The Chemical Evolution of Fluorine in the Bulge*

High-resolution K-band spectra of giants in three fields

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ABSTRACT

Context. Possible main formation sites of fluorine in the Universe include AGB stars, the ν-process in Type II supernova, and/or Wolf-Rayet stars. The importance of the Wolf-Rayet stars has theoretically been questioned and they are probably not needed in the modelling of the chemical evolution of fluorine in the solar neighborhood. It has, however, been suggested that Wolf-Rayet stars are indeed needed to explain the chemical evolution of fluorine in the Bulge. The molecular spectral data, needed to determine the fluorine abundance, of the often used HF-molecule has not been presented in a complete and consistent way and has recently been debated in the literature.

Aims. We intend to determine the trend of the fluorine-oxygen abundance ratio as a function of a metallicity indicator in the Bulge to investigate the possible contribution from Wolf-Rayet stars. Additionally, we present here a consistent HF line list for the K- and L-bands including the often used 23358.33 Å line.

Methods. High-resolution near-infrared spectra of eight K giants were recorded using the spectrograph CRIRES mounted at VLT. A standard setting was used covering the HF molecular line at 23358.33 Å. The fluorine abundances were determined using spectral fitting. We have also re-analyzed five previously published Bulge giants observed with the Phoenix spectrograph on Gemini using our new HF molecular data.

Results. We find that the fluorine-oxygen abundance in the Bulge probably cannot be explained with chemical evolution models including only AGB-stars and the ν-process in supernovae Type II, i.e. a significant amount of fluorine production in Wolf-Rayet stars is likely needed to explain the fluorine abundance in the Bulge. Concerning the HF line list, we find that a possible reason for the inconsistencies in the literature, with two different excitation energies being used, is two different definitions of the zero-point energy for the HF molecule and therefore also two accompanying different dissociation energies. Both line lists are correct, as long as the corresponding consistent partition function is used in the spectral synthesis. However, we suspect this has not been the case in several earlier works leading to fluorine-abundances ~0.3 dex too high. We present a line list for the K- and L-bands and an accompanying partition function.

Key words. Galaxy: bulge – Galaxy: evolution – Stars: abundances – Infrared: stars

1. Introduction

From a nucleosynthetic perspective fluorine is a very interesting element and its cosmic origin is truly intriguing. Its creation and destruction in stellar interiors is very sensitive to the physical conditions (see for example [Lucatello et al. 2011]), meaning that observations of fluorine abundances can provide strong constraints to stellar models. It will also be possible to observationally constrain the main stellar nuclear production sites of fluorine in the Universe at different epochs and in different stellar populations. To do this, observations of the chemical evolution of fluorine as a function of metallicity for different stellar populations have to be confronted with model predictions.

Theoretical considerations have offered three main production mechanisms which all should work under prevailing conditions during different phases of stellar evolution. Their relative importance at different stages of evolution and in different stellar populations is only starting to be investigated. The different production sites of \(^{19}\)F, the only stable isotope of fluorine, that have been proposed are:
- **nucleosynthesis in supernovae Type II (SNe II)**

  The core collapse of a massive star, following a SN II explosion, leads to a prodigious neutrino flux. In spite of the small cross sections, the large amount of neutrinos gives rise to a significant spallation of $^{20}$Ne to $^{19}$F (Woosley & Haxton 1988) in the overlying (neon-rich) shells of the core. Hartmann et al. (1991) estimates the total (mu- and tau-) neutrino energy to $E_{\nu} = 3 \times 10^{53}$ erg. Note that the contributions from W-R stars are underestimated in these models, because the elements such as C, N, and possibly F that are newly produced and have been lost via stellar winds before supernova explosions are not included. The models show a good agreement with field stars of higher metallicities. At lower metallicities the models cannot reproduce the observations of Li et al. (2013), but still the model that fits best include the $\nu$ process with $E_{\nu} = 3 \times 10^{53}$ erg.

  The abundance of fluorine in stars is difficult to measure due to a paucity of suitable spectral lines. Highly ionized F and F v lines in the UV have been used by Werner et al. (2005) in extremely hot post-AGB stars and a handful of F i lines between 6800-7800 Å have been used in extreme helium stars and R Coronae Borealis stars. Pandey et al. (2008) and Jorissen et al. (1992) and Abia et al. (2011). All other studies we are aware of have been made using HF molecular lines in the K-band and mostly the HF(1−0) R9 line at 23358.329 Å.

- **Thermal-pulsing Asymptotic Giant Branch (TP-AGB) stars**

  Low-mass (2 ≤ M/M$_{\odot}$ ≤ 4) TP-AGB stars have been suggested to produce fluorine in different burning phases during the thermal pulse stage, by nuclear reaction chains starting from $^{14}$N (Forestini et al. 1992; Jorissen et al. 1992; Abia et al. 2011; Kobayashi et al. 2011a; Gallino et al. 2010). Fluorine is then transported up to the surface by the 3rd dredge-up. Fluorine production in AGB-stars is expected to be accompanied by the slow-neutron capture nucleosynthesis (the s-process), producing elements like Sr, Y, Zr, Nb, Ba, and La (e.g. Mowlavi et al. 1998). Goriely & Mowlavi 2001, Abia et al. 2009. It has been demonstrated observationally that AGB stars do produce fluorne, see for example Jorissen et al. (1992) and Abia et al. (2011).

