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Abundances of Sr and Zr in the atmospheres of red giants in Galactic globular cluster 47 Tuc

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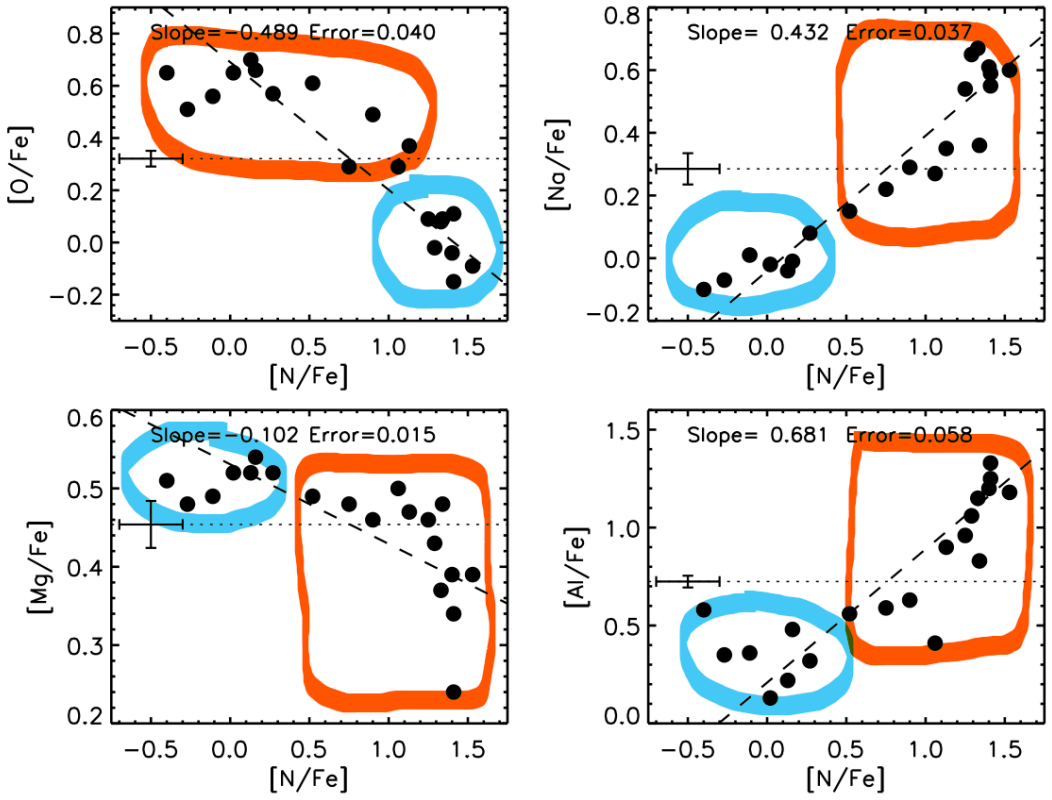
Multiple populations in globular clusters (GGCs)

1st population (1P) | 2nd population (2P)

- Spreads in light element abundances (Li, C, N, O, Na, Al, sometimes Mg), correlations/anticorrelations between abundance ratios.
- He abundance varies as well.
- The sum of C+N+O abundances is constant.
- [Fe/H] is constant in Type I clusters, however, not in Type 2 clusters.
- Abundance spreads occur in all old and massive GGCs.
- Abundance patterns imply proton capture reactions in H-burning at high temperatures.

e.g. reviews by Bastian & Lardo 2017, Gratton et al. 2019



NGC 6752 (Yong et al. 2008).

CNO cycle, T ~ 20 MK
Ne-Na chain, T ~ 40 MK
Mg-Al chain, T ~ 70 MK

Multiple populations in globular clusters (GGCs)

Generic scenario of formation of multiple populations:

1. 1P forms from pristine intra-cluster gas.
2. 1P stars enrich intra-cluster medium with processed material.
3. 2P forms from enriched gas.
4. Core collapse supernovae end star formation.

Multiple populations in globular clusters (GGCs)

Possible candidate 1P polluters:

- intermediate-mass (~3-8 $M_{\odot}$) AGB stars (D'Ercole et al. 2008; D'Antona et al. 2016);
- massive stars (>15 $M_{\odot}$, de Mink et al. 2009; Krause et al. 2013);
- very massive stars (~10^4 $M_{\odot}$, Denissenkov & Hartwick 2014; Gieles et al. 2018).

Currently, we can not discriminate between the possible pollution scenarios!

Multiple populations in globular clusters (GGCs), s-process elements

Can knowledge about s-process element abundances help?

