Fluorine abundances in dwarf stars of the solar neighbourhood[*]

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ABSTRACT

Context. In spite of many observational efforts to characterize the chemical evolution of our Galaxy, not much is known about the origin of fluorine (F). Models suggest that the F found in the Galaxy might have been produced mainly in three different ways, namely, Type II supernovae, asymptotic giant branch nucleosynthesis, or in the core of Wolf-Rayet stars. Only a few observational measurements of F abundances are available in the literature and mostly for objects whose characteristics might hamper an accurate determination of fluorine abundance (e.g., complex mixing and nucleosynthesis processes, external/internal contamination).
Aims. We acquire data using the high-resolution IR-spectrograph CRIRES and gather FEROS data from the European Southern Observatory archive. The classical method of spectral synthesis in local thermodynamic equilibrium has been used to perform the abundance analysis.
Methods. We derive the F abundances of nine cool main-sequence dwarfs in the solar neighbourhood, based on an unblended line of the HF molecule at 2.3 microns. In addition, we study the s-process elements of five of these stars.
Results. Several of the analysed stars seem to be slightly fluorine enhanced with respect to the Sun, although no correlation is found between the F abundance and the iron content. In addition, the most fluorine enriched stars are also yttrium and zirconium enriched, which suggests that AGB fluorine nucleosynthesis is the dominant source of fluorine production for the observed stars. Nevertheless, the correlation between [F/Fe] and the s-elements is rather weak and possibly masked by the uncertainties in the F abundance measurements. Finally, we compare our derived F abundances to previous measurements of alpha-element and iron-peak element abundances. Type II core collapse supernovae do not appear to be the main site of F production for our targets, as no correlation seems to exist between the [F/Fe] and the [α/Fe] ratios.

Key words. stars: abundances – stars: solar type – solar neighbourhood

1. Introduction

Fluorine is currently believed to come from three main different astrophysical sources. First, it is thought to be produced in type II supernovae through neutrino spallation of one proton of ^{20}Ne, following the core-collapse phase of a massive star (e.g. Woosley et al. 1990). Second, low-mass ($2-4$ $M_\odot$) asymptotic giant branch (AGB) stars are also believed to be producers of F during He-burning pulses. Several lines of evidence confirm that the nucleosynthesis of F occurs in AGB stars: correlations of F enhancements with other products of AGB nucleosynthesis such as the C/O ratio and the s-element abundances (Jorissen et al. 1992; Abia et al. 2010); the observation of an enhancement in the fluorine content of planetary nebulae (Liu 1998; Otsuka et al. 2008) or post-AGB stars (Werner et al. 2005); and the detection of the AlF molecule in the circumstellar envelope of the AGB star IRC+10216 (Cernicharo & Guelin 1987). Moreover, there is evidence that fluorine is produced in the cores of Wolf-Rayet (WR) stars at the begining of their He-burning phase (Meynet & Arnould 2000; Stancliffe et al. 2005), and is spread

into the interstellar medium by the strong mass-loss rate of these objects (with relatively high metal content). As for the AGB stars, ^{19}F in this case is produced from ^{14}N nucleii (e.g. Zhang & Liu 2005). Nevertheless, Palacios et al. (2005), who included rotation in their models, showed that the WR contribution to Galactic fluorine remains quite open. In addition to the above-mentioned sources of F, a fourth possible contributor was proposed by Longland et al. (2011), who suggested that F could be synthesised in the merger of a helium white dwarf and a carbon-oxygen white dwarf.

Which of the above-mentioned sources is the most important one is currently under debate. In spite of the many uncertainties regarding the origin of F in the Galaxy, there have not been many observational studies of this element. A pioneering study was carried out in 1992 (Jorissen et al. 1992), where F abundances were derived from HF lines for a set of Galactic K and M giants, as well as a large number of s-process enriched Galactic AGB stars. All the targets had metallicities near solar. Since then, other works have studied the nucleosynthesis of F in AGB stars. Abia et al. (2009, 2010 and 2011) revised the F enhancements of the C-rich objects in the Jorissen et al. (1992) sample and determined for the first time F abundances in six extragalactic carbon stars. Their measurements are

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in closer agreement with the most recent theoretical nucleosynthesis predicions (Cristallo et al. 2009), although they have a different dependence on the stellar metallicity. However, Lucatello et al. (2011) measured the F abundance of ten Galactic extrinsic carbon-rich, low-metallicity stars concluding also that predictions from nucleosynthetic models for low-mass, low-metallicity AGB stars account for the derived F abundances, while the upper limits on the F content derived for most of the stars are lower than the predicted values.