- **Wolf-Rayet (W-R) stars**

  Meynet & Arnould (1993, 1996, 2000) suggested that W-R stars could contribute significantly to the galactic fluorine budget. $^{19}$F is produced in the convective cores of W-R stars, during the core He-burning phase. Due to a large mass loss caused by a metallicity-dependent, radiatively-driven wind, the destruction of $^{19}$F by the (a, p) reaction is prevented since the convective core shrinks. The fluorine left behind is eventually exposed at the surface as the heavy mass loss strips the star of the outer layers. This mechanism depends on key parameters, such as initial mass, metallicity, and rotational velocity. Fluorine is produced from $^{14}$N, which means that the more $^{14}$N is available the more fluorine is expected. A second metallicity-dependent effect is the metallicity-dependent winds. Both circumstances favor the fluorine production at higher metallicities. Palacios et al. (2005) show that when incorporating newer yields and including models of rotating W-R stars, the yields from this mechanism are significantly reduced, implying that W-R stars might not be a major contributor of fluorine. However, they conclude that due to large uncertainties in key nuclear-reaction rates and mass-loss rates, the question of the contribution to galactic $^{19}$F from W-R stars is still open.

Using a semi-analytic multizone chemical-evolution model, Renda et al. (2004) show for the first time the impact of the AGB and W-R star contributions to the Galactic chemical evolution of fluorine. They show that $\nu$ nucleosynthesis was dominant in the early universe and that AGB stars’ significance successively grows. Based on the old yields and non-rotating models, they further show that the contribution of W-R stars is significant for solar and super-solar metallicities, increasing the [F/O] ratio by a factor of two at solar metallicities. Their conclusion is that all three production sites are needed in order to explain the Galactic chemical evolution of fluorine for a range of metallicities.

Kobayashi et al. (2011a) modeled the evolution of fluorine in the solar neighborhood including AGB stars and $\nu$ nucleosynthesis with two different neutrino energies ($E_{\nu} = 3 \times 10^{53}$ erg and $E_{\nu} = 9 \times 10^{53}$ erg). Note that the contributions from W-R stars are underestimated in these models, because the elements such as C, N, and possibly F that are newly produced and have been lost via stellar winds before supernova explosions are not included. The models show a good agreement with field stars of higher metallicities. At lower metallicities the models cannot reproduce the observations of Li et al. (2013), but still the model that fits best include the $\nu$ process with $E_{\nu} = 3 \times 10^{53}$ erg.

The abundance of fluorine in stars is difficult to measure due to a paucity of suitable spectral lines. Highly ionized F v and F i lines in the UV have been used by Werner et al. (2005) in extremely hot post-AGB stars and a handful of F i lines between 6800-7800 Å have been used in extreme helium stars and R Coronae Borealis stars. Pandey et al. (2008) and Abia et al. (2011). All other studies we are aware of have been made using HF molecular lines in the K-band and mostly the HF(1−0) R9 line at 23358.329 Å.

Relevant for the observations we present in this paper, is the study by Cunha et al. (2008) who present the first study of the chemical evolution of fluorine in the Galactic Bulge, by investigating six red giants in Baade’s Window (five of these spectra are re-analyzed in this paper). They find that the fluorine to oxygen abundance ratio in the Bulge follows and extends the solar neighborhood trend. The trend at higher metallicities needs other sources of fluorine in addition to the $\nu$ process contribution, which is sufficient at lower metallicities. These are the AGB star and W-R star contributions. By investigating the correlation with abundances of s-process elements, the authors conclude that, for the Bulge, the W-R wind contribution to the fluorine budget should be important and larger than for the Disk. They therefore suggest that W-R stars might have played a vital role in the chemical evolution of the Galactic Bulge.

In this paper, we observationally investigate the chemical evolution of fluorine in the Bulge, by analyzing red giants from three fields. We discuss the relative contributions of the different main nucleosynthetic sites suggested, by comparing with the latest and most updated models for the evolution of fluorine in the Bulge. Our main conclusion is that a significant fluorine production in W-R stars is likely needed to explain the fluorine abundance in the Bulge, meaning that the production in AGB-stars and SNe II is probably not enough.

## 2. Observations

We have observed eight K giants in the galactic Bulge using the spectrometer CRIRES (Kaufl et al. 2004; Moorwood 2005, Kaufl et al. 2006), mounted on VLT. The K-band observations explored in this paper are, with one exception, of the same stars as the H-band observations analyzed by Ryde et al. (2010), in turn a sub-sample of the full visual sample used in Zoccali et al. (2006), Lebreur et al. (2007), and Barbuy et al. (2013). The basic data of our stars are listed in Table 1 and the Figure 1 shows the location of our three fields (B3, BW and B6) in comparison to the COBE/DIRBE outline of the Galactic Bulge (Weiland et al. 1994) and the micro lensed Bulge dwarfs of Bensby et al. (2013). The stars were observed with the CRIRES-setting 24/1/1 giving a spectral coverage from approximately 23070 Å to 23510 Å and therefore including the HF-line at 23358.33 Å. The spectral resolution is around R~40000, as determined from narrow telluric lines. The observations were reduced using the CRIRES pipeline and the continua are normalized with the IRAF task continuum. Subsequently, the telluric lines plaguing
Table 1. Basic data for the observed red giants.