- s-process elements are produced by AGB or massive stars, which are also candidate polluter stars in GGCs:
  - one would expect to see s-process abundance spreads/correlations as well.
- However: there seem to be no s-process element abundance spreads in the GGCs.
- But: there have been claims that relations between the abundances of s-process and light elements may exist in some clusters (e.g. Gratton et al. 2013; Yong et al. 2013).

Multiple populations in globular clusters (GGCs), s-process elements

Can knowledge about s-process element abundances help?

What could be a possible way forward?

- Many studies of abundances of s-process elements are mostly based on small stellar samples.
- Accurate s-process abundances of large stellar samples may help to detect weak correlations and allow to constrain the mass range of possible polluters.

Multiple populations in globular clusters (GGCs), s-process elements

Test bed: Galactic globular cluster 47 Tuc

- Well studied Type 1 GGC:
  - [Fe/H] is constant;
  - correlations/anticorrelations between light elements (e.g. Na-O anticorrelation).
- Tentative detection of Na – Ba correlation by Gratton et al. 2013.

GGC 47 Tuc

Image credit: ESO/M.-R. Cioni/VISTA Magellanic Cloud survey.

Abundances of s-process elements, Sr and Zr

We determined s-process element abundances in 47 Tuc:

- zirconium (237 RGB stars);
- strontium (31 RGB stars).

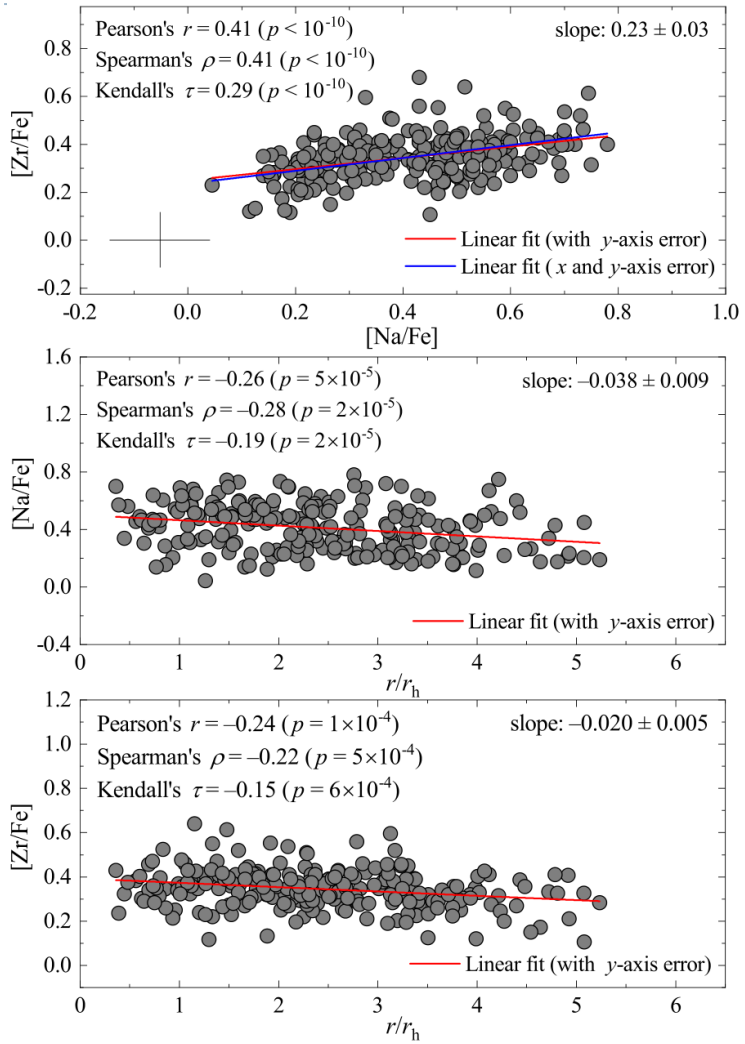
Observations and analysis:

- GIRAFFE and UVES spectra taken from ESO archive.
- $S/N \approx 80$.
- Three Zr I lines: $\lambda_0 = 612.7$ nm, 613.4 nm, 614.3 nm.
- One Sr I line: $\lambda_0 = 650.3$ nm.
- ATLAS9 code – stellar model atmospheres.
- IRAF package – line equivalent widths.
- WIDTH9 package – abundance determination.
- SynthE package – synthetic spectra calculation.