The fluorine abundance patterns in the low-metallicity regime were also explored by Cunha et al. (2003), who derived F abundances for a sample of giants in the Large Magellanic Cloud and in the globular cluster ω Cen. They found that the abundance ratio of F/O declines as the oxygen abundance decreases. They therefore suggested that the observed low values of F/O exclude AGB synthesis as the dominant source of fluorine in their targeted stellar populations. In particular, the targeted stars in ω Cen did not have enhanced F abundances, despite their large s-process abundance values. In addition, they claimed a qualitative agreement with what is expected if ^{19}F is produced via H- and He-burning sequences in very massive stars (fluorine being ejected in high mass-loss rate WR winds). Finally, they found a quantitative agreement between the Galactic and Large Magellanic Cloud results with the predictions of models in which ^{19}F is produced from neutrino nucleosynthesis during core collapse in supernovae of Type II.

The same authors studied fluorine abundances in three low-mass young stars in the Orion Nebula Cluster (Cunha et al. 2005), and in red giants of the southern globular cluster M4 (Smith et al. 2005). The later work revealed that the abundance of fluorine is found to vary by more than a factor of six among cluster stars. The ^{19}F variations are correlated with already established oxygen variations, and anticorrelated with the sodium and aluminium variations, suggesting a link with the abundance anomalies caused by the pollution from previous generations of stars. In addition, ^{19}F is found to decrease in the M4 stars, as the signature of H burning appears. Finally, Cunha et al. (2008) derived F abundances in a sample of six bulge red giants. The lack of an s-process enhancement in the most fluorine-rich bulge giant in this study lead the authors again to conclude that WR stars contribute more than AGB stars to F production in the bulge and even more so than they do in the disc.

The aforementioned observational results combined with theoretical models currently indicate that all three suggested sources of fluorine contributed to the observed abundances of this element in different epochs of the evolution of the Galaxy (Renda et al. 2004; Kobayashi et al. 2011). However, the relative contributions of the three F producers remains disputed. The targets observed so far are probably not the most appropriate one for deriving accurate F abundances. First, most of them are giant stars, where mixing may have occurred, changing the surface elemental ratios. In addition, some of these are globular cluster giants, where some important external pollution (from previous generations of stars) may have taken place (e.g. Gratton et al. 2000; Smith et al. 2005) or very young cool dwarfs, which likely have infra-red disk emission.

In other words, an improvement in our knowledge of the possible fluorine astrophysical sources is necessary to solve long-standing discrepancies between Galactic chemical-model predictions and observed F abundances. Clues to the site of fluorine synthesis lie in the run of the fluorine abundance with metallicity in the Galaxy and in different stellar populations. We present here the fluorine abundances derived for nine field main-sequence dwarf stars in the solar neighbourhood, belonging to

the samples studied by Santos et al. (2004), Smith et al. (2005) and Sousa et al. (2006). In addition, s-process elements abundances were also determined for six of the target stars using FEROS spectra taken from the European Southern Observatory (ESO) archive. Section 2 describes the observations and the data analysis. The derived fluorine and s-element abundances are presented in Sect. 3 and compared to the abundances of several other elements already available for those stars from homogeneous analysis in the literature. Finally, conclusions are discussed in Sect. 4.

2. Observations and analysis

We used the high-resolution IR-spectrograph CRIRES (Käufl et al. 2004) mounted on the 8.2 m Antu telescope of ESO's Very Large Telescope on Cerro Paranal observatory to observe nine cool main-sequence dwarfs of the solar neighbourhood. The resolving power of the spectra was $R \sim 50\,000$ and the exposure times were chosen to achieve a signal-to-noise ratio (S/N) larger than 200. The reduction and calibration of the spectra were carried out 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.