| Star   | OGLE no     | RA (J2000) (h:m:s) | Dec (J2000) (d:am:as) | I   | V − I | H   | K   |
|--------|-------------|--------------------|-----------------------|-----|------|-----|-----|
| B3-b1  | 132160C4    | 18:08:15.840       | -25:42:09.83          | 16.345 | 2.308 | 11.325 | 11.310 |
| B3-b7  | 282804C7    | 18:09:16.540       | -25:49:26.08          | 16.355 | 2.304 | 11.614 | 11.351 |
| B3-b8  | 240083C6    | 18:08:24.602       | -25:48:44.39          | 16.488 | 2.427 | 11.395 | 11.130 |
| B3-f3  | 95424C3     | 18:08:49.628       | -25:40:36.93          | 16.316 | 2.259 | 11.676 | 11.464 |
| BW-f6  | 392918      | 18:03:36.890       | -30:07:04.30          | 16.370 | 2.017 | 12.043 | 11.832 |
| B6-b8  | 108051C7    | 18:09:55.950       | -31:45:46.33          | 16.290 | 2.107 | 11.883 | 11.653 |
| B6-f1  | 23017C3     | 18:10:04.460       | -31:41:45.31          | 15.960 | 1.941 | 11.914 | 11.671 |
| B6-f7  | 100047C6    | 18:10:52.300       | -31:46:42.18          | 15.950 | 1.891 | 11.904 | 11.734 |

Notes.

a Using the same naming convention as Lecureur et al. (2007).

Fig. 1. Location of the four fields (B3, BW, B6, and BL) of Lecureur et al. (2007) in comparison to the COBE/DIRBE outline of the Galactic Bulge (Weiland et al. 1994) and the study of Bensby et al. (2013). Our stellar sample is a subset of the B3-, BW-, and B6-stars. The five re-analyzed stars from Cunha et al. (2008) are in the BW-field.

In addition to these eight giants, K-band spectra from three K giants and two M giants in Cunha et al. (2008) (in turn from Cunha & Smith (2006)) have been re-analyzed. These stars are all in Baade’s Window and were observed using the Phoenix spectrograph at Gemini-South (Hinkle et al. 1998). For a com-

...his part of the IR spectra, were carefully removed by dividing the normalized spectra with that of a telluric standard of high signal-to-noise ratio, which we observed in the same setting and reduced in the same way, using the IRAF task telluric.

The stellar parameters were re-determined from the visual observations with the UVES spectrometer described in Lecureur et al. (2007) and the oxygen abundances were re-determined from the H-band data described in Ryde et al. (2010). The UVES observations were carried out May-Aug 2003-2004 and the CRIRES observations were done May-Aug 2007-2008 and a summary of the observations and the S/N reached, is presented in Table 2. The large optical extinction in the Bulge direction is the cause of the large differences in exposure times between the visual and the infrared observations. The extinction in the K band is a factor of 10 lower that in the V band (Cardelli et al. 1989).
complete description of these observations, see Cunha et al. (2008) and Cunha & Smith (2006).

Table 2. Summary of the observations with VLT/UVES and VLT/CRIRES.

| Star       | Total integration time | S/Na |
|------------|------------------------|------|
|            | Visual  | H   | K   | Visual | H | K |      |
| B3-b1      | 10 h    | 40 m | 32 m | 20     | 35 | 44 |
| B3-b7      | 10 h    | 10 h | 20 m | 38     | 31 | 37 |
| B3-b8      | 10 h    | 1 h  | 34 m | 36     | 55 | 80 |
| B3-f3      | 11 h 50 m | ... | 56 m | 31     | 55 |
| BW-f6      | 6 h 25 m | 1 h 20 m | 1 h 20 m | 34 | 46 |
| B6-b8      | 5 h 30 m | 1 h 04 m | 1 h 20 m | 55 | 35 |
| B6-f1      | 5 h 15 m | 32 m | 40 m | 75     | 33 |
| B6-f7      | 5 h 15 m | 32 m | 1 h 20 m | 30 | 42 |

Notes.
a S/N per pixel as measured by the IDL-routine der_snr.pro, see http://www.stsci.edu/software/ASTROsoft/DER_SNR

3. Analysis

The visual, as well as the infrared spectra, were analyzed using the software Spectroscopy Made Easy, SME (Valenti & Piskunov 1996). SME simultaneously fits a chosen number of parameters by fitting calculated synthetic spectra to parts of an observed spectrum using χ²-minimization. The parts, called line masks and continuum masks, mark regions with spectral lines of interest and points which SME should treat as continuum points. The latter are used if a linear rectification in predefined narrow windows of the already continuum-normalized observed spectrum is needed (see Section 3.2).

SME uses spherical symmetric, [α/Fe]-enhanced, LTE MARCS-models. Within the Gaia-ESO collaboration Gilmore et al. (2012) it has also been developed to handle NLTE for many iron lines. We have no knowledge of estimated 3D-effects on the fluorine line used in the analysis for our stellar parameters, but Li et al. (2013) have calculated 3D-corrections for more metal-poor stars showing that they are small.