GGC 47 Tuc

Zr abundance in Galactic globular cluster 47 Tuc

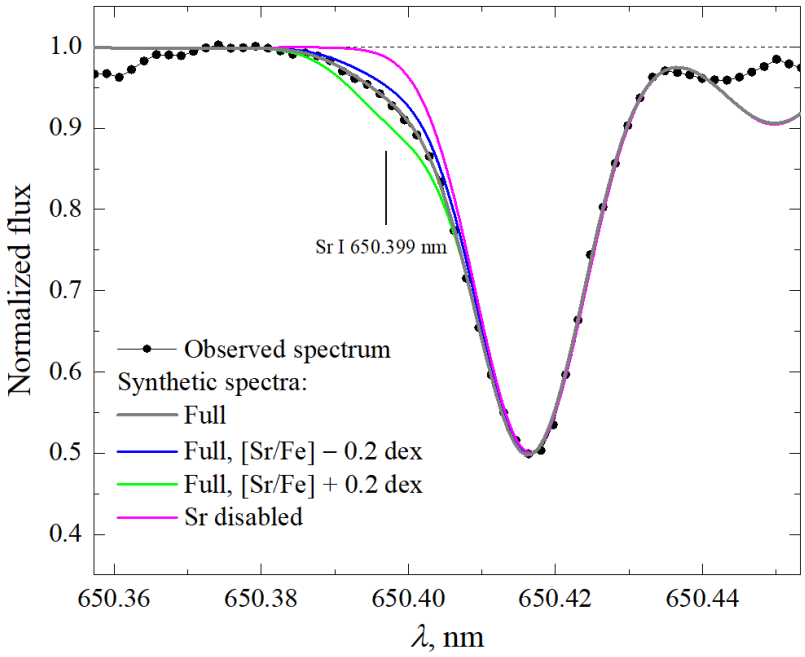
- Detection of weak correlation between Zr and Na abundances, only possible because of:
  - large number of stars;
  - high quality spectra;
  - accurate atomic data.
- 2P stars tend to concentrate towards the cluster centre.
- Our results suggest that Zr can by synthesised in either:
  - AGB stars (1.5 – 5 $M_{\odot}$); or
  - massive stars (12 – 25 $M_{\odot}$).

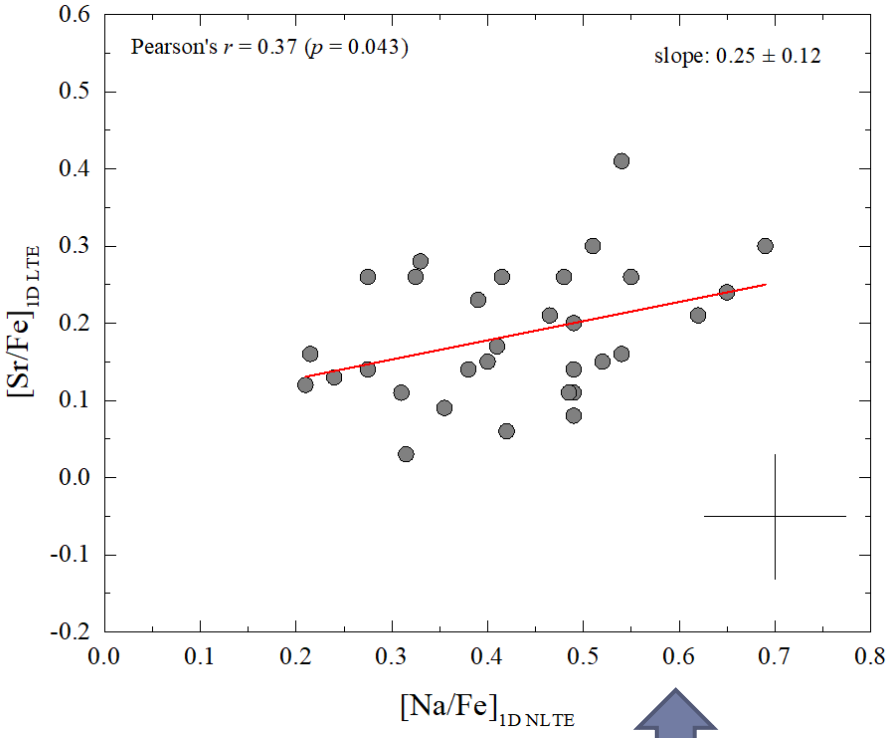


Kolomiecas et al. 2022 (2022A&A...660A..46K)

Sr abundance in Galactic globular cluster 47 Tuc

- A possible weak correlation between Sr and Na abundances?
- Without high quality spectra or accurate atomic data, detection of such weak correlations would be impossible.



