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Is the fluorine abundance problem in AGB stars solved?

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Abstract. A reanalysis of the fluorine abundance in Galactic AGB carbon stars has been performed from several HF (1-0) molecular lines in the 2.3 μm range. High-resolution and high signal to noise spectra from the FTS spectrograph were obtained from the NOAO archive. Using spectral synthesis in LTE we derive fluorine abundances that are systematically lower by ~ 0.7 dex on average with respect to previous estimates. We conclude that the reason for this relies mainly on differences in the molecular line list, which has been largely improved in this work. The new F abundances are in much better agreement with the predictions from full network stellar models of low mass AGB stars.

Key words. Stars: abundances – Stars: atmospheres – Stars: AGB

1. Introduction

The origin of the sole stable isotope of fluorine, ^{19}F, is not well known. Three are three proposed sites of F production: neutrino spallation in gravitational supernovae (SNII) (Woosley & Haxton 1988); hydrostatic He-burning in heavily mass-losing Wolf-Rayet (WR) stars (Meynet & Arnould 2000); and 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 controversial, although Renda et al. (2004) concluded that the inclusion of all three components is necessary to explain the observed fluorine Galactic evolution. However, recent observational and theoretical works (Federman et al. 2005; Palacios et al. 2005) seem to leave no space for a significant production of F in SN II and WR stars. This leaves AGB stars as the only significant producers. Nevertheless, even this third pos-

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sible source has recently been put in doubt: an abundance analysis in a few Galactic AGB carbon stars by Abia et al. (2009) obtained F abundances significantly lower than those in the sole previous study by Jorissen et al. (1992, hereafter JSL), leaving the question of the origin of this element open.

Aimed by this latest result and, 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 a more extended sample of galactic AGB carbon stars. Most of them were included in the JSL sample. We base this study on the analysis of several HF lines at $\lambda \sim 2.30$ μm, using improved atomic and molecular line lists in this spectral range and the latest generation of MARCS carbon enhanced atmosphere models for cool giants (Gustafsson et al. 2008). We confirm the previous result by Abia et al. (2009) and show that the new F values nicely agree with the most recent AGB stellar models. This confirms AGB stars as the only objects where there is evidence of an ongoing F production.

2. The new analysis

Our data mainly consist of high-resolution spectra near 2.3 μm obtained with a Fourier Transform Spectrometer at the 4 m telescope in the Kit Peak Observatory. Typical resolutions ranged from 0.05 to 0.14 cm^{-1} (R= 87000 to 30000). High resolution optical spectra (R~160000) obtained at the 3.5 m TNG at La Palma Observatory with the SARG echelle spectrograph were also used to derive the *s*-element content in some stars. Our sample star contains the majority of the AGB carbon stars studied by JSL. We adopted the stellar parameters (T$_{eff}$, log g, [Fe/H], ξ, 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. The method of analysis involves the comparison of theoretical LTE spectra 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 Abia et al. 2009, for details).

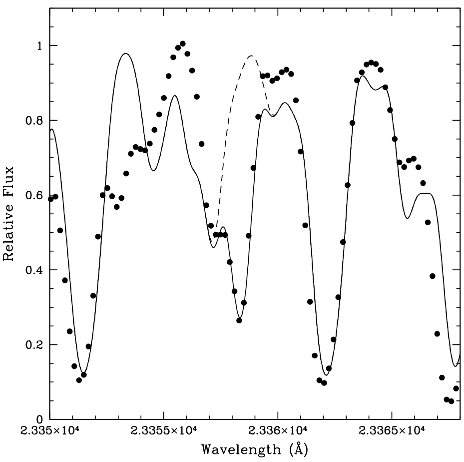

Fig. 1. Synthetic fits (lines) to the observed spectrum (dots) of the SC-type star WZ Cas ([Fe/H]≈0.0) in the region of the R9 HF line at 2.3358 μm. The dashed line is a theoretical spectrum computed with no F, while the continuous line is computed assuming a F enhancement of [F/Fe]=+1.15, our best fit. WZ Cas shows the highest F enhancement among the stars studied.