3.1. Stellar parameters

In order to be consistent, we use SME in our analysis, both for our optical and infrared spectra. We have, thus, also re-determined the stellar parameters for our stars based on the method described in Jönsson et al. (in prep.). In short, we determine all the stellar parameters (Teff, log g, [Fe/H], and ξmicro) simultaneously, with SME using a well-chosen line-list of weak, unblended Fe I, Fe II, and Ca I lines and gravity-sensitive Ca II wings. All lines except some Fe II-lines have lab-measured oscillator strengths with excellent accuracy (according to the Gaia-ESO line-list categorization of Heiter et al. (in prep.)) and for all iron lines NLTE-corrections have been used. The resulting parameters are listed in Table 3 and are in agreement, within uncertainties, with the ones in Ryde et al. (2010).

In Table 3 we also list the stellar parameters used for the Bulge stars of Cunha et al. (2008) that we re-determine the fluorine abundance for Cunha & Smith (2006). These stellar parameters are determined from a combination of photometry and IR spectroscopy which might lead to systematic differences to the stellar parameters of the B3-BW-B6 data set. Note also that the two M giants are cooler and have a lower surface gravity than the rest of the stars perhaps leading to systematic differences as well.

Table 3. Determined stellar parameters for the reference star Arcturus and our program stars. Also listed are the stellar parameters of the re-analyzed stars from Cunha et al. (2008).

| Star       | Teff [K] | log g | [Fe/H]b | [α/Fe]b | ξmicro [km s⁻¹] |
|------------|----------|-------|---------|---------|----------------|
| Arcturusc  | 4262     | 1.62  | −0.63   | 0.23    | 1.62           |
| B3-b1      | 4372     | 1.11  | −1.03   | 0.39    | 1.45           |
| B3-b7      | 4261     | 1.86  | −0.09   | 0.01    | 1.57           |
| B3-b8      | 4282     | 1.67  | −0.75   | 0.28    | 1.47           |
| B3-f3      | 4573     | 2.55  | 0.19    | 0.00    | 1.76           |
| BW-f6      | 4117     | 1.22  | −0.54   | 0.20    | 1.70           |
| B6-b8      | 3989     | 1.30  | 0.17    | 0.05    | 1.46           |
| B6-f1      | 4101     | 1.52  | −0.10   | 0.02    | 1.65           |
| B6-f7      | 4221     | 1.83  | −0.41   | 0.14    | 1.63           |
| BMB 78d    | 3600     | 0.8   | −0.08   | 0.01    | 2.5            |
| BMB 289g   | 3375     | 0.4   | −0.10   | 0.02    | 3.0            |
| I−322d     | 4250     | 1.5   | −0.29   | 0.10    | 2.0            |
| IV−072d    | 4400     | 2.4   | 0.19    | 0.00    | 2.2            |
| IV−329d    | 4275     | 1.3   | −0.57   | 0.21    | 1.8            |

Notes.
a We use log ε(Fe) = 7.50 (Asplund et al. 2009).
b Following the SME MARCS model trends with [α/Fe]=0.4 for [Fe/H]< −1.0, [α/Fe]=0.0 for [Fe/H]> 0.0, and linearly rising in-between.
c Spectrum from the atlas by Hinkle et al. (2000).
d Stellar parameters from Cunha & Smith (2008).

The uncertainties in our method of determining the stellar parameters from optical spectra and their dependence of S/N will be described in Jönsson et al. (in prep.). In short we have degraded the Arcturus spectrum of Hinkle et al. (2000) to different S/N and determined the stellar parameters for those spectra. The estimated uncertainties for the stars in this paper following this method are δTeff ≲ 70 K, δ log g ≲ 0.2, δ[Fe/H] ≲ 0.1, and δξmicro ≲ 0.1.

3.2. Line data

All optical line data used in this paper has been collected and/or determined within the Gaia-ESO collaboration (Heiter et al., in prep.). The infrared line data except for HF have been extracted from the VALD database Valenti & Piskunov 1996 Ryabchikova et al.1997, Kupka et al.1999, 2000. The line data of the [O i]-line, the three Zr i-lines, and the OH-lines used is listed in Table 2. When it comes to the excitation energies and transition probabilities for HF we calculate them in Section 3.2.1.

3.2.1. HF molecule

The excitation energies and transition probabilities for HF have not been presented previously in a complete and comprehensive manner. The values of Jorissen et al. (1992), who cite private communications with Tipping, are often used. Lucatello et al. (2011), D’Orazi et al. (2013), and Nault & Pilachowski (2013), however, use the excitation energy for the 23358.329 Å-line from Deccin (2000), in turn from private communications with Sauval, which differs from the Tipping value by 0.25 eV. As long as the excitation energies and partition functions are con-
Table 4. Atomic and molecular data for the spectral lines used for O and Zr abundance determination.

| Element | Wavelength | $\chi_{\text{exc}}$ | log($gf$) | Refs. |
|---------|------------|---------------------|-----------------|------|
| Zr ii  | 6127.4400  | 0.154               | -1.060          | 1    |
| Zr ii  | 6134.5500  | 0.000               | -1.280          | 1    |
| Zr ii  | 6143.2000  | 0.071               | -1.100          | 1    |
| [O i]  | 6300.3038  | 0.000               | -9.715          | 2, 3 |
| OH     | 15558.021  | 0.304               | -5.309          | 4    |
| OH     | 15560.241  | 0.304               | -5.309          | 4    |
| OH     | 15565.838  | 3.663               | -4.830          | 4    |
| OH     | 15565.961  | 2.783               | -4.700          | 4    |
| OH     | 15568.780  | 0.299               | -5.270          | 4    |
| OH     | 15572.083  | 0.300               | -5.270          | 4    |

References. (1) Biemont et al. (1981); (2) Wiese et al. (1966); (3) Storey & Zeippen (2000); (4) Goldman et al. (1998)

In this paper we intend to explicitly present which excitation energy of level $i$ can be factored out in Equation 2.