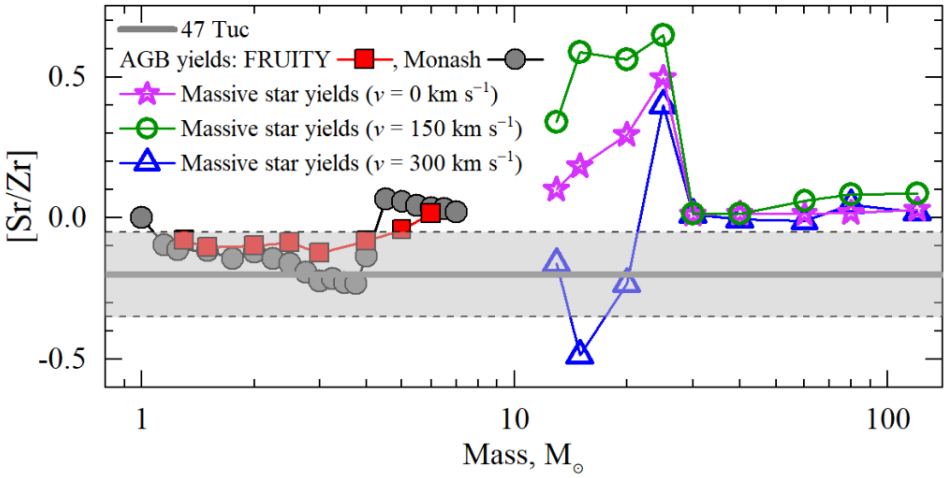


Kolomiecas et al. 2022 in preparation

Larger sample of stars and more accurate abundance measurements would be very helpful!

Sr and Zr abundance in Galactic globular cluster 47 Tuc

- Yield predictions of both AGB and massive stars models agree with our results.
- Possible solution: light to heavy s-process element abundance ratios may help to differentiate between the polluters (Ba, Pb peaks)?



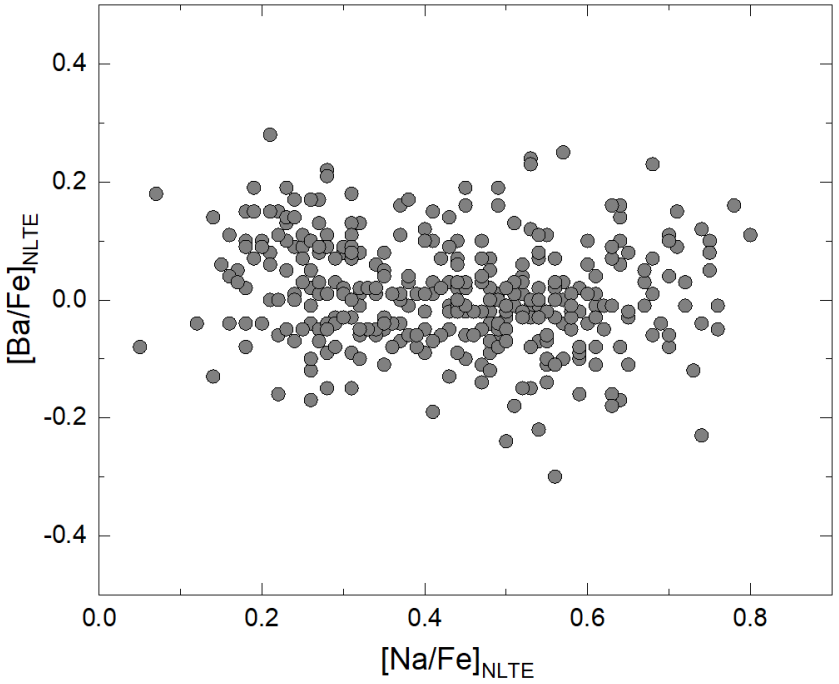
Kolomiecas et al. 2022 in preparation
FRUITY (Cristallo et al. 2016)
MONASH (Karakas et al. 2018)
Massive star yields (Limongi & Chieffi 2018)

However…

Ba abundance in Galactic globular cluster 47 Tuc

- We found no correlation between a heavy s-process element Ba and Na.
- The polluter stars synthesised light s-process elements, e.g. Sr or Zr, but not heavy s-process elements?

Additional constraints for the globular cluster evolution models?



GGC 47 Tuc (Dobrovolskas et al. 2021; 2021A&A...656A..67D)

Summary

- Difficult to explain abundance correlations using only a single kind of polluter:
  - more than one kind of polluter working together?
- Possible way forward - combination of light and heavy *s*-process elements abundances (e.g. ratios of La/Sr, Pb/Zr):
  - select those elements that are produced in different types of stars of different masses.
- Do such correlations exist for other s-process elements in other GGCs?
- Further improvements in the evolutionary models of the GGCs are needed!