Fluorine abundances were derived from an unblended line R9 (1−0) of the HF molecule at $\lambda \sim 2.3358$ μm (Abia et al. 2009). We used the classical method of spectral synthesis in LTE for the abundance analysis. Theoretical spectra were computed with the TURBOSPECTRUM code (Alvarez & Plez 1998, and further improvements) and convolved with Gaussian functions to mimic the corresponding instrumental profiles. To this purpose, we used model atmospheres computed from the new version of the MARCS code (Gustafsson et al. 2008). The atomic and molecular line lists are the same used previously by Abia et al. (2009). They have been calibrated using the spectra of the Sun and Arcturus (the adopted solar abundance of F is 4.56 dex according to Asplund et al. 2009). Accurate stellar parameters and iron abundances for all the program stars, presented in Table 1, were taken from Santos et al. (2004, 2005) and Sousa et al. (2006). These parameters were derived from a homogeneous analysis of optical spectra, thus minimizing the relative errors.

Figure 1 shows the comparison between the observed spectrum of one of our targets (HD 131977) and our best fit synthetic spectrum in the region of the HF R9 line. In addition, two synthetic spectra, corresponding to the errors of the fit for the F abundance (±0.1 dex with respect to the best fit spectrum) are plotted in a zoom window of the same figure.

In addition to the CRIRES data, and for six of our target stars, we used FEROS spectra from the ESO archive to derive the abundances of two light s-elements: yttrium and zirconium. To this purpose, two wavelength regions, 6120 to 6150 Å and 6420 to 6450 Å, were investigated. Within these regions spectral features for iron, yttrium and zirconium were analysed using the spectral synthesis programme MOOG (Sneden 1973) with MARCS stellar atmosphere models (Gustafsson et al. 2008). We tried to measure other s-element abundances, as Ba and Nd, but the quality of the lines was not good enough for the analysis. The Eu II line at 6437 Å was not detected, as expected for a solar Eu abundance at this effective temperature range. We therefore suspect that our target stars are probably not enriched in r-elements, which are produced in Type II supernovae, with an upper limit of 0.3 dex in [Eu/H]. The S/N of the FEROS spectra was between 65 and 85 per pixel, depending

Table 1. Adopted atmospheric parameters (from Santos et al. 2004, 2005; Sousa et al. 2006) and derived fluorine, yttrium, and zirconium abundances for the target stars.

