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PoS(NIC XI)201

Neutron-capture element abundances in the globular clusters: 47 Tuc, NGC 6388, NGC 362 & ω Cen

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A spectroscopic study of neutron-capture element abundances has been carried out in the globular clusters, 47 Tuc, NGC 6388, NGC 362 and ω Cen, using high- and medium- resolution data. The stars analysed at high resolution, using data acquired with Ultraviolet Echelle Spectrograph (UVES) on the Very Large Telescope (VLT), were luminous giant stars located near the asymptotic giant branch for 47 Tuc, NGC 6388 and NGC 362. The medium resolution studies have analysed stars that reached below the level of the horizontal branch in at least one cluster, 47 Tuc. We are also exploring the possibility of undertaking large-scale studies using the Fabry–Pérot Interferometer (FPI) on the Robert Stobie Spectrograph on the Southern African Large Telescope. With the high resolution UVES data, two stars were analysed in NGC 6388, five stars in 47 Tuc and eleven stars in NGC 362. The NGC 6388 and 47 Tuc stars showed enhancements in the light (*ls*: Y, Sr, Zr) and heavy (*hs*: Ba, La, Nd) *s*-process elements of [*ls*/Fe]$= 0.56\pm0.09$ dex, [*hs*/Fe]$= 0.39\pm0.10$ dex , [*hs*/*ls*]$= -0.17\pm0.14$ dex and [*ls*/Fe]$= 0.53\pm0.02$ dex, [*hs*/Fe]$= 0.40\pm0.07$ dex, [*hs*/*ls*]$= -0.13\pm0.08$ dex, respectively. In NGC 362 the stars showed heavy *s*-process element abundances that were more enhanced than the light *s*-process ([*ls*/Fe]$= 0.32\pm 0.10$ dex, [*hs*/Fe]$= 0.49\pm0.13$ dex , [*hs*/*ls*]$= +0.17\pm0.16$ dex). A comparison between the *s*-process element abundances of each clusters show a general trend of increasing [*hs*/*ls*] with decreasing [Fe/H]. The small spread in the abundances of these *s*-process elements indicates a homogeneous distribution within each cluster, confirming that the stars analysed here are not producing *s*-process elements internally. Hence the *s*-process element abundance distribution represents a pre-existing chemical signature for each cluster. The previous (Worley et al. 2008) medium resolution study had been less conclusive.

The ω Cen medium resolution (R$\sim 2,000$) data from van Loon et al. (2007) has been used to derive T_{eff}, $\log g$, [Fe/H] and [Ba/Fe] for up to 500 stars. [Ba/Fe] enhancements up to +1.0 dex were determined, uncorrelated with the CN, CH indices. We also present our initial exploration of the use of the FPI technique to determine n-capture element abundances and other stellar parameters for a large sample of stars in a range of globular clusters. This will enable us to make assessments of *s*-process element abundances throughout the HR diagram.

11th Symposium on Nuclei in the Cosmos, NIC XI
July 19-23, 2010
Heidelberg, Germany

PoS(NIC XI)201

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[*] The authors wish to thank the New Zealand Marsden Fund, the University of Canterbury, the Observatoire de la Côte d'Azur and the LOC/SOC of NIC XI for their financial support which enabled C. C. Worley and P. L. Cottrell to attend this meeting.

1. Introduction

There are three key sites of nuetron-capture (n-capture) element nucleosynthesis: Supernova Type II produce *r*-process elements (i.e. Eu); thermally pulsing asymptotic giant branch stars (TP-AGB) which produce both light *s*-process (i.e. *ls* = Y, Sr, Zr) and heavy *s*-process (i.e. *hs* = Ba, La, Nd) elements; and massive He-core burning stars which produce *ls* elements. Determining the abundance distribution of these n-capture elements within globular cluster (GC) stars allows astronomers to dis-entangle the pollution events that occured during the evolution of the GC.

2. n-capture element abundances: 47 Tuc, NGC 6388 & NGC 362

The high resolution spectra of the luminous giants in the GCs 47 Tuc, NGC 6388 and NGC 362 were observed using UVES on the VLT for a programme investigating mass loss rates (McDonald& van Loon, 2007). A subsample of the stars were then analysed for their n-capture element abundances (Worley et al. 2010, Worley & Cottrell, 2010). The chemical abundance analysis of these stars is continuing and this paper refines the values obtained for the Ba and Eu abundances so as to include corrections for hyperfine splitting. We present these values with the previous n-capture element abundances derived for these stars.

