FLUORINE VARIATIONS IN THE GLOBULAR CLUSTER NGC 6656 (M22):
IMPLICATIONS FOR INTERNAL ENRICHMENT TIMESCALES

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ABSTRACT

Observed chemical (anti)correlations in proton-capture elements among globular cluster stars are presently recognized as the signature of self-enrichment from now extinct, previous generations of stars. This defines the multiple population scenario. Since fluorine is also affected by proton captures, determining its abundance in globular clusters provides new and complementary clues regarding the nature of these previous generations and supplies strong observational constraints to the chemical enrichment timescales. In this paper, we present our results on near-infrared CRIRES spectroscopic observations of six cool giant stars in NGC 6656 (M22): the main objective is to derive the F content and its internal variation in this peculiar cluster, which exhibits significant changes in both light- and heavy-element abundances. Across our sample, we detected F variations beyond the measurement uncertainties and found that the F abundances are positively correlated with O and anticorrelated with Na, as expected according to the multiple population framework. Furthermore, our observations reveal an increase in the F content between the two different sub-groups, s-process rich and s-process poor, hosted within M22. The comparison with theoretical models suggests that asymptotic giant stars with masses between 4 and 5 M⊙ are responsible for the observed chemical pattern, confirming evidence from previous works: the difference in age between the two sub-components in M22 must be not larger than a few hundred Myr.

Key words: globular clusters: individual (NGC 6656) – stars: abundances – stars: AGB and post-AGB – stars: Population II

Online-only material: color figures

1. INTRODUCTION

Although Galactic globular clusters (GCs) display a distribution in their global parameters (e.g., mass, metallicity, concentration, horizontal-branch morphology), the internal variation of elements affected by proton captures (hereafter p-capture elements) appears to be a ubiquitous feature (Carretta et al. 2009b, 2009c). It is clear that GC stars exhibit large changes in the C, N, O, Na, Mg, and Al abundances, whereas (in archetypical systems at least) internal spreads in iron-peak, heavy α (Ca, Ti), and slow neutron-capture (s-process) elements all remain within observational uncertainties (Carretta et al. 2009a, 2009c; James et al. 2004; Smith 2008; D’Orazi et al. 2010). The changes in the p-capture elements give rise to a clear chemical pattern: depletion in C, O, and Mg abundances always corresponds to enhancements in N, Na, and Al (the so-called light-element anticorrelations). This behavior bears evidence of H burning at high temperature and points to the presence of multiple stellar generations. It is argued that the ejecta from a fraction of the first generation of stars (initially C–O–Mg rich, sharing the same chemical composition as field stars at the same metallicity) mix with primordial gas, providing a medium from which the second generation and are present from birth. The nature of the stars that enriched the intercluster gas remains uncertain but possible candidates include intermediate-mass asymptotic giant branch (AGB) stars undergoing hot bottom burning (HBB; e.g., D’Antona et al. 1983; Ventura et al. 2001), fast-rotating massive stars (e.g., Decressin et al. 2007), massive binaries (de Mink et al. 2009), and novae (Smith & Kraft 1996; Maccarone & Zurek 2012).

Interestingly, this already complex picture is further obfuscated by the presence of some peculiar clusters, such as ω Centauri (Johnson & Pilachowski 2010; Marino et al. 2011a), NGC 1851 (Yong & Grundahl 2008; Carretta et al. 2010b), Terzan 5 (Ferraro et al. 2009), NGC 6715 (M54; Carretta et al. 2010a), and NGC 2419 (Cohen et al. 2011; see however Mucciarelli et al. 2012 for a different view). In these GCs, along with changes in p-capture elements, internal variations in the heavy-element abundances have been detected. Species ranging from the iron-peak (e.g., Fe) to the s-process elements (Ba, La) vary stochastically from cluster to cluster beyond what is expected from observational errors.

The metal-poor GC NGC 6656 (M22, [Fe/H]9 = −1.70; Harris 1996—updated in 2010) belongs to this class of GCs.
and, due to its peculiar nature, has received extensive attention (Pilachowski et al. 1982; Norris & Freeman 1983; Brown & Wallerstein 1992; Kayser et al. 2008; Marino et al. 2009; Da Costa et al. 2009; Da Costa & Marino 2010; Alves-Brito et al. 2012). Recently, Marino et al. (2011b, hereafter MSK11) presented results from their high-resolution spectroscopic study of 35 giant stars, deriving abundances for iron-peak, α, p-capture, and neutron-capture elements. This detailed abundance analysis provided a unique opportunity to investigate the chemical enrichment history of M22.

