CSIRO PUBLISHING
www.publish.csiro.au/journals/pasa *Publications of the Astronomical Society of Australia*, 2009, **26**, 351–353

Fluorine Abundances in AGB Carbon Stars: New Results?

C. Abia[A,D], *P. de Laverny*[B], *A. Recio-Blanco*[B], *I. Domínguez*[A], *S. Cristallo*[C], *and O. Straniero*[C]

[A] Dpto. Física Teórica y del Cosmos, Universidad de Granada, 18071 Granada, Spain
[B] Observatoire de la Côte d'Azur, Dpt. Cassiopée UMR 6202, 06304 Nice Cedex 4, France
[C] INAF-Osservatorio di Collurania, 64100 Teramo, Italy
[D] Corresponding author. Email: cabia@ugr.es

Received 2008 November 15, accepted 2009 March 11

Abstract: A recent reanalysis of the fluorine abundance in three Galactic Asymptotic Giant Branch (AGB) carbon stars (TX Psc, AQ Sgr and R Scl) by Abia et al. (2009) results in estimates of fluorine abundances systematically lower by ~0.8 dex on average, with respect to the sole previous estimates by Jorissen, Smith & Lambert (1992). The new F abundances are in better agreement with the predictions of full-network stellar models of low-mass ($<3\,M_{\odot}$) AGB stars.

Keywords: nuclear reactions, nucleosynthesis, abundances — stars: abundances — stars: AGB — stars: carbon — stars: evolution

1 Introduction

There are three proposed sites for ^{19}F production: neutrino spallation on ^{20}Ne in core collapse 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). To date, the contribution of Wolf-Rayet and supernova sources to the F content of the Universe is still controversial (Federman et al. 2005; Palacios, Arnould & Meynet 2005). This leaves AGB stars as the only significant producers.

The first evidence of F production in AGB stars was provided by 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→MS→S→C). JSL found [F/Fe] ratios up to ~100-times solar and a clear correlation between 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 F production in AGB stars. Nevertheless, nucleosynthetic models in AGB stars have failed to quantitatively reproduce the largest [F/Fe,O] ratios found in the JSL 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 the search for alternative nuclear chains (e.g. Lugaro et al. 2004), or for non-standard mixing processes capable to increase the F production (e.g. the cool bottom process, see Busso et al. 2007). However, no satisfactory solution has been found, making this large fluorine enhancement a major challenge for stellar nucleosynthesis.

2 Discussion

Very recently Abia et al. (2009; hereafter A09) mainly based on the analysis of the R9 (1-0) HF line at $\lambda_{air} = 2.33583\,\mu$m, found F abundances on average ~0.8 dex lower than those in JSL. A09 carefully discussed the possible reasons of this discrepancy concluding that the most probable cause is the existence of significant atomic and/or molecular blends in the HF lines used in both works that were taken into account in a very different way. These blends might be due to carbon-bearing molecules, since in the sole O-rich giant star in common (Arcturus) the F abundance derived by JSL and A09 agrees within the abundance uncertainties. In fact, A09 argued that the molecular line list used by them is rather complete because of the small dispersion among the F abundance derived from seven HF lines in TX Psc (one of the stars in common), $\epsilon(^{19}\mathrm{F}) = 4.83 \pm 0.11$ dex. This dispersion is much lower than the expected error due to uncertainties in the stellar parameters (see A09 for a detailed discussion).

How does such a large reduction of the F abundances in AGB carbon stars fit in the framework of the current nucleosynthesis models during the AGB phase? An immediate test would be the comparison between F and *s*-element abundances in the same object. Theoretically, simultaneous production of F and *s*-elements is expected during the AGB phase since, for both species, neutrons coming from the ^{13}C$(\alpha, n)^{16}$O reaction are required. In Figure 1 we show the relative abundances with respect to Ba derived in TX Psc ([Fe/H] = −0.4, see A09). They are

10.1071/AS08038 1323-3580/09/03351

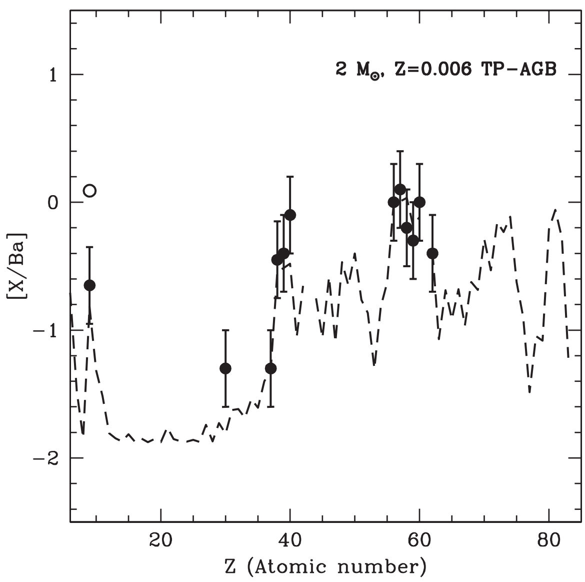

Figure 1 Detailed reproduction of the derived [X/Ba] ratios (solid circles) in the AGB carbon star TX Psc with the *s*-process nucleosynthetic predictions in a 2 $M_\odot$ TP-AGB model from Cristallo et al. (2009) after the 11th TP. The open circle at $Z = 9$ is the [F/Ba] ratio obtained if the fluorine abundance derived in JLS is adopted.