Fig. 1 shows an example of the comparison between the observed and theoretical spectrum for the carbon star WZ Cas (SC-type) in the spectral range of the R9 HF line. Our best estimation in this star (log $\epsilon(F)$ =5.8, continuous line in Fig. 1) fits also quite well the six other HF lines used in the analysis of this star; the mean dispersion found is ±0.15 dex. Similar quality fits were obtained for the rest of the stars in the sample. In fact, the typical mean dispersion among the different HF lines used in a specific star is of ±0.08 dex. The formal error in the F abundance due to uncertainties in the stellar parameters ranges from 0.30 − 0.35 dex in the [F/H][1] ratio, depending on the particular HF line.

For the [F/Fe] ratio we estimate a total uncertainty somewhat lower, ±0.25 dex. The final

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[1] The solar F abundance adopted here is 4.56 (Grevesse et al. 2007).

F abundances derived here are systematically lower than those derived by JSL for the stars in common, the differences range from 0.3 dex up to more than 1 dex. The average difference value found is $\Delta\log\epsilon(F)=+0.7$. This confirms the main result of Abia et al. (2009). As noted there, the differences between the molecular line lists used in each study is the main cause of the discrepancy with respect to the analysis of JSL.

For the SC-type stars, it is a combination of that and the use of a different grid of model atmospheres (for these particular stars JSL used Johnson (1982) models). 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 in the case of SC stars. Therefore, the abundance analysis 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.

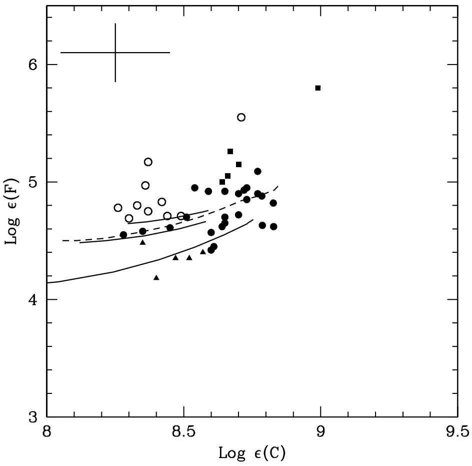

Fig. 2. Logarithmic abundances of fluorine vs. carbon. Symbols: solid circles, N-stars; triangles, J-type stars; squares, SC-type stars and open circles, intrinsic O-rich AGB stars from JSL. Lines are theoretical predictions for a 1.5 $M_\odot$, TP-AGB model with metallicities $Z=0.02$, $Z_\odot$ and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

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 ~1 dex. These enhancements can be accounted for by current low-mass TP-AGB nucleosynthesis models of solar metallicity. During the ascension along the AGB, fresh carbon is mixed within the envelope due to third dredge up (TDU) episodes. Similarly, F is also expected to increase in the envelope during the AGB phase, thus a fluorine vs. carbon correlation should exist.

Fig. 2 shows the observed relationship derived in this study. We have also included in this figure the intrinsic O-rich AGB stars studied by JSL (not analysed here, open circles). Excluding the J-type[2] stars (triangles), a clear increase of the F abundance with the C abundance can be seen. This behaviour is well reproduced by theoretical AGB models. Lines in Fig. 2 show the predicted F and C content in the envelope (Cristallo 2010) for a 1.5 $M_\odot$ with different metallicities (continuous lines) and 2 $M_\odot$ model (dashed line) with solar metallicity. These metallicities match those of the stellar sample ($-0.5\leq[Fe/H]\leq0.1$). 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, Fig. 2 seems to indicate that O-rich stars and SC stars (squares) have F abundances systematically larger than N-type stars for a given C abundance. This may be also simply due to a systematic error affecting the analysis. In fact, for stars of spec-

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[2] The origin of J-type carbon stars is still unknown. They are slightly less luminous than N-type and show chemical peculiarities that are 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).