| Target ID	$T_{\rm eff}$ (K)	$\log g$ (dex)	[Fe/H] (dex)	ξ (km s^{-1})	$\log \epsilon$(F) (dex)	[Y/Fe] (dex)	[Zr/Fe] (dex)
HD 50281	4658 ± 56	4.32 ± 0.24	−0.04 ± 0.07	0.64 ± 0.15	4.53 ± 0.20	0.35 ± 0.17	0.36 ± 0.16
HD 65486	4660 ± 66	4.55 ± 0.21	−0.33 ± 0.07	0.82 ± 0.16	4.47 ± 0.20	–	–
HD 85512	4505 ± 176	4.71 ± 0.96	−0.18 ± 0.19	0.32 ± 1.15	4.73 ± 0.20	–	–
HD 101581	4646 ± 96	4.80 ± 0.39	−0.37 ± 0.09	0.58 ± 0.35	4.61 ± 0.20	0.37 ± 0.17	0.32 ± 0.16
HD 111261	4529 ± 62	4.44 ± 0.64	−0.35 ± 0.08	0.78 ± 0.17	4.44 ± 0.20	–	–
HD 131977	4693 ± 80	4.36 ± 0.25	0.07 ± 0.10	0.97 ± 0.16	5.16 ± 0.20	0.33 ± 0.17	0.17 ± 0.16
HD 156026	4568 ± 94	4.67 ± 0.76	−0.18 ± 0.09	0.60 ± 0.26	4.41 ± 0.20	0.33 ± 0.17	0.20 ± 0.16
HD 209100	4629 ± 77	4.36 ± 0.19	−0.06 ± 0.08	0.42 ± 0.25	4.75 ± 0.20	0.30 ± 0.17	0.27 ± 0.16
HD 216803	4555 ± 87	4.53 ± 0.26	−0.01 ± 0.09	0.66 ± 0.28	4.64 ± 0.20	0.15 ± 0.17	0.06 ± 0.16
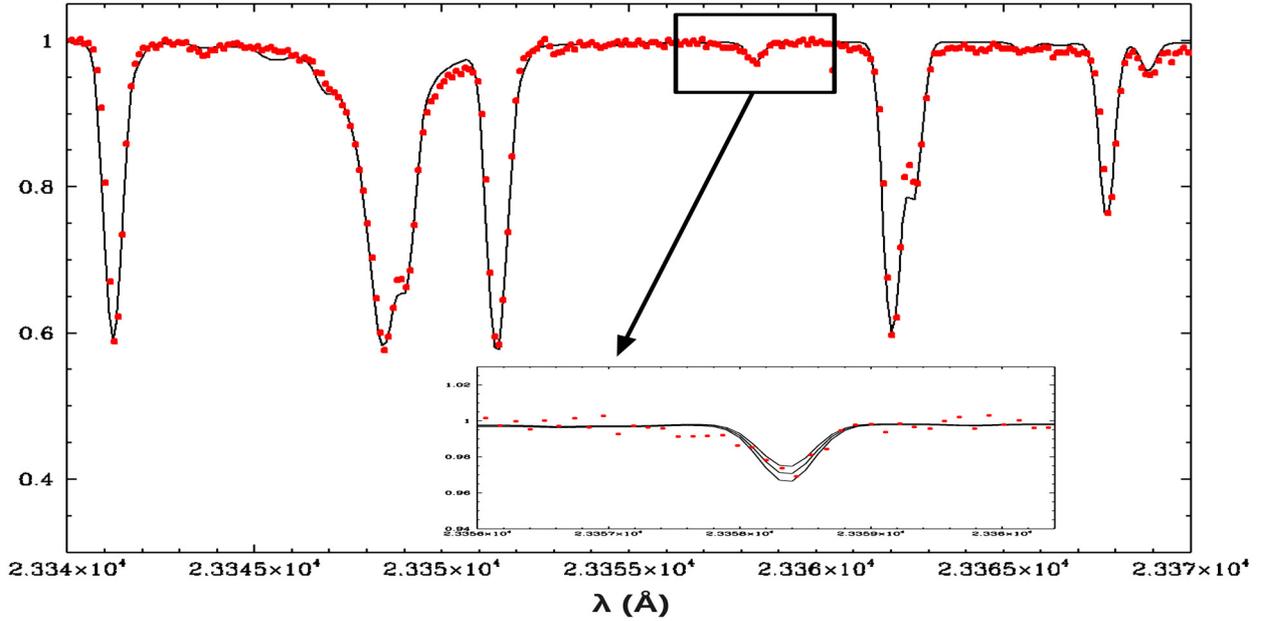
Fig. 1. CRIRES spectrum of HD 131977 (red points) and our best fit synthetic spectrum (black line). The embedded window shows a zoom of the line R9 (1−0) of the HF molecule at $\lambda \sim 2.3358$ μm. The central synthetic spectrum corresponds to the fluorine abundance of our best fit, while the other two lines show the flux variation for an error of 0.10 dex with respect to the best fit.

on the star. The atomic and molecular linelists were collated using the most recent laboratory values where possible, as outlined in Worley et al. (2010) and references therein. For the purposes of this analysis, the linelists were calibrated to the Sun using the MARCS solar atmosphere model. The Fe abundances determined by spectrum synthesis, from both Fe I and Fe II lines, were in good agreement with the metallicities determined previously for these stars by Santos et al. (2004, 2005), and Sousa et al. (2006).

3. Results on fluorine and s-element abundances

The derived abundances of fluorine, yttrium, and zirconium for the target stars are presented in Table 1. For each element, the abundance uncertainty was calculated taken into account the error in the fit (as shown in Fig. 1) and the individual sensitivities of the derived abundances to the adopted effective temperature, surface gravity, metallicity, and microturbulence velocity within the corresponding uncertainties (see Table 1). The resulting abundance uncertainties for these different sources of error were then summed in quadrature to determine the final formal uncertainty that is equal to 0.20 dex for [F/H] and 0.16 dex for [Y/Fe] and [Zr/Fe].

Figure 2 shows our derived fluorine abundances with respect to iron as a function of the iron content taken from Santos et al. (2004, 2005), and Sousa et al. (2006). The corresponding value for the Sun is indicated as a reference. Taken into account the error bars, at least three of the analysed stars seem to be fluorine-enhanced with respect to the Sun (up to 0.35−0.55 dex). No correlation with metallicity can be detected: the two more fluorine-overabundant stars of the sample are HD 131977 with [Fe/H] = +0.07 ± 0.10, and HD 101581 with [Fe/H] = −0.37 ± 0.09. The corresponding Pearson correlation coefficient between [F/Fe] and [Fe/H] is also very low ($r = -0.22$).

