes, dates of observation etc.) can be seen in Wallace & Hinkle (1996). The NOAO spectra include many other HF lines, among them the R15 ($\lambda \sim 2.2826 \, \mu m$) and R16 ($\lambda \sim 2.2778 \, \mu m$) (1-0) HF lines used in the JSL’s analysis of AGB carbon stars. For TX Psc, we also analysed the optical spectrum obtained with the SARG spectrograph at the 3.5 m TNG at the Roque de los Muchachos Observatory. The resolving power of this spectrum is $\sim 160000$ and the S/N ratio achieved largely exceeded 100 in the analysed spectral range (4700 $-$ 8100 Å). This allowed us to derive the $s$-element abundances in this carbon star.

Atmospheric parameters were derived in the following way: for Arcturus we adopted those deduced by Peterson et al. (1993): $T_{\text{eff}} = 4300$ K, $\log g = 1.5$, [Fe/H] = $-0.5$ and $\xi = 1.7 \, \text{km s}^{-1}$. For the carbon stars, the effective temperatures derived from infrared photometry calibrations by Bergeat et al. (2001) were adopted. For the other parameters (namely, gravity, metallicity, microturbulence and the CNO abundances), the values derived by Lambert et al. (1986) were used. We verified, for instance, that such metallicity values are compatible with the metallicity that we derive from a Fe I line at $\lambda \sim 2.3308 \, \mu m$ and from a Na I line at $\lambda \sim 2.3348 \, \mu m$, both covered in the spectral range studied here. These stellar parameters were considered, nevertheless, as a starting point, the final adopted values (Table 1) were obtained through an iterative process by comparing the observed spectra with theoretical ones. We advance that the stellar parameters deduced here for all the stars are very similar to those adopted in JSL, so that the resulting differences in the F

\(^3\)ftp://ftp.noao.edu/catalogs/hiresK/.
abundances cannot be ascribed to that.

We used spherically symmetric model atmospheres computed from a new version of the MARCS code for cool O-rich and C-rich stars assuming a mass of 1 $M_\odot$ for Arcturus, and 2 $M_\odot$ for the rest of the stars in the sample. Details of this new grid of model atmospheres can be seen in Gustafsson et al. (2008) and some details on the C-rich models can be found in de Laverny et al. (2006). For the infrared spectra, the linelist used for $C_2$ is from Wahlin & Plez (2005). The CO lines come from the linelist of Goorvitch (1994), whereas the CN and CH lines were assembled from the best available data and are described in Hill et al. (2002) and Cayrel et al. (2004). Our molecular list also include lines of CaH, SiH, FeH and H$_2$O taken from the HITRAN database (Rothman et al. 2005). Unfortunately, almost no absorption of these molecular species is seen in the spectra of the Sun and/or Arcturus in the 2.3 $\mu$m region, thus they cannot be calibrated using these stars. Nevertheless, when fitting the spectra of the carbon stars in this spectral region, dominated by CO, CN and $C_2$ absorptions (in this order), we verified that only a few of these molecular absorptions need wavelength correction. The line list for the HF lines is the one computed by R.H. Tipping (unpublished) and it is the same used previously by JSL and recently by Uthentaler et al. (2008). The calculated list of Tipping can be regarded as quite accurate (see the discussion in these authors). For the optical spectra of TX Psc, we used the same atomic and molecular line lists as in de Laverny et al. (2006). We refer to these authors for details. Finally, the atomic lines in the infrared were taken from the VALD database (Kupka et al. 2000) and calibrated/corrected by the standard indirect method using the spectra of the Sun and Arcturus.