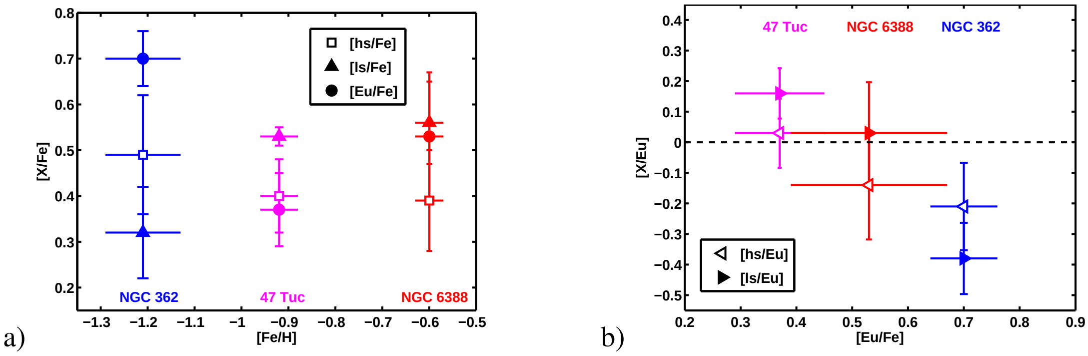

Figure 1: a) Mean [*hs*/Fe],[*ls*/Fe] and [Eu/Fe] vs [Fe/H] for NGC 362 (blue), 47 Tuc (magenta) and NGC 6388 (red) as indicated by the symbols in the legend. The errorbars are the standard deviation for each GC. b) As for a) but showing [*hs*/Eu] (and [*ls*/Eu] against [Eu/Fe]. Values above zero indicate *s*-process element residual enhancements.

The *hs* and *ls* elements show enhancement in all three clusters, as seen in Figure 1. Considered alone it could be assumed that source of the *ls* and *hs* element abundances are due to pollution by TP-AGB stars. However, the so designated *s*-process elements can also have contributions from the *r*-process. The *r*-process element, Eu, can be used as an indicator of the degree of contribution of n-capture elements due to pollution by Type II Supernova. Also shown in Figure 1a, Eu is clearly enhanced in all three clusters, particularly for NGC 362, which has the greatest enhancement in *hs* compared to *ls*. However, *ls* is more enhanced than *hs* for both 47 Tuc and NGC 6388, which are more metal rich and less enhanced in Eu.

Figure 1b compares the residual *ls* and *hs* element signatures as a ratio to the Eu abundance ([*ls*/Eu],[*hs*/Eu]). The comparably small spreads in Fe, Eu, *hs* and *ls* indicates homogeneity of these elements in all three clusters, which is evidence that the observed stars are not producing these elements internally but rather they are the chemical signature of pollution events in the respective clusters' history. In doing this we remove the *r*-process contribution to the n-capture elements and what remains is the signature of pollution by some other event (TP-AGBs, massive stars). Each cluster shows a distinctly different residual *s*-process signature.

These n-capture element abundance signatures suggest the following pollution scenarios for each of the clusters. For 47 Tuc, initially there was pollution by Type II Supernova as indicated by the Eu abundances. The residual *s*-process signature showed enhancements in both the *ls* and *hs* with $ls > hs > 0$. This indicates later pollution by low or intermediate mass TP-AGB. In NGC 6388 there was also some initial pollution by Type II Supernova, although less Eu enhancement than in 47 Tuc. The residual *s*-process signature showed enhancements in *ls* only, indicating later pollution by low mass TP-AGB or massive He-core burning star. For NGC 362 there was pollution by Type II Supernova but no residual *s*-process signature indicating no secondary n-capture element pollution.

3. Ba in ω Cen

An analysis is currently being undertaken using the data set of van Loon et al. (2007) (vL07). This is a spectral atlas of the post-main-sequence population in ω Cen using the 2dF instrument of the AAO, with spectral resolution of ∼2000. It includes the Ba II spectral line centered at 4555 Å. This line is being used to determine the [Ba/Fe] of the 1,500 stars in the vL07 data set.