The dissociation energy used is the same as in Gustafsson et al. (2008, and references therein), which is an updated version of the one from Sauval & Tatarski (1984). This partition function is shown in Equation 2 and in Figure 2.

From this we calculated the transition frequencies (and wavelengths) from the differences of the energy levels of the upper and lower level of the lines. The wavenumbers and wavelengths of the HF lines in the 22700-25000 Å region (R branch, including the band head at 22700 Å) and 25500-39200 Å region (P branch) are given in columns 4 and 5, respectively, in the Tables 5 and 6. The R-branch lines lie in the K band, whereas the P-branch lines originating from higher rotational levels lie in the L band.

We have also computed the HF ro-vibrational Einstein coefficients for spontaneous emission using the transition matrix-element expansion coefficients given by Arunan et al. (1992). They used accurate dipole-moment functions based on experimental data to find these coefficients:

$$A_{v→v'}(m) = \frac{64\pi^4}{3\hbar^2} \frac{|m|^3}{2J'+1} |R_{v→v'}(m)|^2,$$

where $m = J'' + 1$ for the R branch, i.e. $J' \leftarrow (J'' - 1)$ and $m = -J''$ for the P branch, i.e. $J' \leftarrow (J'' + 1)$. The upper state is designed with a prime, $'$, and the lower state with a double prime, $''$. The transition matrix elements, $R_{v→v'}(m)$, are given by $R_{v→v'}(m) = a_0 + a_1m + a_2m^2 + a_3m^3$, where the expansion

![Fig. 2. Partition function of the HF molecule used in the MARCS code and SME for a relevant temperature range.](image-url)
Table 5. HF line data* for the $R$ branch ($v' = 1$ and $v'' = 0$).

| Line | $J'$ | $J''$ | wavenumber [cm$^{-1}$] | $\lambda_{\text{air}}$ [Å] | $\lambda_{\text{exc}}$ [Å] | $\sigma$ [cm$^{-1}$] | $\chi_{\text{exc}}$ [eV] | $A_{v',v''}$ | log $gf$ |
|------|------|------|------------------------|-----------------|-----------------|-----------------|-----------------|--------------|----------|
| R(0) | 1    | 0    | 4000.989               | 4987.001        | 63.42           | -4.749          |
| R(1) | 2    | 1    | 4038.962               | 24987.001       | 74.07           | -4.468          |
| R(2) | 3    | 2    | 4075.293               | 24531.418       | 77.02           | -4.313          |
| R(3) | 4    | 3    | 4142.846               | 24324.642       | 77.29           | -4.313          |
| R(4) | 5    | 4    | 4173.979               | 23951.417       | 76.26           | -4.313          |
| R(5) | 6    | 5    | 4203.296               | 23784.365       | 74.47           | -4.313          |
| R(6) | 7    | 6    | 4230.756               | 23629.991       | 72.19           | -4.313          |
| R(7) | 8    | 7    | 4256.322               | 23488.052       | 69.54           | -4.313          |
| R(8) | 9    | 8    | 4279.960               | 23358.329       | 66.64           | -4.313          |
| R(9) | 10   | 9    | 4301.637               | 23240.623       | 63.53           | -4.313          |
| R(10)| 11   | 10   | 4321.321               | 22957.938       | 60.28           | -4.313          |
| R(11)| 12   | 11   | 4340.337               | 22778.249       | 57.91           | -4.313          |
| R(12)| 13   | 12   | 4358.986               | 22640.574       | 55.46           | -4.313          |
| R(13)| 14   | 13   | 4376.152               | 22512.733       | 53.46           | -4.313          |
| R(14)| 15   | 14   | 4390.364               | 22386.862       | 51.45           | -4.313          |
| R(15)| 16   | 15   | 4404.184               | 22262.986       | 49.97           | -4.313          |
| R(16)| 17   | 16   | 4408.955               | 22149.249       | 48.59           | -4.313          |
| R(17)| 18   | 17   | 4406.176               | 22036.837       | 47.19           | -4.313          |
| R(18)| 19   | 18   | 4401.256               | 21925.589       | 45.79           | -4.313          |
| R(19)| 20   | 19   | 4404.184               | 21814.859       | 44.50           | -4.313          |
| R(20)| 21   | 20   | 4404.950               | 21699.488       | 43.21           | -4.313          |
| R(21)| 22   | 21   | 4403.548               | 21585.359       | 41.92           | -4.313          |
| R(22)| 23   | 22   | 4399.973               | 21471.213       | 40.63           | -4.313          |
| R(23)| 24   | 23   | 4394.221               | 21357.951       | 39.34           | -4.313          |
| R(24)| 25   | 24   | 4386.294               | 21244.690       | 38.05           | -4.313          |
| R(25)| 26   | 25   | 4376.191               | 21131.510       | 36.76           | -4.313          |

Notes.

* The consistent partition function is given in the text.