The classical method of spectral synthesis in LTE for the abundance analysis was used. Theoretical spectra were computed with the TURBOSPECTRUM code (Alvarez & Plez 1998, and further improvements) in spherical geometry and convolved with Gaussian
functions to mimic the corresponding instrumental profiles adding a macroturbulence velocity typically of $\sim 5 - 7 \text{ km s}^{-1}$. A model atmosphere constructed with preliminary parameters derived as mentioned above, was used to produce synthetic spectra in the studied regions. Comparison of synthetic and observed spectra provided new estimates of the CNO abundances, in particular of the C/O ratio that dominates the shape of the spectra, and metallicity, which were then used to select a new model atmosphere. Several clean CO, CN and C$_2$ lines are present in the observed spectral range allowing an independent determination of C and O abundances and of the C/O and $^{12}$C/$^{13}$C ratios. This region contains also interesting $^{12}$C$^{17}$O and $^{12}$C$^{18}$O lines suitable for the determination of the oxygen isotopic ratios (e.g. Harris et al. 1987, and below). This iterative process, which involved also $T_{\text{eff}}$ and gravity (the N abundance has only a minor role in the theoretical spectrum), was carried out until a satisfactory fit to the infrared spectra (and optical, in the case of TX Psc) was found. For the C-rich objects, the derived C/O ratios in that way have an additional uncertainty due to the adopted O abundance which we cannot determine independently. This is because theoretical spectra are almost insensitive to a large variation in the O abundance provided that the difference $\epsilon(C)-\epsilon(O)$ is kept constant. Therefore, this ambiguity allows a range of oxygen abundances and C/O ratios giving almost identical synthetic spectra. Nevertheless, even considering an uncertainty of a factor three in the oxygen abundance, the C/O ratios derived in our C-stars are uncertain in less than a factor $\sim 1.2$. When the final atmosphere parameters were found (see Table 1), the HF lines were included in the computation of the synthetic spectrum and we changed the F abundance until a good fit was obtained to the R9 HF line (and others HF features in the case of TX Psc).

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4The sole HF line detectable in the infrared spectrum of $\alpha$ Boo is the R9 line. For AQ Scl and R Scl, the CRIRES set-up does not allow the simultaneous covering of other HF lines if
The dependence of the fluorine abundance on the stellar parameters relies on the particular HF line used, although it is rather similar for all of them. The results for the R9 line presented below can be considered as a representative case. The changes were computed using a baseline model for TX Psc. A change of +100 K leads to an increase of +0.15 dex in the fluorine abundance; a change of +0.5 in log g produces a variation of −0.15 dex in F and changes of $\xi = +0.5$ kms$^{-1}$ results in a modification of −0.15 dex. Variations in the metallicity of the model atmosphere scale linearly to the F abundance derived. This means that the [F/Fe] ratio is almost independent of the [Fe/H] value adopted in the model atmosphere. An interesting point is that the R9 line is almost insensitive to moderate changes in the C/O ratio (or the CNO content). This is because this line, according to our molecular and atomic line lists, is apparently free of blends (see Figs. 1 and 2 and the discussion below). However, for the other HF lines, for instance the R15 and R16 lines, a change of $\pm 0.05$ dex in the C/O ratio translates directly into a $\pm 0.05$ dex variation of the F abundance. This makes the R9 line very useful for F abundance derivations in cool C-rich objects since in these objects the C/O ratio is the critical parameter determining the structure of the atmosphere and thus, the appearance of the spectrum. The quadratic addition of all these sources of error gives a total uncertainty of $\pm 0.30$ dex for the absolute abundance of F. Adding the uncertainty of the continuum position and the dispersion in the F abundance when derived from several lines, a conservative total error would be $\pm 0.35$ dex. However, the abundance ratio between F and any other element certainly is lower than this value, since some of the above uncertainties cancel out when deriving the abundance ratio: for instance, for the [F/Fe] ratio we estimate a total uncertainty of $\pm 0.25$ dex. This discussion does not include the possible systematic errors as the uncertainty in the model atmospheres and/or N-LTE effects.

