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# A different view on light-element anticorrelations in globular clusters: fluorine abundances

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**Abstract.** The light-element variations among globular cluster (GC) stars are nowadays accepted as the signature of self-enrichment from previous generations of stars. It is expected that these extinct progenitors experienced hot H-burning and, as fluorine is involved in the complete CNO cycle, the F abundance in GCs can provide new clues about the previous generation(s). Along with Na-O and Mg-Al anti-correlations, theory predicts an anti-correlation between F and Na and a positive correlation between F and O. Moreover, relatively low-mass AGB stars are F producers (and are also responsible for C+N+O and *s*-process element variations). We present our results on F abundances in four GCs (NGC 6656, NGC 6752, 47 Tucanae and $\omega$ Centauri), which exhibit notably different *s*-process and/or C+N+O abundance patterns.

**Key words.** Stars: abundances – Stars: Population II – Galaxy: globular clusters – Stars: AGB and post-AGB

## 1. Introduction

A large variety of studies have revealed the complex nature of GCs. Abundance variations

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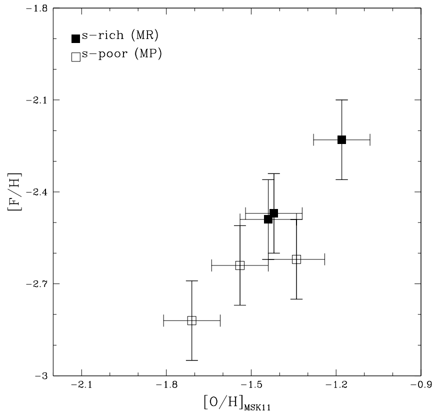


**Fig. 1.** [F/H] as a function of [O/H] for our six target stars in M22. The [O/H] abundances and s-processing grouping are as determined by Marino et al. (2011, MSK11).

in the lighter elements (e.g., Li, C, N, O, Na, Mg and Al), recognised since the 1970's (e.g., Cohen 1978), demand that some material must have been processed through the entire CNO cycle: element pairs C-N, O-Na, and Mg-Al are anti-correlated such that the abundances of C, O and Mg are depleted and N, Na and Al are enhanced. It is now well accepted that this pattern is related to a self-enrichment mechanism due to a previous generation of stars, whereby those elements affected by proton-captures and ultimately responsible for the observed anti-correlations, are synthesised in the stellar interiors. The origin of the polluters responsible is still debated (e.g., intermediate-mass AGB stars by Ventura et al. 2001 or fast rotating massive stars by Decressin et al. 2007). While the study of the Na, O, Mg, and Al abundances in GCs has received extensive attention during the years, with samples made of thousands of stars (e.g., Carretta et al. 2009), the F abundances have been mostly overlooked. Determining the F content in GCs provides us an extremely powerful (perhaps unique?) tracer of the polluter nature because its production/destruction is highly dependent on the stellar mass.

Theoretical models of AGB stars predict that F is produced from the reaction $^{18}$O(p,$\alpha$)$^{15}$N($\alpha$,$\gamma$)$^{19}$F in the He intershell during thermal pulses associated with He burning. The peak of F production in AGB stars is reached for stars of initial masses $\sim$ 2 $M_\odot$ (Lugaro et al. 2004). In AGB stars with masses larger than roughly 5 $M_\odot$, and depending on the metallicity, F is destroyed both via $\alpha$ captures in the He intershell, and via proton captures at the base of the convective envelope due to hot bottom burning (HBB). Moreover, AGBs undergoing HBB can also destroy O and Mg and produce Na and Al. Thus, according to the MPS, we should expect the abundances of F to be correlated with O (and Mg) and anti-correlated with those of Na (and Al). This prediction was indeed observationally confirmed in the GCs M4 and NGC 6712 by Smith et al. (2005) and Yong & Grundahl (2008).

## 2. Our project

### 2.1. NGC 6656 (M22)

By analysing 35 giant stars in the GC NGC 6656 (M22, [Fe/H]=−1.70), Marino et al. (2011) found that it is composed of two distinct stellar groups, characterised by an

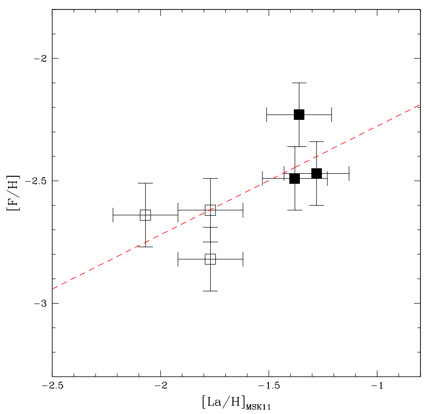


**Fig. 2.** [F/H] as a function of [La/H] for our sample of six stars in M22.

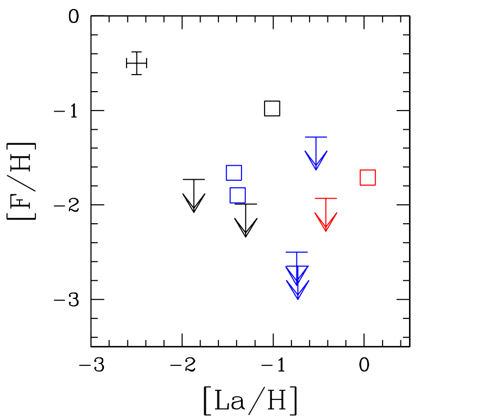


**Fig. 3.** F *vs*. La for $\omega$ Cen stars. Black, blue, and red symbols are for metal-poor, metal-intermediate, and metal-rich stars. Errorbars in F and La are shown in the top left corner.

offset in metallicity and in *s*-process element content, namely $\Delta$[Fe/H]=0.15±0.02 and $\Delta$[*s*/Fe]=0.36±0.02 dex.

These authors suggested that the *weak s*-process component, activated in massive stars (M$\gtrsim$ 25 $M_{\odot}$) during core He-burning and C-shell phases, may have played a role in the observed abundance patterns. This is in contrast with a recent study by Roederer et al. (2011) who focused on the heavy element content (from Y to Th) across the two stellar subgroups and ruled out the massive star origin.

We decided to approach the problem from a different perspective, deriving F abundances for a sample of six cool giant stars in M22, by employing the NIR spectrograph CRIRES@VLT. These stars were carefully selected from both sub-stellar groups as defined by Marino et al. (2011): three stars belong to a metal-poor (MP, s-process poor) population and three stars to a metal-rich (MR, s-process rich) one, as determined by Marino et al. (2011). We refer the reader to D'Orazi et al. (2013) for details on observations, data reduction, abundance analysis and error estimates. We detected star-to-star variations in F abundances, with values ranging from [F/H]=−2.82 to [F/H]=−2.23 dex (i.e., a factor of ~4). Such a large spread is beyond the measurement uncertainties. Moreover, the variations are not random but are positively correlated with O and anti-correlated with Na. The observed chemical pattern can be explained by the presence of H-burning at high temperatures which leads to the destruction of F simultaneously with O depletion and Na enhancement. Interestingly, those (anti)correlations are detectable in each of the M22 sub-components (the *s*-rich and *s*-poor groups, see Figure 1).