This GC is comprised of two distinct groups of stars, which are characterized by an offset in metallicity and in s-process element content. The first group displays a metallicity of $\langle [\text{Fe/H}] \rangle = -1.82 \pm 0.02$ with $\langle [s/\text{Fe}] \rangle = -0.01 \pm 0.01$ and the second group has $\langle [\text{Fe/H}] \rangle = -1.67 \pm 0.01$ with $\langle [s/\text{Fe}] \rangle = +0.35 \pm 0.02$. Note that the $[s/\text{Fe}]$ ratios were computed by averaging the abundances of Y, Zr, Ba, La, and Nd (see MSK11 for details). Each of these two subgroups exhibits the classical Na-O and C-N anticorrelations shown by the archetypical GCs. Given that the $[\text{Eu}/\text{Fe}]$ ratio serves as a rapid neutron-capture ($r$-process) tracer10 and that enhancements in the s-process elements are not accompanied by a similar trend in the $[\text{Eu}/\text{Fe}]$ ratio, it can be inferred that the dichotomy in the $n$-capture abundances may be due to a first generation of polluters that produced the s-process only. One possible scenario, which was advocated by MSK11, is that the weak s-process component activated in stars with masses larger than $\sim 25 M_\odot$ during core He-burning and C-shell phases (Raiteri et al. 1993; Pignatari et al. 2010) may have contributed to the observed abundance patterns. However, in a complimentary study, Roederer et al. (2011) focused on the heavy-element content (from Y to Th) of six stars across the two stellar subgroups and ruled out the massive star origin. They concluded that the gas from which the second stellar population formed was enriched in s-process material from a class of relatively massive AGB stars ($M \approx 5 M_\odot$). In these stars, the production of s-process elements is due to the activation of the $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ neutron source, whereas in their lower-mass counterparts, the main neutron source is the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction (Busso et al. 1999).

Neither of the proposed scenarios provides a comprehensive explanation for all the observed chemical features and we are left with numerous unsolved issues. For example, Roederer et al. (2011) questioned why the s-process dichotomy is only present in M22: if massive AGB stars are the cause of the GC Na-O anticorrelation, then the s-process elements correlated with Na and anticorrelated with O should be present to all clusters, which is not observed (e.g., D’Orazi et al. 2010).

In this paper, we turn to an alternative diagnostic. We present fluorine abundances for a sample of six cool giant stars in M22, carefully selected from both sub-stellar groups as defined by MSK11. Fluorine abundances are a powerful tracer of the polluter mass range in M22 because the F production is highly dependent on the stellar mass.

Theoretical models of AGB stars (e.g., Jorissen et al. 1992) predict that F is produced due to the activation of the chain of reactions $^{18}\text{O}(p, \alpha)^{15}\text{N}(\alpha, \gamma)^{19}\text{F}$ in the He intershell during the recurrent thermal pulses associated with He burning. During the early phases of each thermal pulse, the H-burning ashes are ingested in the convective region developing in the He intershell. These ashes are rich in $^{13}\text{C}$ and $^{14}\text{N}$ and their ingestion in the He-burning layer results in production of $^{18}\text{O}$ due to $\alpha$ captures on $^{14}\text{N}$. At the same time, protons are released by the $^{14}\text{N}(p, \gamma)^{15}\text{C}$ reaction, with neutrons coming from $^{13}\text{C}(\alpha, n)^{16}\text{O}$. After the quenching of each thermal pulse, the envelope may sink in mass deep in the He intershell and carry $^{19}\text{F}$ to the convective envelope via a process known as the “third dredge up” (TDU). The peak of F production in AGB stars is reached for stars of initial masses of $\sim 2 M_\odot$ (Lugaro et al. 2004). If the mass of the stars is higher than roughly $5 M_\odot$, and depending on the metallicity, fluorine is destroyed both via $\alpha$ captures in the He intershell and via proton captures at the base of the convective envelope due to HBB. AGB stars that experience HBB can also destroy O and Mg and produce Na and Al; as a consequence, according to the multiple population scenario, we should expect the abundances of F to be correlated with O (and Mg) and anticorrelated with those of Na (and Al). This prediction was observationally confirmed by Smith et al. (2005) in the intermediate-metallicity GC M4 and by Yong et al. (2008) in NGC 6712.

Other sites have also been suggested for F production: the $\nu$-process in core-collapse supernovae (SNe; Woosley et al. 1990) and core He burning in Wolf–Rayet stars (Meynet & Arnould 2000; Palacios et al. 2005). However, low-mass AGB stars are the only sites that have been observationally confirmed (Jorissen et al. 1992; Abia et al. 2010).

This paper is organized as follows: observations are described in Section 2, while details on abundance analyses are given in Section 3. Our results are then presented in Section 4 and discussed in Section 5. A summary closes the paper (Section 6).

2. OBSERVATIONS

Our sample includes six giant stars for which stellar parameters ($T_{\text{eff}}$, log g, [Fe/H], and microturbulence $\xi$) along with $p$-capture and s-process element abundances were derived by MSK11. We selected three stars belonging to the metal-poor (MP) component (also s-process poor) and three stars from the metal-rich (MR, s-process rich) one. Within each of these sub-groups we also selected both O-rich (Na-poor) and O-poor (Na-rich) stars, spanning a range from $[O/\text{Fe}] = +0.11$ to $[O/\text{Fe}] = +0.48$ dex.