the R9 is included.
Figures 1 and 2 show comparisons between observed and synthetic spectra for different F abundances in the spectral region of the R9 line for the AGB carbon stars of this study. Figure 1 displays also the comparison in the spectral ranges of the R15 and R16 lines in the star TX Psc. Final abundances are summarised in Table 1 with the CNO and $^{19}\text{F}$ values, and the corresponding $[\text{F/Fe}]$ and $[\text{F/O}]$ ratios derived here. The second figure in column eight of Table 1 shows the $\epsilon(19\text{F})$ value derived by JSL in the same stars. We derived also the $^{16}\text{O}/^{17}\text{O}$ ratio in the carbon stars of our sample. To do this, we used the $^{12}\text{C}^{17}\text{O}$ line at $\lambda \sim 23357$ Å that can be appreciated to the left wing of the HF R9 line in Figures 1 and 2. We derived 1240, 1200 and 4000 for the $^{16}\text{O}/^{17}\text{O}$ ratio in the stars TX Psc, AQ Sgr and R Scl, respectively. The typical uncertainty in these ratios is $\pm 500$. These ratios are similar to the typical values found in AGB C-stars by Harris et al. (1987). For TX Psc these authors derived $1050^{−500}_{+700}$, which is consistent with the value obtained here. A detailed discussion of the oxygen isotopic ratios in these stars is outside the scope of the present work. Note, nevertheless, that the F abundance derived from the R9 line is not affected at all by the actual $^{16}\text{O}/^{17}\text{O}$ ratio.

From Figures 1 and 2 and Table 1, it is evident that the F abundances derived here are considerably lower that those obtained by JSL. The mean difference in $\epsilon(19\text{F})$ in the four stars is $−0.63$ dex (in the sense this work minus JSL) but, excluding the O-rich star $\alpha$ Boo, where the F abundances derived agree within the error bar, the mean difference increase up to $−0.96$ dex. This difference would be somewhat lower ($−0.83$ dex) if a solar metallicity was adopted in the analysis of R Scl. The metallicity of this star is actually uncertain since we found several combinations of the average metallicity and CNO abundances given a reasonable fit to its spectrum. The theoretical fit to the observed spectrum of this star is indeed difficult. In Figure 2 (top) it can be seen that the spectrum of this star shows broader and more asymmetric lines as compared with the TX Psc and AQ Sgr spectra. Our best estimate of the metallicity in R Scl is $[\text{Fe/H}]= −0.5$, but a $[\text{Fe/H}]\sim 0.0$ value might be
also compatible. In that case, the F abundance derived here would increase by $\sim +0.5$ dex, however the [F/Fe,O] ratios would remain almost the same as those shown in Table 1. In the next section we discuss the possible reasons for the large discrepancy between the F abundances derived here and those in JSL and its consequences concerning the F production in AGB stars.

3. Discussion

As noted in §2, the stellar parameters derived here (see Table 1) for all the stars are very similar to those derived by Jorissen et al. (1992). The major differences are in the $T_{\text{eff}}$ values, which, in any case, do not exceed 150 K. This difference in $T_{\text{eff}}$ cannot explain the difference of about 1 dex in the F abundance of carbon stars. Differences in the spectroscopic parameters of the HF lines (excitation energies and/or oscillator strength) are also discarded since we actually used exactly the same line data than JSL. A possible source of systematic difference might be the use of different model atmospheres. JSL used C-rich model atmospheres computed with an older version of the MARCS code. Actually, the models are the same ones used in the study of the CNO content in AGB stars by Lambert et al. (1986). We analysed our stars with this older version of MARCS models and, depending of the actual stellar parameters, we found a maximum difference of only $\sim -0.15$ dex with respect to the new generation used here (see §2), in the sense of new models minus the older ones. Thus, the only possibility left is the existence of significant atomic and/or molecular blends in the HF lines that have been taken into account in a very

\footnote{We guess that a solar metallicity was used in the analysis of R Scl by JSL considering that for all the AGB stars in their sample they adopted the same stellar parameters than in Lambert et al. (1986).}
different way in both works.