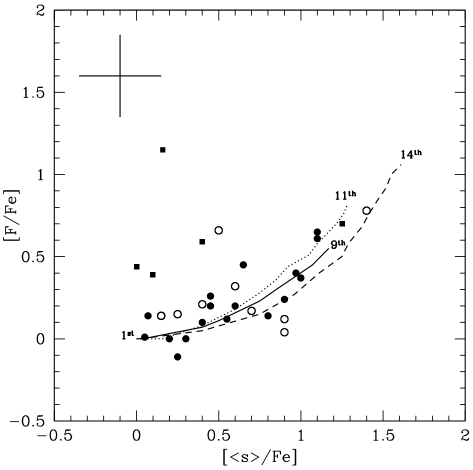

Fig. 3. Fluorine vs. average *s*-element enhancements in Galactic AGB stars. Symbols as in Fig. 2. Lines are theoretical predictions for 1.5, 2 and 3 $M_{\odot}$, *Z*=0.008 TP-AGB models (solid, dashed and dotted lines, respectively) from Cristallo (2010). The number of TPs achieved by each models is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

tral 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. These K and M stars are sub-giants or RGB stars, thus they are not expected to present F enhancements. Indeed, blends may also play a role in the analysis of F lines in O-rich stars. By decreasing the F abundances by 0.13 dex in the O-rich stars, the agreement with theoretical predictions would be definitely better.

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 ([Fe/H]~0.0, at the right upper corner of Fig. 2), which shows a huge F enhancement (see Fig. 1). We restate, however, that this star is indeed peculiar: it is one of the few super Li-rich carbon 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 TP. 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 about 70% of the total F production. 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.

Fig. 3 shows the new [F/Fe] ratios in C-stars vs. the observed average *s*-element enhancement (Abia et al. 2002). J-type stars are not shown in this figure as they do not have *s*-element enhancements (Abia & Isern 2000). Similar to Fig. 2, we have included the intrinsic O-rich stars analysed by JSL and 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 (Cristallo 2010). The theoretical predictions in Fig. 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 analysed here) starting from the 1^{st} TP.

The number of TPs calculated until the occurrence of the last TDU is indicated in the figure for each model. In addition, with the combination of models with different stellar

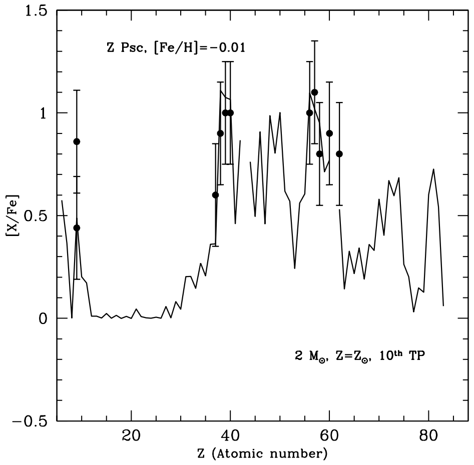

Fig. 4. Comparison of observed (points) and predicted element ratios [X/Fe] in the AGB carbon star Z Psc. The continuous line represents the [X/Fe] ratios expected in the envelope in a 2 M$_\odot$ AGB mass model of solar metallicity after ten TPs Cristallo et al. (2009). The point at Z=9 and [X/Fe]≈0.85 is the [F/Fe] ratio derived by Jorissen et al. (1992). For Z Psc we derive a lower enhancement, [F/Fe]=0.45. We do not find any combination of an AGB mass model and metallicity able to fit the observed abundance pattern in the stars studied when adopting the F abundance obtained by these authors.

mass and metallicity, it is possible not only to reproduce the new observed [F/Fe] vs. s-element relationship, but also the detailed F and $s-$element abundance pattern observed in a particular star (see Fig. 4). Note that this was not possible for most of the stars when adopting the F determinations of JSL.

As already noted, most of the SC-type stars in the present sample 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 (on 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 et al. 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 mechanism which operates only for M≥4 M$_\odot$. Detailed abundance studies (including F) in a larger sample of SC-stars is needed to confirm this hypothesis.

4. Conclusions

Fluorine abundances in Galactic AGB carbon stars are determined from high resolution infrared spectra. We derive F abundances that are in average ∼0.7 dex lower than those derived in the sole previous study by JSL. The reason of this is most probably the use of different molecular line list in the 2.3 μm spectral domain that have been considerably improved here. A clear correlation between the F and s-element enhancements is found. This correlation and the new fluorine enhancements can be explained by standard low-mass ($<$ 3 M$_\odot$) AGB stellar models. This apparently solves the long standing problem of the F abundances in Galactic AGB carbon stars without requiring the operation of non-standard mixing/burning processes during the AGB phase.

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