The main objective of our investigation was the determination of the fluorine abundances. Observationally, F (whose only stable isotope is $^{19}\text{F}$) is difficult to detect spectroscopically; the only atomic lines (the ground-state transitions of F) that might be revealed lie in the far-UV. On the other hand, HF molecular transitions are easily observable in the near-infrared (around $\sim 23,000 \text{ Å}$). Our analysis focuses on the HF($1\rightarrow0$) R9 transition, located at 23358.3 Å. Although not being the strongest feature in this wavelength range, this line is considered to be one of the best abundance indicator for F because it is free of blends (Abia et al. 2009; Lucatello et al. 2011).

High-resolution, near-infrared spectroscopic observations were carried out in service mode with CRYogenic high-resolution InfraRed Echelle Spectrograph (CRIRES; Kaeufl et al. 2004) located at VLT UT1 on 2011 April, July, and August (program: 087.0319(A), PI: VD). In Table 1, we list information on target stars, reporting identifications, magnitudes (see MSK11 for details), exposure times, and signal-to-noise ratios (S/Ns) per pixel around the HF feature. Note that our selection was limited to the cooler stars in MSK11’s sample due to our imposed requirement of relatively strong HF lines. We also observed several (hot) early-type stars before and/or after

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10 In the solar system, $\approx 97\%$ of Eu was synthesized via the r-process (Burris et al. 2000 and references therein).
observations of each target in order to remove telluric contamination from our scientific frames.

We employed the 0′4 slit and the grating order 24, achieving a resolution of $R \sim 50,000$ and a wavelength coverage from 22948.5 Å to 23410.3 Å. This allowed us to include the HF(1−0) R9 line, numerous $^{12}$C$^{16}$O vibration/rotation lines (used to derive C abundances), and the Na I line at 23739 Å.

Data reduction was accomplished by means of the CRIORES pipeline (version 2.4), running under the GASGANO environment,\footnote{11} which provides one-dimensional, wavelength-calibrated spectra. Telluric feature subtraction, rest-frame translation, and continuum normalization were then carried out within IRAF.\footnote{12} An example of our spectra is shown in Figure 1 for star III-52; HF, CO, and Na I lines are marked.

### 3. ABUNDANCE ANALYSIS

Fluorine abundances were determined through spectral synthesis using the MOOG code (Sneden 1973, 2011 version) and the Kurucz (1993) set of stellar atmosphere models (with no overshooting) as in MSK11’s analysis, from which we retrieved stellar parameters as well as O and s-process element abundances. However, had we instead adopted the MARCS grid (Gustafsson et al. 2008), the difference in the resulting abundances would have been less than 0.04 dex.

Concerning the HF feature, we took as an excitation potential (EP) $\chi = 0.227$ eV (Decin 2000) and $\log gf = -3.971$ (Lucatello et al. 2011). This last value is very close to that used in previous studies focusing on the F abundance determination in GCs (e.g., Smith et al. 2005; Yong et al. 2008; Alves-Brito et al. 2012), $\log gf = -3.955$ (from Jorissen et al. 1992). On the other hand, our EP is about 0.25 eV lower compared to those works: this difference implies an offset of roughly 0.30 dex between our abundances and those previously published in the literature (see also the discussion in Section 4.1). Furthermore, we derived C abundances. For this purpose, we assumed O values from the optical range given by MSK11, since our spectra did not cover any suitable OH line, whose stronger transitions extend in the H band (around $\sim 15,000$ Å). The CO line lists come from Gustafsson et al. (2008). Finally, for the Na I line at 23739 Å, atomic parameters ($\chi = 3.750$ eV; $\log gf = 0.530$) were taken from VALD.\footnote{13}

As a first step, we checked our line list on the infrared atlas of the Arcturus spectrum (Hinkle et al. 1995, available at ftp://ftp.noao.edu/catalogs/arcturusatlas/). Assuming a $T_{eff} = 4286$ K, $\log g = 1.67$, $\xi = 1.74$ km s$^{-1}$, and [Fe/H] = −0.52 (following Ramírez & Allende Prieto 2011) we obtained an $[\text{F/Fe}] = -0.15$,\footnote{14} to be compared to the value given by Abia et al. (2009) of $[\text{F/Fe}] = 0.10$ dex. The difference is completely explained by the higher EP adopted in that study.

Moreover, we inferred a C abundance of $A(C) = 8.01$ (under the assumption that $A(O) = 8.81$, that is [O/Fe] = 0.40, with a solar abundance of $A(O)_{\odot} = 8.93$), which is in very good agreement with the values of Abia et al. (2009) (i.e., $A(C) = 8.06$ and Ryde et al. (2010) ($A(C) = 8.08$). As for the C solar abundance, we adopted the value of $A(C)_{\odot} = 8.56$, leading to [C/Fe] = −0.03.

Finally, from the Na I feature at 23739 Å, we derived $A(\text{Na}) = 6.01$, which results in [Na/Fe] = +0.2 dex (setting $A(\text{Na})_{\odot} = 6.33$).

Comparison between synthetic and observed spectra were carried out in a similar way for our sample stars; an example of spectral synthesis is given in Figures 2 and 3 for star C.

The sensitivity of the F abundance to input stellar parameters was evaluated by separately changing the effective temperature, surface gravity, and microturbulence values. The intensity of the synthetic line of the HF is particularly sensitive to the adopted $T_{eff}$, the other parameters affect it to a lower degree (see also Abia et al. 2009, 2011). A change of $\Delta(T_{eff}) = +70$ K, $\Delta(\log g) = +0.15$, and $\Delta(\xi) = +0.13$ km s$^{-1}$ (conforming to error estimates given in Table 4 of MSK11) results in a difference in $A(F)$ of +0.10, 0.02, and −0.02 dex, respectively. The variation of the input metallicity in the model atmosphere has, instead, a negligible effect. These are the typical uncertainties that we then summed in quadrature providing a total error, due to stellar parameters, of 0.11 dex in our [F/H] ratios. Errors due to the best-fit determination (related to the S/N of the spectra and including uncertainties due to the continuum placement) are instead ±0.07 dex. However, we caution the reader that this value should be treated as a lower limit, since the impact of the telluric correction on this considerably weak feature is significant (see Section 4).

\begin{table}[h]
\centering
\caption{Information on Target Stars}
\begin{tabular}{|l|c|c|c|c|c|}
\hline
Star & R.A. & Decl. & V & K & Exposures & S/N \\
     & (hh:mm:ss) & (°′′) & (mag) & (mag) & (s) & \\
\hline
IV-97 & 18:36:41.06 & −23:58:18.9 & 11.043 & 6.759 & 10 × 90 & 300 \\
III-14 & 18:36:15.10 & −23:54:54.6 & 11.134 & 6.743 & 17 × 120 & 400 \\
\hline
\end{tabular}
\end{table}
D’Orazi et al.

Figure 2. Synthesis of the HF feature for star C.

The total internal error in [F/H] is then obtained by adding both uncertainties in quadrature, resulting in 0.13 dex.

Finally, as far as C and Na are concerned, the typical uncertainties are 0.12 and 0.10 dex, respectively.

4. RESULTS

Our results are shown in Table 2, where we report stellar parameters and abundances from MSK11 along with our estimates for F, C, and Na. Even within our quite limited sample (six stars), we found that the F abundance shows a large star to star variation, ranging from [F/H] = −2.82 dex to [F/H] = −2.23 dex (i.e., a factor of ∼4). The average abundance is ⟨[F/H]⟩ = −2.55 ± 0.08 (rms = 0.20), implying that the amplitude of this change is beyond the measurement uncertainties (see Section 3). Moreover, taking into account the typical errors for O and F abundances, our study suggests that the F variation is comparable with that of O, as also found by Yong et al. (2008) in the GC NGC 6712.

In Figures 4 and 5, we plot [F/H] ratios as a function of [O/H] and [Na/H], respectively. As one can see, the F abundances are positively correlated with O: considering the whole sample, the Pearson correlation coefficient results in r = 0.89, with a smaller than 2% probability of being random. Focusing on the F–Na diagram (Figure 5), there is a hint of an F–Na anticorrelation, but in our small sample the linear correlation coefficient is not statistically meaningful. However, this does not prove the lack of an anticorrelation because we are dealing with small numbers (only six points), heavily reducing the power of statistical tests. In addition, there is no a priori reason why we should combine the two sub-groups as far as the F–Na plane is concerned because we do not expect that they must behave in the same way. If we look at each component separately, the presence of an F–Na anticorrelation is indeed much more evident (given that we have only three points for each group, it is not meaningful to perform a statistical test separately).

The observed chemical pattern can be explained as evidence of H burning at high temperatures, via the CNO cycle, which causes the destruction of F, in conjunction with O depletion and Na enhancement. More interestingly, those (anti)correlations are revealed in each of the M22 sub-components (the s-rich and s-poor groups); the implications of this finding are discussed in detail in Section 5.

Regarding Na, we show our estimate from near-infrared spectroscopy as well as LTE abundances from the optical range given by MSK11 (right- and left-hand panels of Figure 5). A difference of Δ([Na/Fe]) = 0.31 ± 0.04 (rms = 0.09) dex is found between the two estimates (see Figure 6), where we compare the two measurements; non-LTE effects can totally account for such a discrepancy (e.g., Lind et al. 2011). The total average Na abundance is ⟨[Na/Fe]⟩ = 0.05 ± 0.13 (rms = 0.33); separately considering the two groups we instead obtain ⟨[Na/Fe]⟩s-rich = −0.12 ± 0.23 and
Table 2
Stellar Parameters and Elemental Abundances

<table>
<thead>
<tr>
<th>Star</th>
<th>T_\text{eff}^\text{a} (K)</th>
<th>log g^a</th>
<th>[\text{Fe}/H]^a</th>
<th>\xi^a (\text{km s}^{-1})</th>
<th>[O/Fe]^a</th>
<th>s-rich^a</th>
<th>[C/Fe]</th>
<th>[F/Fe]</th>
<th>[Na/Fe]</th>
</tr>
</thead>
<tbody>
<tr>
<td>IV-97</td>
<td>4000</td>
<td>0.05</td>
<td>-1.94</td>
<td>2.00</td>
<td>0.40</td>
<td>no</td>
<td>-1.10</td>
<td>-0.70</td>
<td>-0.40</td>
</tr>
<tr>
<td>III-14</td>
<td>4030</td>
<td>0.35</td>
<td>-1.82</td>
<td>2.15</td>
<td>0.48</td>
<td>no</td>
<td>-1.10</td>
<td>-0.80</td>
<td>-0.30</td>
</tr>
<tr>
<td>III-15</td>
<td>4070</td>
<td>0.40</td>
<td>-1.82</td>
<td>1.85</td>
<td>0.11</td>
<td>no</td>
<td>-1.15</td>
<td>-1.00</td>
<td>0.34</td>
</tr>
<tr>
<td>C</td>
<td>3960</td>
<td>0.30</td>
<td>-1.69</td>
<td>2.25</td>
<td>0.25</td>
<td>yes</td>
<td>-0.60</td>
<td>-0.80</td>
<td>0.30</td>
</tr>
<tr>
<td>III-52</td>
<td>4075</td>
<td>0.60</td>
<td>-1.63</td>
<td>1.75</td>
<td>0.45</td>
<td>yes</td>
<td>-0.10</td>
<td>-0.60</td>
<td>0.05</td>
</tr>
<tr>
<td>V-2</td>
<td>4130</td>
<td>0.65</td>
<td>-1.57</td>
<td>1.75</td>
<td>0.15</td>
<td>yes</td>
<td>-0.40</td>
<td>-0.90</td>
<td>0.31</td>
</tr>
</tbody>
</table>

Note. a From MSK11.

Figure 4. Fluorine abundances ([F/H]) as a function of [O/H].

Figure 5. [F/H] vs. [Na/H] from MSK11 (left panel) and from this study (right panel). Symbols are as in Figure 4.

Figure 6. [Na/Fe] from the optical range by MSK11 and from this study.

Finally, our sample displays an average C abundance of \([\text{C/Fe}]_{\text{s-rich}} = 0.22 \pm 0.08\), which implies \(\Delta_{\text{poor}} [\text{Na/Fe}] = 0.34 \pm 0.17\) dex. This value is in good agreement with that derived by MSK11, based on the whole sample of 35 giants, being \(\Delta_{\text{poor}} [\text{Na/Fe}] = 0.23 \pm 0.07\).

Finally, our sample displays an average C abundance of \([\text{C/Fe}]_{\text{s-rich}} = -0.74 \pm 0.18\), with \([\text{C/Fe}]_{\text{s-poor}} = -1.12 \pm 0.02\) and \([\text{C/Fe}]_{\text{s-rich}} = -0.37 \pm 0.14\). Thus, on average, s-rich stars exhibit larger C abundances, which qualitatively agrees with previous works (e.g., Brown et al. 1990). However, while the difference between the two groups from the optical CH bands derived by MSK11 is \(\Delta_{\text{poor}} [\text{C/Fe}] = 0.35 \pm 0.13\) dex, we achieved a much larger value of \(\Delta_{\text{poor}} [\text{C/Fe}] = 0.75 \pm 0.10\) dex. The same conclusion was reached by Alves-Brito et al. (2012) who found a variation of \(\Delta_{\text{poor}} [\text{C/Fe}] = 0.78 \pm 0.15\) dex, from high-resolution, near-infrared spectroscopy of nine cool giants (see also Section 4.1). The reason for such a difference in C abundance from the optical and from the near-infrared is not clear and no obvious trends with stellar parameters (e.g., temperature, gravity, microturbulence, and/or metallicity) seem to be present. Further investigations are needed to explore this issue.

4.1. Comparison with Alves-Brito et al. (2012)

In a recent paper, Alves-Brito et al. (2012) carried out high-resolution \((R = 50,000)\), near-infrared (both \(H\) and \(K\) bands)
spectroscopic observations of nine red giant branch (RGB) stars in M22 with Phoenix at Gemini-South. They investigated their F content, presenting also C, N, O, Na, and Fe abundances.

Four of our six stars are in common with that study, namely, III-14, III-15, III-52, and IV-97. For stars III-14 and III-52, those authors inferred [F/Fe] = −0.40 and [F/Fe] = −0.20 dex, respectively, while we obtained [F/Fe] = −0.80 and [F/Fe] = −0.60 dex. The adopted EP value can easily justify this divergence, accounting for about 0.30 dex (see Section 3); the source of the remaining −0.1 dex can be ascribed to the continuum placement, which is critical in determining abundances from such a weak line. On the other hand, for stars III-15 and IV-97, Alves-Brito et al. (2012) obtained [F/Fe] = 0.28 and [F/Fe] = 0.25 dex, entailing discrepancies with our estimates larger than a factor of 10. Note that stellar parameters (Teff, log g, and ξ) are the same in both works, as they come from the analysis of MSK11; for the input metallicity, Alves-Brito et al. instead used their own values, which came from the IR spectroscopy and showed an offset of +0.13 dex compared to the optical ones. We investigated the nature of this substantial discordance and attributed it to the telluric feature subtraction. In the upper panel of Figure 7, we directly compare our spectrum for star III-15 (solid line) with that used by Alves-Brito et al. (2012; dotted line). Their spectrum presents stronger features in the vicinity of the HF line, features expected from telluric contributions (dotted line). Their spectrum presents stronger features in the vicinity of the HF line, features expected from telluric contributions (dotted line). The adopted EP value can easily justify this divergence, accounting for about 0.30 dex (see Section 3); the source of the remaining −0.1 dex can be ascribed to the continuum placement, which is critical in determining abundances from such a weak line. On the other hand, for stars III-15 and IV-97, Alves-Brito et al. (2012) obtained [F/Fe] = 0.28 and [F/Fe] = 0.25 dex, entailing discrepancies with our estimates larger than a factor of 10. Note that stellar parameters (Teff, log g, and ξ) are the same in both works, as they come from the analysis of MSK11; for the input metallicity, Alves-Brito et al. instead used their own values, which came from the IR spectroscopy and showed an offset of +0.13 dex compared to the optical ones. We investigated the nature of this substantial discordance and attributed it to the telluric feature subtraction. In the upper panel of Figure 7, we directly compare our spectrum for star III-15 (solid line) with that used by Alves-Brito et al. (2012; dotted line). Their spectrum presents stronger features in the vicinity of the HF line, features expected from telluric contributions (dotted line). The adopted EP value can easily justify this divergence, accounting for about 0.30 dex (see Section 3); the source of the remaining −0.1 dex can be ascribed to the continuum placement, which is critical in determining abundances from such a weak line. On the other hand, for stars III-15 and IV-97, Alves-Brito et al. (2012) obtained [F/Fe] = 0.28 and [F/Fe] = 0.25 dex, entailing discrepancies with our estimates larger than a factor of 10. Note that stellar parameters (Teff, log g, and ξ) are the same in both works, as they come from the analysis of MSK11; for the input metallicity, Alves-Brito et al. instead used their own values, which came from the IR spectroscopy and showed an offset of +0.13 dex compared to the optical ones. We investigated the nature of this substantial discordance and attributed it to the telluric feature subtraction. In the upper panel of Figure 7, we directly compare our spectrum for star III-15 (solid line) with that used by Alves-Brito et al. (2012; dotted line). Their spectrum presents stronger features in the vicinity of the HF line, features expected from telluric contributions (dotted line). The adopted EP value can easily justify this divergence, accounting for about 0.30 dex (see Section 3); the source of the remaining −0.1 dex can be ascribed to the continuum placement, which is critical in determining abundances from such a weak line. On the other hand, for stars III-15 and IV-97, Alves-Brito et al. (2012) obtained [F/Fe] = 0.28 and [F/Fe] = 0.25 dex, entailing discrepancies with our estimates larger than a factor of 10. Note that stellar parameters (Teff, log g, and ξ) are the same in both works, as they come from the analysis of MSK11; for the input metallicity, Alves-Brito et al. instead used their own values, which came from the IR spectroscopy and showed an offset of +0.13 dex compared to the optical ones. We investigated the nature of this substantial discordance and attributed it to the telluric feature subtraction.

In the upper panel of Figure 7, we directly compare our spectrum for star III-15 (solid line) with that used by Alves-Brito et al. (dotted line). Their spectrum presents stronger features in the vicinity of the HF line, features expected from telluric contribution. To completely remove the contamination, Alves-Brito et al. realized that they needed early-type star targets before and after each scientific frame, but the logistics of their run made this very difficult. We could instead observe such targets: the correction to our data in turn affects the placement of the continuum and removes many strong features (as shown in the lower panel of Figure 7). As expected, such an effect is significant for the HF feature, due to its intrinsic weakness, but only marginally affects the C and Na abundance determinations (due to the strength of their lines), and hence most of the conclusions in that paper. This is shown in Figure 8, where we plot our [X/Fe] ratio as a function of those from Alves-Brito et al. (2012) for the four stars in common: C and Na are comparable between the two studies, with differences of Δ[C/Fe] = +0.20 ± 0.17 dex and Δ[Na/Fe] = +0.18 ± 0.11 dex (in the sense of Alves-Brito et al.’s study minus our values). If we take into account the offsets in [Fe/H] and in the adopted solar abundances (they assumed A(C)⊙ = 8.42 and A(Na)⊙ = 6.17), those values become Δ[C/Fe] = +0.19 ± 0.17 and Δ[Na/Fe] = +0.15 ± 0.11 dex. On the other hand, the discrepancies in F are significant and cannot be recovered from the different EP and/or solar abundances, since they are for the whole sample of Δ[F/Fe] = +0.75 ± 0.19 dex.

5. DISCUSSION

Our main result is that the detection of F variations across our sample are significantly larger than the observational uncertainties. As shown in Figures 4 and 5, the changes in the F abundances are correlated with O and anticorrelated with Na. This chemical pattern qualitatively matches the predictions from the multiple population scenario, according to which the stellar ejecta from which second-generation stars formed carry the signature of hot H burning that causes enhancements in Na (N and Al) and depletions in O and F (C and Mg). The F–O diagram presented in Figure 9 demonstrates that M22 shares a similar behavior as M4 and NGC 6712, the other two GCs for which F has been explored.15

Furthermore, the F–O–Na (anti) correlations can be marked separately within each of the two sub-groups enclosed in M22 as clearly illustrated in Figures 4 and 5, where the s-process poor and the s-process-rich stars are labeled with empty and filled symbols, respectively. The same conclusion was drawn by MSK11 when considering the Na–O and C–N planes.

15 Cunha et al. (2003) presented F abundances for two giants in ω Cen. However, they provide an F measurement only for star ROA219, giving an upper limit for star ROA 324. Discussion related to the internal F variation in this peculiar GC is still not possible with the currently available measurements. For this reason we acquired CRIRES spectra of 12 ω Cen giants; results will be presented in a forthcoming paper (S. Lucatello et al., in preparation).
Very interestingly, beyond the internal spread in F characterizing each sub-component, we measured an increase in the F content between the two different stellar generations in M22. The s-process-rich group has, on average, larger F abundances than the s-process-poor group. This is shown in Figure 10, where we plot our F abundances ([F/H]) as a function of [La/H] from MSK11. There is a positive correlation between the two ratios, suggesting that the polluters responsible for the s-process production must account for a simultaneous F production.

There are two classes of objects producing both s-process elements and fluorine. The first one is very massive stars (mass roughly \( >40 M_\odot \)). These produce F in the initial phases of core He burning and expel it in the interstellar medium via winds during the Wolf–Rayet phase (Meynet & Arnould 2000). They also produce s-process elements during core He and shell C burning (e.g., Pignatari et al. 2010). Production of both F and s-process elements in these massive stars depends on the initial CNO abundances and thus decreases with the stellar metallicity. Inclusion of stellar rotation enhances the s-process production at low metallicity (Pignatari et al. 2008; Chiappini et al. 2011); however, it appears to decrease the production of fluorine (Palacios et al. 2005). One problem already stressed by Roederer et al. (2011) when considering these stars is that there is no reason why the SNe that enriched the s-process-rich group host the weak component and those that polluted the s-process poor do not (see Roederer et al. for details).

The second class of objects producing both F and s-process elements are AGB stars (Forestini et al. 1992; Jorissen et al. 1992; Mowlavi et al. 1998; Karakas & Lattanzio 2003; Lugaro et al. 2004, 2012). To obtain deeper insights into the nature of the candidate AGB stars possibly responsible for the observed abundance trends in M22, we compare our results with the recent set of models by Lugaro et al. (2012). They presented AGB models for masses 0.9–6.0 \( M_\odot \) and metallicity three times lower than that of the cluster under consideration (i.e., [Fe/H] = −2.3 dex).

From our data we infer that there is an increase of \( \Delta([F/H])_{s\text{-rich}} = +0.40 \pm 0.15 \text{ dex} \) in the fluorine content between the two groups. This estimate was done by taking into account the F content of the O-rich stars only because they do not show any depletion due to the HBB. We averaged the F abundances in stars IV-97 and III-14, both belonging to the s-poor group, finding a mean value \( ([F/H]) = -2.63 \pm 0.01 \text{ dex} \). Since we have only one O-rich star in the s-rich group, III-52, we chose it to be representative of the F abundance for the group, that is, \([F/H] = -2.23 \pm 0.15 \text{ dex}\). The F increase of +0.40 dex is accompanied by a corresponding enhancement in La of \( \Delta([La/H])_{s\text{-rich}} = 0.56 \pm 0.18 \text{ dex} \), since the values are \( ([La/H]) = -1.92 \pm 0.15 \text{ dex} \) and \([La/H] = -1.36 \pm 0.10 \text{ dex} \), respectively, for the two groups.

Comparing these values with the model predictions by Lugaro et al. (2012) we found that AGB stars with masses of \( \approx4–5 M_\odot \) can well reproduce the observed pattern. Lower-mass AGB models do not fit our observational requirements because they overproduce fluorine. This is true even if we consider that these AGB model predictions are roughly 1 dex too high to match the observation of carbon-enhanced MP (CEMP) stars by Lucatello et al. (2011). Production of F in the \( \approx4–5 M_\odot \) mass range depends on the delicate balance between the operation of the TDU and of HBB. These stars suffer HBB and destroy F during the early phases of their AGB evolution; however, toward the end of the evolution, as the mass of the convective envelope decreases, HBB ceases while the TDU is still active resulting in mild F enhancements at the stellar surface. This explains why while the most prolific AGB stars in terms of fluorine production have initial masses around \( 2 M_\odot \), F production still occurs at slightly higher masses. On the other hand, more massive AGB models (\( >5 M_\odot \)) experience hotter HBB and thus more efficient F destruction as well as higher temperatures in the thermal pulses also activating \( ^{19}\text{F} (\alpha, \gamma)^{22}\text{Ne} \) reactions. This, combined with fewer final TDU episodes when HBB has ceased, means that they do not replenish F at the stellar surface.
Interestingly, the same conclusion is drawn by Roederer et al. (2011) by exploring the heavy-element ratios, [hs/ls] and [Pb/hs]. Comparing their abundances with models by Roederer et al. (2010), these authors deduced that the low-mass AGBs (≤3 M☉) cannot account for the observed trend. More importantly, they concluded that a match to the s-process element abundances is provided by the 5 M⊙ AGB model, and this is confirmed by checking the models of Lugaro et al. (2012). Furthermore, and very interestingly, these models predict Na and C production in agreement with the observations.

Our result provides a further, independent confirmation of this previous suggestion: indications from both light (fluorine here) and heavy elements converge toward the AGB stars of the same mass as the best candidate polluters, indicating that the age difference between the two sub-groups in M22 cannot be larger than a few hundred Myr. It should be mentioned that by analyzing the double sub-giant branch (SGB) of this cluster, Marino et al. (2012) concluded that the age spread can be at most ~300 Myr.

The fact that three independent studies, involving different and complementary techniques/approaches, produce the same result is encouraging. However, a comprehensive understanding of the whole picture is still missing. As also stressed by Roederer et al. (2011), if relatively massive AGBs (4–5 M⊙) produced the s-process elements, and if these stars are also responsible for the observed p-capture element anticorrelations, then it is not explained why s-process enrichment is present in M22 but is not associated with O and Na abundance anomalies, nor is it seen in any other GCs where the Na–O anticorrelations are observed.

On the other hand, it is clear from the observed F abundance trends that we must select slightly more massive AGBs, i.e., ≥6 M⊙, if we wish to explain the light-element variations in GCs, since this is the AGB mass range where F and O can be destroyed by HBB, resulting in the observed F–O correlation. We might tentatively suggest that perhaps the production of the s-process elements in AGB models with an initial mass ≥6 M⊙ is less efficient than currently predicted. This could be the result of a stronger mass-loss rate or a less efficient TDU in this mass range than those employed in the models by Lugaro et al. (2012). This possibility is well within model uncertainties and needs to be investigated; in a forthcoming paper (V. D’Orazi et al., in preparation) we will attack these issues, presenting new observations and AGB models and discussing their strength/weakness in reproducing the observed abundance trends in GCs.

Alternatively, we may conclude that massive AGBs are not the intercluster polluters; however, several lines of evidence point to those stars, such as the need for an Li production between first- and second-generation stars (as in the case of M4, D’Orazi & Marino 2010; Mucciarelli et al. 2011; Monaco et al. 2012). Further efforts, from both observational and theoretical perspectives, are needed; in particular, the lack of a complete set of models for AGB stars and massive rotating stars with different mass and metallicity, following the whole nucleosynthetic path from Li to Pb, still hampers a quantitatively robust comparison between theory and observations.

6. SUMMARY AND CONCLUDING REMARKS

We presented fluorine abundances for a sample of six RGB stars belonging to the metal-poor globular cluster M22. The sample was selected to include s-process-rich and s-process-poor stars, as defined in MSK11. In addition, within each of these cluster sub-components, we targeted both O-rich (Na-poor) and O-poor (Na-rich) stars. We gathered evidence of the presence of an F–O correlation and of an F–Na anticorrelation. Such a chemical pattern, notably revealed in each cluster sub-group, is in agreement with F destruction during the hot H burning: fluorine follows the same trend defined by O, Na, C, N, Mg, and Al, as predicted by the multiple population scenario.

Most interestingly, we found that the s-process-(metal-)rich component is also characterized by a larger F content than the s-process-(metal-)poor component. The comparison between our observations and the AGB models points to stars with masses around 4–5 M⊙ as being responsible for such a trend, corroborating previous suggestions by Roederer et al. (2011) and Marino et al. (2012), and confirming that the age spread across the two different stellar generations in M22 cannot be larger than a few hundred Myr.

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