Parameters from vL07 are being using in conjunction with parameters from Johnson et al. (2009) (J09) who used the Blanco 4 m telescope and Hydra multi-fiber spectrograph. They measured 66 stars from a wider data set of which there were 38 in common with vL07. In this analysis the van Loon spectra are being compared to synthetic spectra produced by MOOG (Sneden 1973).

The stellar parameters (T_{eff}, $\log g$, [Fe/H], with microturbulence of 2 kms^{-1}) and the [Ba/Fe] ratio were determined here using the wavelength interval 4510 Å to 4590 Å. These parameters compare favourably with those found by vL07 and J09, and provide a large dataset of [Ba/Fe] abundances rather than the Ba index of vL07. Using CN and CH indices defined by vL07 there is no correlation between high (low) barium abundances in the stars and high (low) carbon abundances in the stars. Figure 2a shows the spectra of five vL07 stars that have a range of barium abundances. All five stars were found to be best fitted by a stellar model atmosphere with parameters of $T_{eff} = 4500$, $\log g = 1.0$ and $[\mathrm{Fe/H}] = -1.5$. Synthetic spectra generated using this model with variations in Ba abundances are included in Figure 2a. The placement of these stars in the colour-magnitude diagram (CMD) is shown in Figure 2b. This work will be extended to the analysis of the full vL07 data set and to look at other spectral features to determine if there are overall enhancements of *s*-process element abundances in the stars that feature Ba enhancements.

The Fabry-Perot interferometer (FPI) can be used as a tunable narrow-bandwidth filter to sample a spectral line in each star in the field of view simultaneously (Rangwala et al. 2009). By imaging the field at a series of wavelengths that cover a spectral feature, hundreds and perhaps thousands of stellar spectra can be obtained without the overhead involved in other multi-object spectroscopy techniques. Using the FPI mode on the Robert Stobie Spectrograph (RSS) of the Southern African Large Telescope (SALT) it will be possible to observe the 6496.9 Å line of Ba II with a spectral resolution of about 8,000.

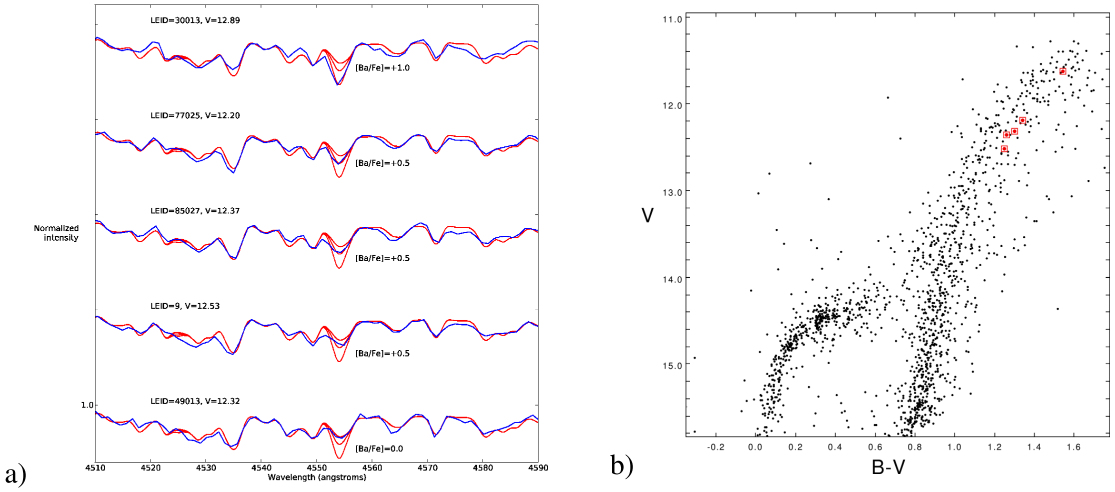

Figure 2: a) Examples of five spectra taken from the vL07 dataset. The blue line is the observed spectrum. The red lines are synthetic spectra with barium enhancements corresponding to +0.0, +0.5 and +1.0 dex. b) The CMD of the vL07 data set. Highlighted are the stars which are featured in Figure 2a. In order of increasing B magnitude they are 77025, 49013, 85027, 9 and 30013.

4. Conclusion

These two lines of analysis have so far focussed on n-capture element abundances. However, the abundances of key elements lighter than iron will provide further discrimination between the potential pollution scenarios that occurred in each of these four clusters. