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A different view on light element anti-correlations in globular clusters: fluorine abundances in NGC 6656 (M22)

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Observed chemical (anti)correlations in the light elements C, N, O, Na, Mg, and Al among globular cluster (GC) stars are presently recognised as the signature of self-pollution from previous generations of stars. This defines the multiple population scenario (MPS). Since fluorine is involved in the complete CNO cycle, determining its abundance in GCs provides new and complementary clues regarding the nature of these previous generations. In fact, along with the Na-O and Mg-Al anti-correlations, the MPS also predicts an anti-correlation between F and Na and a positive correlation between F and O. Furthermore, theoretical models suggest that low-mass ($\lesssim 5 M_\odot$) asymptotic giant branch (AGB) stars are F producers (and are also responsible for C+N+O and *s*-process element variations). We present our results on near-infrared CRIRES spectroscopic observations of six giant stars in the metal-poor GC NGC 6656 (M22): we aim at inferring the F content and its (possible) variation in this GC, which exhibits a rather peculiar abundance pattern, with variations in both light (C, N, O, Na, Mg, Al) and heavy (Fe-peak and *s*-process) elements.

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1. Scientific framework

A large variety of studies have revealed the complex nature of elemental abundances in GCs. Abundance variations in the lighter elements (Li, C, N, O, Na, Mg and Al), recognised since the 1970's (e.g., [1]), demand that some material must have been processed through the entire *hot* 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 (intermediate-mass AGB stars by [12] or fast rotating massive stars by [2]). The global picture is further complicated by the presence of some peculiar clusters, the most famous case being ω Centauri (see e.g., [3]), where variations in Fe-peak and *s*-process elements have also been observed. The metal-poor GC M22 ([Fe/H]=$-$1.70) is one such GC. Analysing 35 giant stars, Marino and collaborators ([7]) found that this GC is comprised of two distinct stellar groups, characterised by an offset in metallicity and in *s*-process element content, namely Δ[Fe/H]=0.15$\pm$0.02 and Δ[*s*/Fe]=0.36$\pm$0.02 dex. These authors suggested that the *weak s*-process component, activated in massive stars (M$\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 to a recent study by [9] who focused on the heavy element content (from Y to Th) across the two stellar sub-groups and ruled out the massive star origin. We decided to approach the problem from a different perspective, deriving fluorine (F) abundances for a sample of six cool giant stars in M22. These stars were carefully selected from both sub-stellar groups as defined by [7]. The F content is a powerful tracer of the polluter mass range in M22 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,α)^{15}N(α,p)^{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$_\odot$ [5]. In AGB stars with masses larger than roughly 5 M$_\odot$, and depending on the metallicity, F is destroyed both via α 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 [11] and [13].

2. Sample, observations, and abundance analysis

Our sample includes six Red Giant Branch (RGB) stars (stellar parameters, Na, O, and La abundances were determined by [7]): three stars belong to the metal-poor (MP, s-process poor) population and three stars to the metal-rich (MR, s-process rich) one, as according to [7]. We employed the high-resolution near-IR spectrograph CRIRES@VLT, with a 0.4" slit (R=50,000), covering a wavelength range of 22950-23520 Å, which includes the unblended HF feature at 23358 Å, as well as several CO lines and the Na I line at 23379 Å. For each target, the spectrum of an early-type star was acquired, aimed to perform the telluric feature subtraction. The abundance analysis was