compared with recent theoretical nucleosynthetic predictions for a 2 $M_\odot$, $Z = 0.006$ TP-AGB model by Cristallo et al. (2009). From Figure 1, it is evident that the observed and predicted [X/Ba] ratios are in a remarkable agreement when the revised F abundance is used instead of the JSL value (open circle). We compare observed and predicted abundances with respect to Ba rather than absolute enhancements ([X/Fe]) because the relative abundances between *s*-elements after a few thermal pulses and dredge-up episodes 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.

Nevertheless, the derived [X/Fe] ratios in TX Psc can be fitted within the experimental error bars at the TP numbers 4, 5 or 6 according to our 2 $M_\odot$, $Z = 0.006$ AGB model. Considering the uncertainty in the metallicity of this star and in its actual mass, fits of similar quality to the observed *s*-process pattern can be found using AGB models of 1.5 and/or 3 $M_\odot$ with a slightly different metallicity at different thermal pulses (Domínguez, private communication). Indeed, according to Cristallo et al. (2009), a ratio [F/Ba] $\sim +0.2$ (JSL's value) is only obtained for a 2-$M_\odot$ AGB model with much lower metallicity, $Z \sim 0.001$. However, according to A09, such metallicity assumption for TX Psc does not allow a correct fit to 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. We note that although there is no information in the literature about the *s*-element content in AQ Sgr and R Scl (the other C stars in common between A09 and JSL), interestingly enough the ratio [F/Fe] $= +0.05$ derived by A09 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) and hence would not show F enhancements either.

A point of concern is, however, the simultaneous fit of the observed C/O ratio and *s*-element enhancements in TX Psc. At the TP numbers mentioned above, the predicted C/O ratios in the 2-$M_\odot$ $Z = 0.006$ model, range between 2 and 4, higher than the observed value of $\sim$1.03 (see A09). A C/O ratio slightly larger than unity is already obtained in the second TP, but in that case the predicted [X/Fe] ratios are too low, actually we obtain [F/Fe] $\sim +0.35$, marginally in agreement with the observed value (see Cristallo et al. 2009 for details). This is not new, since the current theoretical models are known to predict higher C/O ratios than observed in AGB carbon stars (see e.g. de Laverny et al. 2006) for a given average *s*-element enhancement. The reason for this is still unknown but may be related to both an observational bias and the extreme dependence of the predicted envelope mixing in AGB stars on the model parameters (mass loss, TDU efficiency etc., see e.g. Straniero et al. 2003).

How would these new F abundances affect the observed and predicted [F/O] versus C/O or *s*-element enhancement correlation? Obviously, F abundances have to be derived in a larger sample of *s*-enhanced (intrinsic or extrinsic) carbon stars before extracting any conclusion. Nevertheless, we note that the observed [F/O] versus C/O correlation derived by JSL might be affected by large systematic uncertainties. The difficulty relies not only on the fact that the correlation is not well established (since most of the AGB carbon stars show C/O ratios very close to 1), but also on the very uncertain absolute O abundances of these stars.

The point is that the main parameter controlling the shape of the spectrum in a carbon star is the C/O ratio. For a given C/O ratio, there is a degeneracy in the absolute O abundance since, keeping C/O constant, there is a range of O abundances giving exactly the same theoretical spectrum. This is because in carbon stars, when adding equal quantities of C and O, the only effect is to form more CO without affecting the continuous opacity and, thus, the synthetic spectrum. de Laverny et al. (2006) found that variations of at least a factor 3 in the absolute abundance of O are indistinguishable in the synthetic spectrum for a given C/O ratio. Such degeneracy in the O abundance might have dramatic systematic effects on the derived [F/O] ratio. For this reason, we believe that [F/Fe] ratios instead of [F/O] should be used when comparing with theoretical models, even if the Fe abundance in these stars is derived from a few lines. In any case, previous theoretical models (e.g. Goriely & Mowlavi 2000), as well as those used here (Cristallo et al. 2009), predict a correlation between [F/O] and [C/O]. This correlation should, hence, be tested with more and accurate F and O determinations in AGB carbon stars in a wider range of C/O ratios.