First, it is important to note that the large differences between our F abundances and those by JSL are found only in the C-rich objects. For α Boo, an O-rich star, the F abundance derived agrees within the error bar considering the differences in the adopted model atmosphere parameters. This means that the cause of the discrepancy has to be related with spectral features of C-bearing molecules that become intense when C/O ≥ 1 in the atmosphere. This might explain why Cunha et al. (2003), by using the R9 line, found a good agreement with JSL in their reanalysis of some of the O-rich stars (spectral types M, MS and S). Indeed, it can be seen in Figures 1 (right most panel) and 2, that in the synthetic model computed with no F for the R9 line, the theoretical pseudo-continuum almost reaches the relative flux equal to 1. This means that, according to our atomic and molecular line list, the R9 line is nearly free of blends, provided high resolution spectroscopy is used (R ≥ 30000). On the contrary, for the R15 and R16 lines (those used by JSL, see Fig. 1), the theoretical spectrum with no F clearly shows the presence of blends. Actually, the blending is very important for the R15 line (see Fig. 1 middle panel). According to our molecular line list both, the R15 and R16 lines, are affected by several CO, CN and C2 absorptions. In the R16 case, the most important contributing feature seems to be a $^{12}\text{C}^{12}\text{C}$ line at $\lambda \sim 22778.775$ Å, while in the R15 case, a strong $^{12}\text{C}^{14}\text{N}$ line at $\lambda \sim 22827.354$ Å. No blends with atomic species seem to exist at the position of these lines. On the other hand, JSL used the classical method of equivalent width measurement and curve-of-growth in their analysis. This method might be affected by significant systematic errors when using low S/N spectra and low spectral resolution. However, this is not the case in the JSL’s observational data. These authors indicate that all HF lines were checked for blends and that even in their clean lines (R15 & R16), they take into account the contribution of CN lines when computing the total equivalent widths. Thus, the immediate conclusion is that the molecular line list used here and in JSL differ significantly in the spectral region
of the HF lines. This is unfortunate because there is no way to test the quality of these molecular lists: all the contributing C-bearing molecular features at the R9, R15 and R16 spectral regions are absent in the spectra of any standard star with well known stellar parameters (e.g. the Sun, Arcturus etc) and cannot be indirectly calibrated. Nevertheless, we believe that the molecular line list used here is rather complete. This is supported by the small dispersion among the F abundance derived from several HF lines in TX Psc. Indeed, other HF lines in addition to R9, R15 and R16, fall in the NOAO’s spectrum of TX Psc. We also studied the R13, R14, R17, R18, R20, R21, R22 and R23 HF lines in this star. The R14, R17, R18, R20 and R21 were finally discarded because our synthetic spectrum did not fully reproduced the observed features (indicating that probably our line list is incomplete there) but, the average F abundance derived from the remaining lines (i.e. R9, R13, R15, R16, R17 and R23) was \( \epsilon^{(19F)} = 4.83 \) with a dispersion of only \( \pm 0.11 \) dex. This dispersion is much lower than the expected error due to the uncertainties in the stellar parameters, suggesting that the values adopted here for TX Psc are close to the real atmosphere and, most importantly, that the possible atomic and molecular blends in the region of these six HF lines are properly taken into account. We can safely conclude that our line list is accurate in these spectral regions. A further test to illustrate that the difference between the atomic and molecular line lists used is probably the main cause of the discrepancy with the analysis of JSL is to use TX Psc as the reference star instead of the Sun. The choice of this star is justified considering the good fits that we obtain to its observed spectrum in the 2.3 \( \mu \)m region (see Fig. 1). In that case, our relative abundances would be \([F/H]_{\text{TX Psc}}^{\text{this work}} = -0.18\) and \(-0.28\) dex for R Scl\(^6\) and AQ Sgr, respectively. These numbers have to be compared with \([F/H]_{\text{TX Psc}}^{\text{JSL}} = -0.15\) and \(-0.07\) dex obtained from the

\(^6\)For a better comparison, the \([F/H]_{\text{TX Psc}}\) ratio quoted for R Scl is that obtained assuming [Fe/H] = 0.0 for this star. This probably was the metallicity adopted by JSL (see §2).
JSL analysis of this star. It is clear now that the relative abundances \([F/H]_{\text{TXPsc}}\) between both works agree within the error bar.

The existence of blends in the infrared HF lines has been also reported in O-rich AGB stars. Recently, Uttenthaler et al. (2008) studied the F abundance in the bulge O-rich star M1347 from 10 lines of the (1-0) band of HF. They found peak differences in the F abundance from line to line up to 0.8 dex, with an average dispersion of \(\sim \pm 0.3\) dex. In this case, because the O-rich nature of this star, the main blending source is probably a veiling of O-bearing molecules. Finally, we have to stress a weakness point in this reasoning. The stars for which JSL reported the largest F abundances (and \([F/Fe,O]\) ratios) are carbon stars of SC-type. The origin of these objects is not well established (see e.g. Guandalini et al. 2008) although it is generally accepted that they are transition objects between S and C stars. Their C/O ratio is 1 within \(\pm 0.01\) (or even thousandths of dex!), therefore, according to the above argument, the HF lines should not be very much affected by C-bearing molecular blends. However, it should be mentioned that the structure of the atmosphere can change dramatically with a tiny variation of the C/O ratio when it is very close to the unity. Therefore, SC stars may be the most affected by systematic differences between the model atmosphere and the real star. A more extended study of the F abundances in SC stars is in progress.

How such large reduction of the F abundances in AGB carbon stars would fit in the framework of the current nucleosynthesis models during the AGB phase? Obviously, before extracting any definite conclusion, a similar analysis has to be done in a larger sample of AGB stars (both O-rich and C-rich) within a wider range of metallicity. However, an immediate test would be the comparison between F and s-element abundances in the same object. As mentioned in §1, a simultaneous production of F and s-elements is expected during the AGB phase since, for both species, neutrons coming from the \(^{13}\text{C}(\alpha,n)^{16}\text{O}\)
reaction which is active in the He-shell during the thermal pulse and interpulse phase, are required. Theoretically, the fluorine enhancement in the envelope is mainly determined by the occurrence of TDU episodes, whose efficiency and number depend on the initial metallicity of the star (the lower the metallicity is, the deeper the TDU), on the initial mass and on the mass loss rate. Therefore, the largest F enhancements are expected at low metallicities. Indeed, the F enhancements so far found in planetary nebulae of different metallicities (Zhang & Liu 2005) and in the carbon enhanced metal poor star HE 1305+0132 (Schuler et al. 2007) agree with this theoretical expectation. In Figure 3 we show the relative abundances with respect to Ba derived in TX Psc. They are compared with recent theoretical nucleosythetic predictions for a 2 M_{⊙}, Z = 0.006 TP-AGB model by Cristallo et al. (2008). The s-element abundances in this star were derived from our SARG optical spectrum (see §2) taken for other purposes. Details on the method, approximations and uncertainties of the chemical analysis can be found in our previous works on AGB C-stars (e.g. Abia et al. 2002; de Laverny et al. 2006) and will not be repeated here.