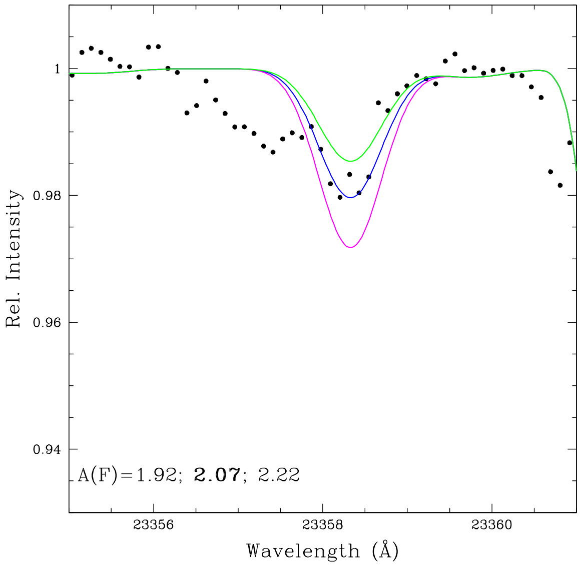

Figure 1: Spectral synthesis for the HF line for one of our sample stars.

carried out using the driver *synth* in MOOG ([10]) and the Kurucz's set of model atmospheres ([4], with no overshooting. An example of the spectral synthesis for the HF feature is given in Fig. 1. Internal errors affecting our F abundances are mainly due to the adopted set of stellar parameters and to the best-fit determination. The sensitivity of the F abundance to input stellar parameters was evaluated by separately changing effective temperature, surface gravity and microturbulence values; we obtained a typical uncertainty of 0.11 dex in [F/H]. Errors due to the best-fit determination (owed mainly to the S/N of the spectra) are instead ±0.07 dex. The total internal error is then calculated by summing in quadrature both uncertainties (0.13 dex).

3. Results and discussion

We detected star-to-star variations in F abundances, with values ranging from [F/H]=−2.82 dex to [F/H]=−2.23 (i.e., a factor of ∼4). Such a large spread is beyond that of the measurement uncertainties (see previous Section). Moreover, the variations are not random but are positively correlated with O and anti-correlated with Na, as shown in Fig. 2. The observed chemical pattern can be explained by the presence of H-burning (via the CNO cycle) at high temperatures which leads to the destruction of F in conjunction 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).

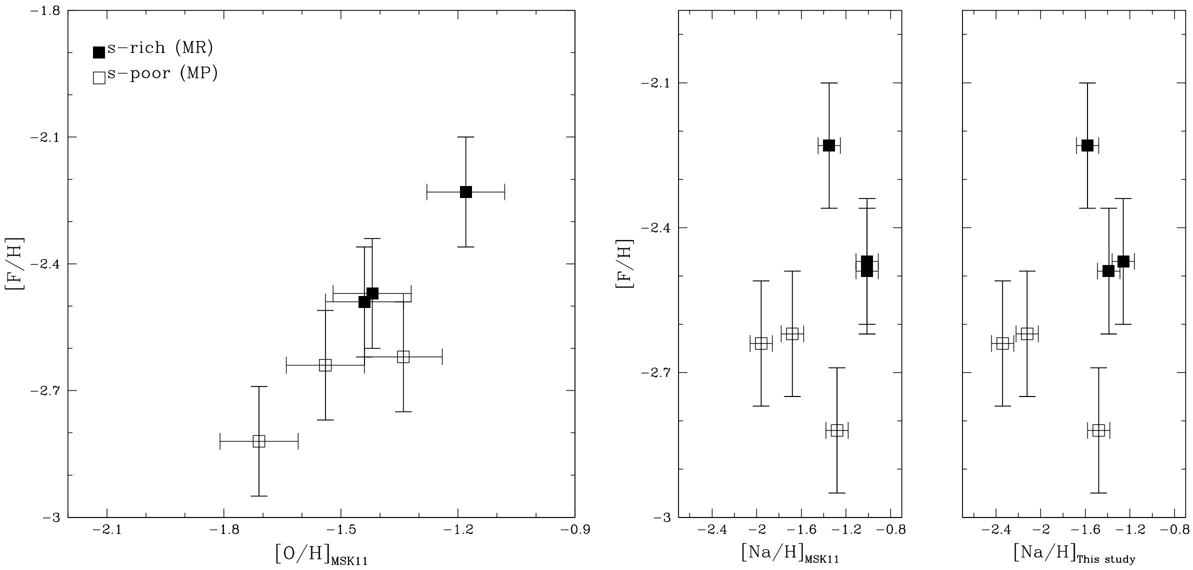

Figure 2: Run of F with O (left-hand panel) and Na (right-hand panel; we show both our Na values from infra-red spectroscopy and the optical ones derived by [7]). Metal-poor (s-poor) and metal-rich (s-rich) stars are labelled as empty and filled symbols, respectively.