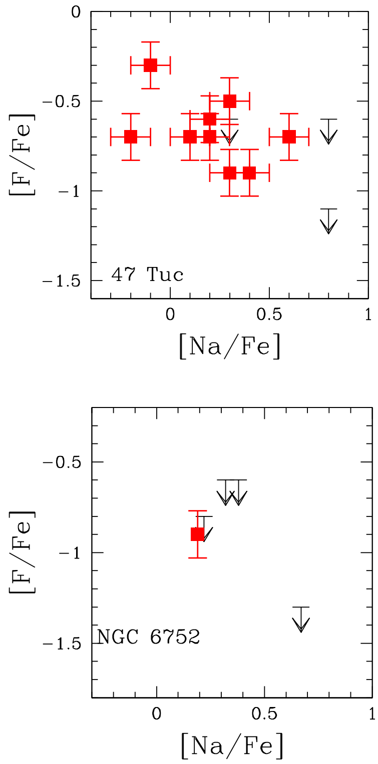


**Fig. 4.** [F/Fe] as a function of [Na/Fe] for 47 Tuc and NGC 6752.

Beyond the internal spread in F characterising 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 (see Fig. 2). This finding implies that the polluters responsible for the *s*-process production must also account for the F production.

Comparing our abundances with models by Lugaro et al. (2012) we found that AGB stars with masses of $\approx 4-5$ $M_\odot$ can reproduce the observed pattern. Interestingly, Roederer et al. (2011) reached the same conclusion by exploring the heavy-element ratios, such as [Pb/*hs*][1]. Thus, observational constraints from both light (F) and heavy elements point to the same polluter mass range (i.e. AGBs with masses around $4-5$ $M_\odot$ ), and imply a difference in age not larger than a few hundred Myr. Notably, Marino et al. (2012) chemically characterised the double sub-giant branch of this cluster, and concluded that the age spread can be *at most* ~300 Myr.

### 2.2. NGC 5139 ($\omega$ Centauri)

We derived F abundances for a sample of ten cool RGB stars in the extremely peculiar cluster $\omega$ Cen (e.g., Johnson & Pilachowski 2010), targeting stars belonging to the three different sub-populations, characterised by different [Fe/H] and *s*-process element abundances. We detected the hint for a positive correlation between F-O and an F-Na anticorrelation only in the more metal-poor group (Lucatello et al., in prep.). More interestingly, in contradiction with M22, there is no evidence for a F production in this GC (see Figure 3): this indicates that low-mass AGBs are ruled out as candidate polluters, confirming previous finding from the heavy element ratios by D'Orazi et al. (2011).

[1] *hs* is for second-peak *s*-process elements, e.g., Ba, La, Ce.

### 2.3. The calibrator clusters: NGC 6752 and NGC 104 (47 Tuc)

In addition to derive the F abundances in the "peculiar" GCs M22 and $\omega$ Cen, we also performed a chemical analysis in the more standard GCs NGC 6752 and 47 Tuc, for which no variations in the *s*-process elements nor in the C+N+O ratios have been detected. Concerning NGC 6752, we could measure F abundance for only one RGB star, gathering upper limits for the remaining ones (this is due to a combination of temperature and low metallicity): as can be seen in Figure 4 (lower panel), we found that F and Na abundnaces are consistent with an anticorrelation. Finally, from a sample of 12 giants we obtained that in 47 Tuc the abundances of F and Na are anticorrelated, though with a large scatter (upper panel of Fig. 4).

## References


Carretta, E., et al. 2009, A&A, 505, 117
Cohen, J.G. 1978, ApJ, 223, 487
Decressin, T., et al. 2007, A&A, 464, 1029
D'Orazi, V., et al. 2011, A&A, 534, 29
D'Orazi, V., et al. 2013, ApJ, 763, 22
Johnson, C.I., Pilachowski, C.A. 2010, ApJ, 722, 1373
Lugaro, M., et al. 2004, ApJ, 615, 934
Lugaro, M., Karakas, A.I., Stancliffe, R.J., Rijs, C. 2012, ApJ, 747, 2
Marino, A. F., et al. 2011, A&A, 532, A8
Marino, A.F., et al. 2012, A&A, 541, 15
Roederer, I.U., Marino, A.F., Sneden, C. 2011, ApJ, 742, 37
Smith, V.V., et al. 2005, ApJ, 633, 392
Ventura, P., D'Antona, F., Mazzitelli, I., Gratton, R.G. 2001, ApJ, 550, L65
Yong, D., & Grundahl, F. 2008, ApJ, 672, L29