Finally, the log $gf$ values are calculated from:

$$\log(gf_{v',v''}) = \log \left( \frac{2J' + 1}{8\pi^2 e^2} \cdot \chi_{\text{exc}} \right) - \chi_{\text{exc}} / kT,$$

where $e$ is the natural logarithm and $k$ is the Boltzmann constant. The calculated log($gf$)-values are given in column 9 in Tables 5 and 6. Arunan et al. (1992) claim that these transition probabilities are reliable and well-established, and that they are in agreement with ab initio calculations of Zemke et al. (1991), providing confidence in the values.

To get an overview of which lines might be important for abundance determinations, we plot in Figure 3 the relative line strengths in the form of $gf \cdot e^{-\chi_{\text{exc}}/kT}$ at $T = 4000$ K, a typical temperature of the line forming regions of a red giant. The R9-line used in this and many other works is marked together with some other lines. The equivalent widths of the lines for a typical model atmosphere, show in principle the same relative strengths.

3.3. Stellar abundances

All abundances for the B3-BW-B6 stars were determined using SME and the stellar parameters described in Table 3. The abundances from the visual spectra were determined using the macro-turbulence determined simultaneously as the stellar parameters, but when determining the abundances from the IR-spectra the macro-turbulence was a global free parameter.

The uncertainties in the determined abundances from the uncertainties in the stellar parameters, see Section 3.1, are given in Table 7.

We note that all abundances are most sensitive to the temperature and that they all increase with higher temperature. This will mean that uncertainties, due to the uncertainties in the stellar parameters, in the ratios $[F/O]$ and $[Zr/F]$ used in Figures 6 and 7 are given in Table 7.

![Relative line strengths](image_url)
we also have to include the uncertainties in the continuum fitting around the O-, HF-, and Zr-lines used, but they are in most cases and Cunha et al. (2008). In particular the most metal-poor star, abundances of the BMB-I-IV stars, see Cunha & Smith (2006) discussion on the uncertainties of the stellar parameters and the and MOOG give the same result to a very good precision. For a Our tests show that, using the same model atmosphere, SME BW-B6 stars, but using MOOG (Sneden 1973) instead of SME. using the same LTE MARCS model atmospheres as the B3-
ples of stars previously analyzed in Cunha et al. (2008) were done to less than 0.1 dex. will be smaller than the quadratic addition of the two uncertainties. When it comes to the total uncertainties in the abundances we also have to include the uncertainties in the continuum fitting around the O-, HF-, and Zr-lines used, but they are in most cases much smaller. Altogether we estimate the total uncertainties in the abundances to approximately 0.15 dex and in the abundance ratios to less than 0.1 dex.

4. Results
The part of the spectra containing the lines used in our investigation together with our best fitted synthetic spectra, are presented in Figure 4 and the resulting abundances are presented in Table 8. In Figure 5 we have plotted our abundances together with our chemical evolution models. The fluorine abundances derived here for the stars from Cunha et al. (2008, light-green circles) are systematically lower than those derived previously on account of the different excitation energies and partition functions used (as described in Section 3.2.1), but also because in this study we use newer, alpha-enhanced stellar model atmospheres.

5. Discussion
From the color-coding in Figures 5-7 which designates the three different Bulge fields observed (see Figure 1), we are not able to trace any spatial variation of the fluorine abundance for the different fields. More stars in every field are needed in order to start discussing abundance trends. Therefore, in the following, we will discuss all our abundances as following a general Bulge-trend. In the right panel of Figure 5 we see the expected decline of \([F/Fe]_{\text{abs}}\) and in Figure 6 we have plotted our abundances together with the chemical evolution models. The fluorine abundances derived here for the stars from Cunha et al. (2008, light-green circles) are systematically lower than those derived previously on account of the different excitation energies and partition functions used (as described in Section 3.2.1), but also because in this study we use newer, alpha-enhanced stellar model atmospheres.