The derived yttrium and zirconium abundances have allowed us to check the existence of a correlation between the fluorine production and the s-element production, and therefore, to test whether the fluorine present in the material from which our target stars were formed comes mainly from AGB stars. As shown in Table 1, the determined values of [Y/Fe] and [Zr/Fe] for each star agree within the errors. A mean s-element abundance was therefore calculated from them and compared to the [F/Fe] abundance (Fig. 3 left panel). We conservatively assume an error of 0.10 dex for the mean s-element abundance with respect to iron. The fluorine-enriched stars clearly also seem to be the most s-element enriched (with ⟨[s/Fe]⟩ equal to 0.27 ± 0.10 dex and 0.36 ± 0.10 dex for the two more F-enriched stars), suggesting
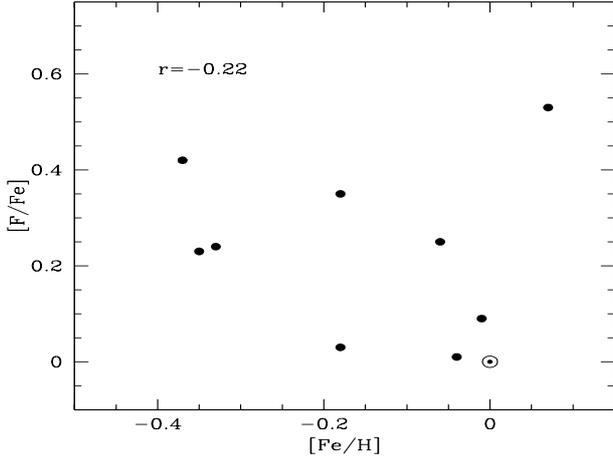
Fig. 2. Derived fluorine abundances with respect to iron (mean error of 0.29 dex) as a function of the iron content (black dots). The corresponding value for the Sun is shown as a reference. The lack of correlation between the [F/Fe] content and the [Fe/H] abundance is indicated by the low value of the Pearson correlation coefficient r.

Fig. 3. Measured fluorine abundances as a function of the mean s-element content (derived from yttrium and zirconium; *left panel*) and the mean [α/Fe] (derived from Si, Ca, and Ti measurements by Gilli et al. 2006; *right panel*). The mean error in [F/Fe] is ∼0.29 dex, and 0.1 dex for $\langle$[s/Fe]$\rangle$ and [α/Fe]. As for Fig. 2, the solar value and the Pearson correlation coefficient are indicated.

a common nucleosynthesis origin. Even if this relation is not so straightfoward for two of the stars (which seem to be s-element overabundant but have very small [F/Fe] enhancements) a general correlation cannot be excluded within the errors. The dispersion in our measurements, coming mostly from the F abundance, could explain the rather low correlation coefficient value of $r = 0.48$.

However, to test the possible Type II supernovae origin of fluorine, it is interesting to compare our F abundances with the alpha-element content, as the latter is a tracer of Type II supernovae nucleosynthesis. Homogeneous abundances for several alpha-elements and iron-peak elements were available from Gilli et al. (2006) for all the targets of our sample. In addition, our analysis and that of Gilli et al. (2006) rely on the same atmospheric parameter values for the stars, taken from Santos et al. (2004, 2005), and Sousa et al. (2006). This parameter consistency allows us to minimise any systematic errors in the element abundance comparisons. The right panel of Fig. 3 shows our F abundances plotted as a function of the Gilli et al. (2006) [α/Fe] content. The correlation between the [F/Fe] abundance and the [α/Fe] is again rather low ($r = 0.54$), and in contrast to the s-element abundances, the F-enhanced stars do not seem to be alpha-element enriched with respect to iron (the dispersion in the [α/Fe] values is very low and the [α/Fe] content for the two more F enhanced stars is equal to 0.03 ± 0.10 dex and 0.08 ± 0.10 dex). This result suggest that Type II supernovae should be excluded as the main F contributors for these stars.