Concerning the observed and predicted correlation between the [F/Fe] (or [F/O]) and the *s*-element enhancement (e.g. [Zr/Ti], see Goriely & Mowlavi 2000), we have

https://doi.org/10.1071/AS08038 Published online by Cambridge University Press

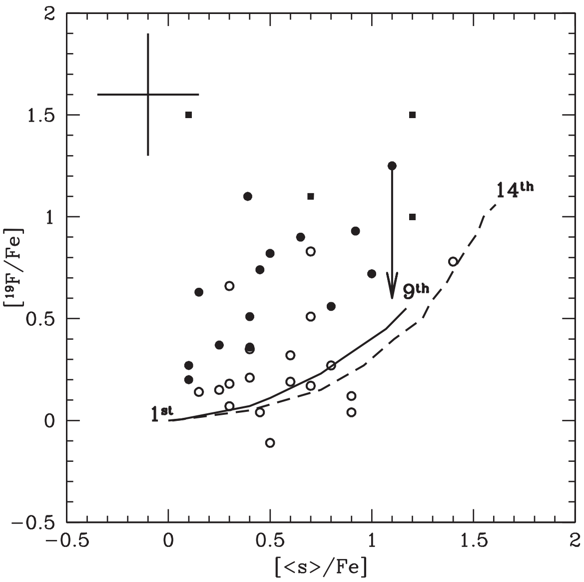

Figure 2 Observed and predicted F and average *s*-element (Sr, Zr, Y, Ba, La, Nd and Sm) enhancement in galactic AGB stars. Solid circles are C-rich stars, open circles O-rich stars and squares SC-type stars. The lines are theoretical predictions in a 1.5 $M_\odot$ (solid line) and 2.0 $M_\odot$ (dashed line) with $Z = 0.006$ according to Cristallo et al. (2009) starting from the first (1st) thermal pulse. The metallicity of the stars are in the range $-0.5 \leq$ [Fe/H] ≤ 0.1. Fluorine abundances are taken from JSL while *s*-element abundances from Smith & Lambert (1990) (O-rich stars) and Abia & Wallerstein (1998) or Abia et al. (2002) (C-rich stars). The arrow indicates the new location of the star TX Psc according to the F abundance derived in A09.

to note that it was constructed using the old *s*-element abundances derived by Utsumi (1985) in AGB carbon stars. Abia et al. (2002) showed that these enhancements were overestimated by a large factor (up to ~1 dex) due to the existence of spectral blends not properly taken into account in Utsumi's analysis. By using these revised *s*-element abundances in C-stars together with those derived in O-rich MS and S-type stars by Smith & Lambert (1990), we have constructed a new plot between the observed [F/Fe] ratios and the average *s*-element enhancements (see Figure 2) in galactic O- and C-rich AGB stars. From Figure 2 it can be seen that there is still a correlation, but that model predictions and observations disagree mainly for C-rich objects. Note however that a systematic reduction in the F abundance of carbon stars on the order of that found in A09 (as in the case of TX Psc, see arrow in Figure 2) would favour the agreement between observations and theory.

3 Summary

We have compared the new (lower) F abundances found by Abia et al. (2009) in galactic AGB carbon stars with the state of the art of low-mass AGB nucleosynthesis models. For the only carbon star (TX Psc) for whose new F and *s*-element abundances exist we find a nice agreement. However, a discrepancy seems still to exist between predicted and observed [F/Fe] ratios in carbon stars if the F abundances derived by Jorissen, Smith & Lambert (1992) are considered. A systematic reduction of F abundances in these stars of the order of that found by Abia et al. (2009) would put into a better agreement observations and nucleosynthesis predictions.

References

Abia, C. & Wallerstein, G., 1998, MNRAS, 293, 89
Abia, C. & Isern, J., 2000, ApJ, 536, 438
Abia, C. et al., 2002, ApJ, 579, 817
Abia, C., Recio-Blanco, A., de Laverny, P., Cristallo, S., Domínguez, I. & Straniero, O., 2009, ApJ, in press (astro-ph/0812.3103)
Busso, M., Wasserburg, G. J., Nollet, K. M. & Calandra, A., 2007, ApJ, 671, 802
Cristallo, S., Straniero, O., Gallino, R., Piersanti, L., Domínguez, I. & Lederer, M. T., 2009, ApJ, 694, 971
de Laverny, P., Abia, C., Domínguez, I., Plez, B., Straniero, O., Wahlin, R., Eriksson, K. & Jørgensen, U. G., 2006, A&A, 446, 1107
Federman, S. R., Sheffer, Y., Lambert, D. L. & Smith, V. V., 2005, ApJ, 619, 884
Forestini, M., Goriely, S., Jorissen, A. & Arnould, M., 1992, A&A, 261, 157
Goriely, S. & Mowlavi, N., 2000, A&A, 362, 599
Jorissen, A., Smith, V. V. & Lambert, D. L., 1992, A&A, 261, 164
Lugaro, M., Ugalde, C., Karakas, A., Görres, J., Wiescher, M., Lattanzio, J. C. & Cannon, R. C., 2004, ApJ, 615, 934
Meynet, G. & Arnould, M., 2000, A&A, 335, 176
Palacios, A., Arnould, M. & Meynet, G., 2005, A&A, 443, 243
Smith, V. V. & Lambert, D. L., 1990, ApJS, 72, 387
Straniero, O., Domínguez, I., Cristallo, R. & Gallino, R., 2003, PASA, 20, 389
Utsumi, K., 1985, in Cool stars with excesses of heavy elements (Dordrecht: D. Reidel Publishing Co.), 243
Woosley, S. E. & Haxton, W. C., 1988, Nature, 334, 5

https://doi.org/10.1071/AS08038 Published online by Cambridge University Press