## Table 6. HF line data$^a$ for the $P$ branch ($\nu' = 1$ and $\nu'' = 0$).

| Line | J$^\prime$ | J$''$ | Wavenumber | Wavelength | $\chi_{\text{exc}}$ | $\chi_{\text{exc}}$ | $A_{\nu', \nu''}$ | log $gf$ |
|------|-----------|-------|-------------|-------------|-----------------|-----------------|-----------------|---------|
| P(1) | 0 1       | 3920.312 | 25501.219 | 41.11 | 0.005 | 199.3 | -4.711 |
| P(2) | 1 2       | 3877.707 | 25781.401 | 123.28 | 0.015 | 135.4 | -4.393 |
| P(3) | 2 3       | 3833.661 | 26077.610 | 246.41 | 0.031 | 123.9 | -4.199 |
| P(4) | 3 4       | 3788.227 | 26390.371 | 410.35 | 0.051 | 119.7 | -4.058 |
| P(5) | 4 5       | 3741.459 | 26720.249 | 614.89 | 0.076 | 117.8 | -3.945 |
| P(6) | 5 6       | 3693.412 | 27067.848 | 859.78 | 0.107 | 116.7 | -3.850 |
| P(7) | 6 7       | 3644.142 | 27433.815 | 1144.73 | 0.142 | 116.1 | -3.769 |
| P(8) | 7 8       | 3593.705 | 27818.843 | 1469.37 | 0.182 | 115.5 | -3.696 |
| P(9) | 8 9       | 3542.159 | 28223.674 | 1833.32 | 0.227 | 115.0 | -3.632 |
| P(10) | 9 10     | 3489.529 | 28649.101 | 2236.14 | 0.277 | 114.4 | -3.573 |
| P(11) | 10 11    | 3435.964 | 29095.974 | 2677.32 | 0.332 | 113.7 | -3.518 |
| P(12) | 11 12    | 3381.432 | 29565.205 | 3156.34 | 0.391 | 113.7 | -3.518 |
| P(13) | 12 13    | 3326.020 | 30057.770 | 3672.62 | 0.455 | 113.8 | -3.468 |
| P(14) | 13 14    | 3269.785 | 30574.715 | 4225.54 | 0.524 | 110.6 | -3.378 |
| P(15) | 14 15    | 3212.784 | 31117.163 | 4814.44 | 0.597 | 109.2 | -3.337 |
| P(16) | 15 16    | 3155.075 | 31686.321 | 5438.62 | 0.674 | 107.7 | -3.299 |
| P(17) | 16 17    | 3096.715 | 32283.483 | 6097.33 | 0.756 | 106.0 | -3.262 |
| P(18) | 17 18    | 3037.758 | 32910.043 | 6789.81 | 0.842 | 104.1 | -3.228 |
| P(19) | 18 19    | 2978.260 | 33567.501 | 7515.25 | 0.932 | 102.1 | -3.195 |
| P(20) | 19 20    | 2918.275 | 34257.427 | 8272.80 | 1.026 | 99.94 | -3.164 |
| P(21) | 20 21    | 2857.858 | 34981.701 | 9061.58 | 1.123 | 97.63 | -3.134 |
| P(22) | 21 22    | 2797.061 | 35742.068 | 9880.69 | 1.225 | 95.18 | -3.106 |
| P(23) | 22 23    | 2735.935 | 36540.611 | 10729.19 | 1.330 | 92.61 | -3.078 |
| P(24) | 23 24    | 2674.531 | 37379.535 | 11606.13 | 1.439 | 89.94 | -3.053 |
| P(25) | 24 25    | 2612.899 | 38261.231 | 12510.51 | 1.551 | 87.16 | -3.028 |
| P(26) | 25 26    | 2551.086 | 39188.299 | 13441.33 | 1.667 | 84.30 | -3.004 |

Notes.
$^a$ The consistent partition function is given in the text.

## Table 7. Uncertainties in the determined abundances due to uncertainties in the stellar parameters.

| Uncertainty | $\Delta$ log $\epsilon$(O) | $\Delta$ log $\epsilon$(F) | $\Delta$ log $\epsilon$(Zr) |
|-------------|-----------------------------|-----------------------------|-----------------------------|
| $\delta$T$_{\text{eff}} = +70$ K | +0.12 | +0.15 | +0.14 |
| $\delta$log g = +0.2 | -0.02 | +0.01 | +0.02 |
| $\delta$[Fe/H] = +0.1 | +0.06 | -0.03 | -0.01 |
| $\delta$$\xi_{\text{micro}} = +0.1$ | -0.01 | -0.01 | -0.01 |
Fig. 4. Observed spectra in black and synthetic spectra in red for the B3-BW-B6 stars. The three Zr-lines, the [O i]-line, the OH-lines, and the HF-line used are marked. The exact wavelengths are listed in Table 4. The OH-lines with obvious cosmic hits have not been included in the fit. Note the different flux scales. An example of the HF-line in the re-analyzed BMB-I-IV can be found in Cunha et al. (2008).
Fig. 5. [F/Fe] and [O/Fe] as functions of [Fe/H] for the B3-BW-B6 stars. The stars are color-coded as the corresponding fields in Figure 1. The black dots are the micro lensed Bulge dwarfs of Bensby et al. (2013) also marked in Figure 1. A conservative estimation of the uncertainties are marked in the upper corners.

Fig. 6. Our fluorine abundances compared to the predictions of our Bulge models including AGB-stars, excluding and including the $\nu$-process with two different energies, and excluding W-R stars. The abundances have been transformed to the scale of the models with $\log \epsilon(F)_{\odot} = 4.56$ and $\log \epsilon(O)_{\odot} = 8.93$ (Anders & Grevesse 1989). The stars are color-coded as the corresponding fields in Figure 1 with the BW-stars of Cunha et al. (2008) added in the right panel in a lighter green color. A conservative estimation of the uncertainties are marked in the upper left-hand corners. We note that the star BMB-78, still after the re-analysis, falls below the rest of the trend, see Section 5 for possible explanations.

[Diagram images of Fig. 5 and Fig. 6 are not included here.]

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Table 8. Determined abundances.