Finally, we searched for possible correlations of the fluorine abundance with several refractory element ones, to determine whether there is no link between the F enhancements and the stellar metallicity. Figure 4 shows our determined F abundance as a function of the Sc, V, Cr, Mn, Co, and Ni content. The corresponding Pearson correlation co-efficient between the F abundance and each element abundance is also indicated. The solar values are again marked as a reference. No significant correlations seem to exist, except maybe between F and Co, but this relation is driven particularly by the values found for the star HD 131977 and is clearly not statistically robust.
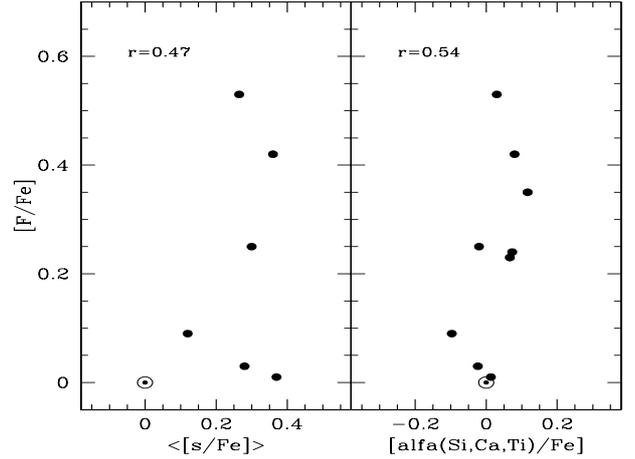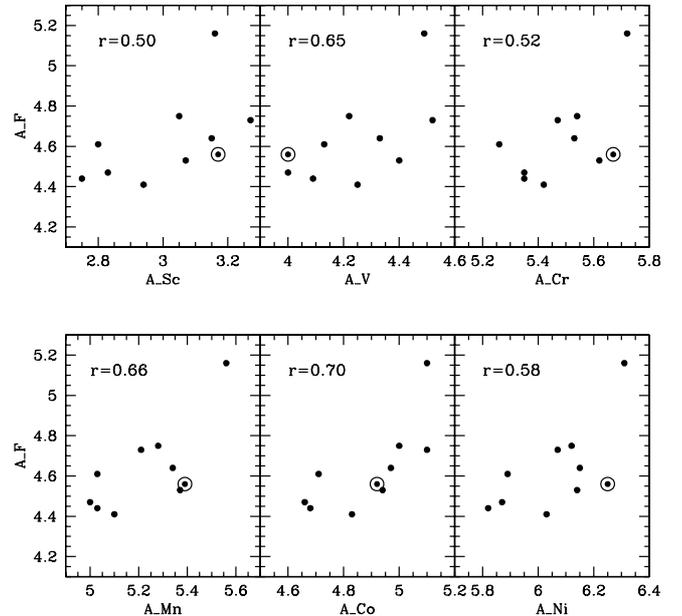

Fig. 4. Derived fluorine abundances as a function of several refractory elements abundances. Simbols are those of Fig. 2. The corresponding Pearson correlation coefficient r between the F abundance and the related element one is also indicated.

4. Conclusions

We have derived, for the first time, fluorine abundances for a set of nine cool main-sequence dwarfs of the solar neighbourhood, from an unblended line of the HF molecule at 2.3 microns. The studied stars have the advantage of being exempt of external pollution and internal mixing processes that can affect the observed F abundance patterns. Several of the analysed stars seem to be fluorine enhanced with respect to the Sun, but no correlation with the stellar iron content is found. We took advantage of FEROS archive spectra, available for six of the targets, to determine their yttrium and zirconium abundances and to test whether AGB fluorine nucleosynthesis can account for the observed F enhancements. The fluorine-enriched stars clearly also seem to be s-element enriched, suggesting that AGB stars could

be the origin of the F present in the studied dwarfs of the solar neighbourhood. Nevertheless, the correlation between [F/Fe] and the s-elements is rather low and possibly blurred by the uncertainties in the F abundance measurements. Finally, our derived F abundances were compared to the alpha-element and iron-peak element abundances of Gilli et al. (2006), which were determined using the same set of stellar atmospheric parameters. Type II core-collapse supernovae are unlikely to be the dominant producers of F for our targets, as no correlation seems to exist between [F/Fe] abundance and the [α/Fe] ratio. This is consistent with our targets not being r-element enriched (upper limits to Eu of 0.3 dex have been found). In addition, the absence of a clear correlation between the abundances of F and the iron-peak elements confirms that the observed F enhancements are not related to the stellar metallicity, in the explored high metallicity range. In summary, the observed fluorine, s-element and alpha-element abundance patterns suggest that AGB stars are the dominant source of fluorine in the studied dwarf stars of the solar neighbourhood.

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