We compare observed and predicted abundances with respect to Ba rather than absolute enhancements because the relative abundances between elements are nearly independent of the details of the AGB modelling (such as the assumed mass loss prescription), and of any possible dilution of the stellar envelope. From Figure 3 it is evident that the observed and predicted [X/Ba] ratios are in a remarkable agreement when the F abundance derived here in TX Psc is used instead of the JSL’s value (open circle). According to Cristallo et al., a ratio [F/Ba] ∼ +0.2 (the JSL’s value) is obtained for a 2 M_{⊙} model but at lower metallicity, Z ∼ 0.001 (or [Fe/H] ∼ −1.14). However, we verified that the assumption of such metallicity for TX Psc, does not allow a correct fit of the observed spectrum and, in addition, the derived relative abundances between the light (ls) s-elements (Sr, Y and Zr) and Ba are not reproduced at all. Unfortunately, there is no information in the literature about the s-element content in AQ Sgr and R Scl but interesting enough, the ratio [F/Fe] = +0.09
derived here in R Scl is compatible with the fact that this star is classified as a J-type carbon star, which typically do not show s-element enhancements (see Abia & Isern 2000). Nevertheless, we can compare the theoretical \([F/hs]\) ratios predicted by the Cristallo et al. low mass AGB models with the observed ratios for some of the MS, S and C-stars in the JSL’s sample (i.e. for the stars that show some s-element enhancement). The s-element abundances for these stars can be taken from Abia et al. (2002) and Abia & Wallerstein (1998) for the C-rich objects, and from Smith & Lambert (1990, and references therein) for the O-rich ones. From the \([\text{Rb}/\text{ls}]\) ratios derived in these stars, Lambert et al. (1995) and Abia et al. (2001) conclude that most of them are low mass (< 3 \(M_{\odot}\)) AGB stars. Therefore, we can safely compare with the predictions for the 2 \(M_{\odot}\) case. Then, the observed average \([F/hs]\) (where hs means the average of Ba, La, Nd and Sm enhancements) is \(-0.22 \pm 0.26\) dex, and \(+0.46 \pm 0.42\) dex for the O-rich and C-rich AGB stars in JSL, respectively. The predicted \([F/hs]\) ratios in the 2 \(M_{\odot}\) \(Z = Z_{\odot}\) model are \(-0.3\) after 4-5 TDU episodes, when \(C/O\sim 0.5 - 0.6\), and \([F/hs]\sim -0.6\) at the end of the AGB (when \(C/O= 1.8\)). That is, models and observations of O-rich stars are in quite good agreement, whereas for the carbon stars, there is almost 1 dex of discrepancy. This discrepancy is almost cancelled when using our new fluorine determinations (see §2).

\[\text{7}\]The nature of J-type stars is also unknown (e.g. Lorentz-Martin 1986). They show larger Li abundances and lower \(^{12}\text{C}/^{13}\text{C}(< 15)\) ratios than the normal N-type carbon stars. These chemical peculiarities might be explained if an extra-mixing and burning mechanism is operating below the convective envelope during the AGB phase (the so called cool bottom process). However, up to date attempts to simultaneously produce fluorine in the framework of this mechanism have failed (e.g. Busso et al. 2007).
4. Conclusions

Fluorine abundances are derived in three Galactic AGB carbon stars of near solar metallicity using the R9 (1-0) HF molecular line and the state of the art of model atmospheres for cool C-rich objects. We show that this line is not very much affected by atomic and molecular blends and therefore is probably the best line to derive F abundances in cool carbon-rich objects. Our results show that the fluorine abundance is systematically reduced in AGB carbon stars by $\sim 0.8$ dex with respect to the sole previous analysis in this kind of stars by Jorissen, Smith & Lambert (1992). For the star TX Psc, where we find a significant F enhancement, the new F abundance agrees nicely with recent nucleosynthesis models of low mass AGB stars of near solar metallicity. We discuss the reasons of the discrepancy with previous measurements and we conclude that most probably blends with C-bearing molecular lines were not properly taken into account in the analysis by JSL. This systematic reduction of the F abundance in AGB carbon stars, if confirmed in a larger sample of stars, could reduce the present difficulty to explain the largest [F/Fe,O] ratios previously found in these stars. In particular, it would not be necessary to search for other nuclear chains and/or non standard mixing mechanism affecting the production/destruction of F in AGB stars. Our results however, do not discard AGB stars as significant F producers, the only way to determine the real contribution of these stars to the F content in the Universe being the interplay between accurate observational data and theoretical modelling.