| Star       | log ($\epsilon$(O)$_{\odot}$) | log ($\epsilon$(O)$_{\odot}$) | log ($\epsilon$(O)$_{\odot}$) | [O/Fe]$_{\text{mean}}$ | log ($\epsilon$(F)) | [F/Fe]$_{\odot}$ | log ($\epsilon$(Zr)) | [Zr/Fe]$_{\odot}$ |
|------------|---------------------------------|---------------------------------|---------------------------------|------------------------|--------------------|-------------------|----------------------|-------------------|
| Arcturus   | 8.56                            | 8.47                            | 8.52                            | 0.47                   | 3.75               | -0.18             | 1.8                  | -0.11             |
| B3-b1      | 8.11                            | 8.29                            | 8.20                            | 0.54                   | $\leq 3.64$        | $\leq 0.11$       | 2.0                  | 0.53               |
| B3-b7      | 8.68                            | 8.65                            | 8.66                            | 0.07                   | 4.45               | -0.02             | 2.4                  | -0.02             |
| B3-b8      | 8.41                            | 8.39                            | 8.40                            | 0.46                   | 3.50               | -0.31             | 2.1                  | 0.33               |
| B3-f3      | 8.95                            | ...                             | 8.95                            | 0.07                   | $\leq 4.90$        | $\leq 0.15$       | 2.5                  | -0.24             |
| BW-f6      | 8.51                            | 8.40                            | 8.45                            | 0.31                   | 3.54               | -0.48             | 1.8                  | -0.22             |
| B6-b8      | 8.54                            | 8.66                            | 8.60                            | 0.08                   | 4.25               | -0.14             | 2.5                  | 0.12               |
| B6-f1      | 8.73                            | 8.68                            | 8.70                            | 0.12                   | 4.33               | -0.13             | 2.3                  | -0.13             |
| B6-f7      | ...                             | 8.66                            | 8.66                            | 0.38                   | 4.07               | -0.08             | 2.2                  | 0.05               |
| BMB-78     | $\ldots$                        | 9.00                            | 9.00$^c$                         | 0.39$^c$              | $\leq 4.09$        | $\leq 0.39$       | $\ldots$             | $\ldots$         |
| BMB-289    | $\ldots$                        | 8.75$^c$                        | 8.75$^c$                         | 0.16$^c$              | 4.61               | 0.15              | $\ldots$             | $\ldots$         |
| I-322      | $\ldots$                        | 8.60$^c$                        | 8.60$^c$                         | 0.20$^c$              | 4.41               | 0.14              | $\ldots$             | $\ldots$         |
| IV-072     | $\ldots$                        | 9.20$^c$                        | 9.20$^c$                         | 0.32$^c$              | 5.21               | 0.46              | $\ldots$             | $\ldots$         |
| IV-329     | $\ldots$                        | 8.35$^c$                        | 8.35$^c$                         | 0.23$^c$              | $\leq 4.01$        | $\leq 0.02$       | $\ldots$             | $\ldots$         |

Notes.

$^a$ Using solar abundances of log ($\epsilon$(O)$_{\odot}$) = 8.69, log ($\epsilon$(F)$_{\odot}$) = 4.56, log ($\epsilon$(Fe)$_{\odot}$) = 7.50, and log ($\epsilon$(Zr)$_{\odot}$) = 2.58 (Asplund et al. 2009).

$^b$ Spectrum from the atlas by Hinkle et al. (1995).

$^c$ From Cunha & Smith (2008).
the outer layers of the stars to be peeled off (Maeder 1992), the contribution from these stars could explain the decline of oxygen in the Bulge (Fulbright et al. 2007; McWilliam et al. 2008). At the same time these massive stars could be an important formation site for carbon in the Galaxy (see for example Gustafsson et al. 1999; Mattsson 2010). Fulbright et al. (2007) and McWilliam et al. (2008) discuss the decline in [O/Mg] and [O/Fe] at solar metallicities and Cescutti et al. (2009) the [C/O] versus [O/H] trends in the Bulge, and show that these are best fitted with models including massive star yields altered by metallicity-dependent winds, just as for W-R stars. Note, however, that Alves-Brito et al. (2011) and Ryde et al. (2010) do not find the large increase in the carbon abundance in the Bulge, which would have been expected if the W-R stars had played an important role. Thus, the question of the role of W-R stars in the Bulge is still open. It will, however, be able to be tested with more observations of the sort that already exists. Detailed modeling is needed and improved data may solve this issue (Rich 2013).

Since fluorine is produced from nitrogen in both AGB-stars and W-R stars, while it is produced from neon in the ν-process, it would be of interest to investigate the trend of F vs. N in the Bulge, but since our stellar sample is made up by giants it is hard to establish the `cosmic' nitrogen abundance to the needed accuracy due to newly produced nitrogen being dredged-up into the atmosphere of the star.

6. Conclusion

At low metallicity, our observed fluorine-oxygen abundance trend in the Bulge is lower than predicted in our Bulge model including the ν-process, showing a steeper slope than the model. This might suggest a metal-dependent production source of fluorine. This source cannot be the ν-process in SNe II because it is not metal-dependent over our metallicity range, and it cannot be AGB-stars because these produce s-elements at the same time as fluorine and would probably not give rise to the observed decline in [Zr/F] for increasing [F/H] (as shown in Figure 7). Therefore our data corroborate the findings of Cunha et al. (2008) that W-R stars might be an important source of fluorine in the Bulge. To fully understand this we need galactic chemical evolution models that include full sets of yields of AGB stars, W-R stars, and supernova explosions.

We believe that some of the earlier reports of high fluorine abundances might be due to the use of mis-matching molecular data for the HF-molecule, but this has to be investigated. To help with this we have presented a HF line-list with a consistent partition function for lines in the K- and L-bands.

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Figure 7. Abundance ratios of fluorine and zirconium in our sample as a function of the solar normalized fluorine abundance. The negative slope alluded by this plot, suggests that W-R stars might be important for producing fluorine in the Bulge. The stars are color-coded as the corresponding fields in Figure 1 and a conservative estimation of the uncertainties are marked in the lower right-hand corner.