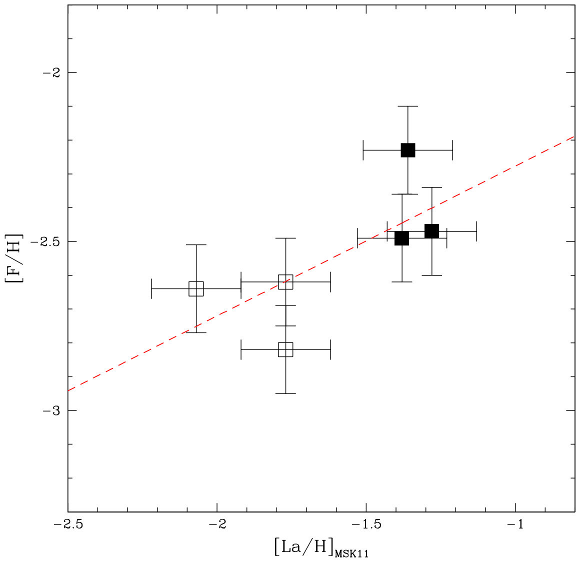

Figure 3: [F/H] as a function of [La/H] for our sample of six stars.

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.* This is shown in Fig. 3, where we plot our F abundances ([F/H]) as a function of [La/H] from [7]. There is a positive correlation between the two ratios, suggesting that the polluters responsible for the *s*-process production must also account for the F production.

Comparing our abundances with models by [6] we found that AGB stars with masses of $\approx 4-5$ $M_{\odot}$ can reproduce the observed pattern. Interestingly, [9] 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 between the different stellar groups in M22, (i.e. AGBs with masses around $4-5$ $M_{\odot}$), and imply a difference in age no larger than a few hundred Myr. Notably, Marino and colleagues chemically characterised the double sub-giant branch (SGB) of this cluster, and concluded that the age spread can be *at most* ~300 Myr.

References

[1] Cohen 1978, ApJ, 223, 487

[2] Decressin, T., Meynet, G., Charbonnel, C., Prantzos, N., Ekström, S. 2007, A&A, 464, 1029

[3] Johnson, C.I., Pilachowski, C.A. 2010, ApJ, 722, 1373

[4] Kurucz, R. 1993, CD-ROM 13, ATLAS9 Stellar Atmosphere Programs and 2 km/s Grid (Cambridge: SAO), 13

[5] Lugaro, M., Ugalde, C., Karakas, A.I., et al. 2004, ApJ, 615, 934

[6] Lugaro, M., Karakas, A.I., Stancliffe, R.J., Rijs, C. 2012, ApJ, 747, 2

[7] Marino, A. F., Sneden, C., Kraft, R.P., et al. 2011, A&A, 532, A8 (MSK11)

[8] Marino, A.F., Milone, A., Sneden, C., et al. 2012, A&A, 541, 15

[9] Roederer, I.U., Marino, A.F., Sneden, C. 2011, ApJ, 742, 37

[10] Sneden, C. 1973, ApJ, 184, 839

[11] Smith, V.V., Cunha, K., Ivans, I.I., et al. 2005, ApJ, 633, 392

[12] Ventura, P., D'Antona, F., Mazzitelli, I., Gratton, R.G. 2001, ApJ, 550, L65

[13] Yong, D., & Grundahl, F. 2008, ApJ, 672, L29

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