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Fig. 1.— From left to right, observed (black dots) and synthetic spectra for the star TX Psc in the regions of the R16, R15 and R9 (1-0) HF lines. In each panel, the solid line is the best fit to the HF line: $\epsilon(^{19}\text{F}) = 4.9, 4.7$ and $4.9$, respectively. The dashed lines are synthetic spectra computed with no F, and assuming the abundance derived by JSL, namely 5.55, using the R15 and R16 lines. The discrepancy is evident. The rest of the features in the spectral ranges shown are CO and CN lines. In fact the feature in the left wing of the R9 line (right panel) is a $^{12}\text{C}^{17}\text{O}$ line from which we estimate a ratio $^{16}\text{O}^{17}\text{O} = 1240$ in this star.
Fig. 2.— Detail of the observed (black dots) and synthetic spectra for the stars R Scl (top) and AQ Sgr (bottom) in the region of the R9 (1-0) HF line. Similar to Fig. 1, solid line is the best fit: $c(^{19}F) = 4.15$ and 4.55, respectively, whereas the dashed lines are synthetic spectra computed with no F, and assuming the abundance derived by JSL, 5.40 and 5.48, respectively. Again the discrepancy between both analysis is evident. For these stars we derive a ratio $^{16}O/^{17}O$ of 4000 and 1200, respectively. Note the arbitrary scale in the y-axis and the much broader lines in the spectrum of R Scl.
Fig. 3.— Detailed reproduction of the derived $s$-element abundances (solid circles) in the AGB carbon star TX Psc with the $s$-process nucleosynthetic predictions in a $2 \, M_{\odot}$, $Z = 0.006$ (or $[\text{Fe/H}] \sim -0.36$), TP-AGB model from Cristallo et al. (2008). All the abundance values are referred to Ba. The open circle at $Z = 9$ is the $[\text{F}/\text{Ba}]$ ratio obtained if the fluorine abundance derived in JLS is adopted. Note the much better agreement of the $[\text{F}/\text{Ba}]$ ratio with theoretical predictions when the F abundance derived here is used (see text for details).
Table 1. Atmosphere parameters and fluorine abundances

| Star  | $T_{\text{eff}}$(K) | $\log g$ | $\xi$ $(\text{kms}^{-1})$ | [Fe/H] | C/N/O | C/O | $^{12}$C/$^{13}$C | $^{16}$O/$^{17}$O | $\epsilon(^{19}\text{F})^a$ | [F/Fe] | [F/O] |
|-------|---------------------|----------|-----------------------------|--------|-------|-----|-----------------|-----------------|------------------|--------|------|
| $\alpha$ Boo | 4300                | 1.5      | 1.7                         | -0.5   | 8.06/7.85/8.83 | 0.17 | 7   | ...            | 4.15, (4.01)    | +0.10            | -0.07   |
| AQ Sgr | 2800                | 0.0      | 2.3                         | 0.0    | 8.79/7.76/8.78 | 1.02 | 50  | 1200           | 4.55, (5.48)    | +0.10            | +0.08   |
| R Scl  | 2500                | 0.0      | 2.2                         | -0.5   | 8.34/6.90/8.32 | 1.05 | 20  | 4000           | 4.15, (5.40)    | +0.09            | -0.07   |
| TX Psc | 3100                | 0.0      | 2.2                         | -0.4   | 8.83/7.72/8.82 | 1.03 | 42  | 1240           | 4.83, (5.55)    | +0.65            | +0.10   |

Note. — The abundances in the Table are given in the usual scale $\epsilon(X) = \log N(X)/N(H) + 12$. The solar abundances adopted here are from Asplund et al. (2005). In particular, according to these authors, the solar fluorine abundance is $4.56 \pm 0.30$.

In this column the first number is the abundance of $^{19}$F derived here (with a typical uncertainty of $\pm 0.35$ dex), whereas the second one (in parenthesis) comes from the analysis by JSL. The [F/Fe,O] ratios shown in the Table are obtained using the F abundances derived here.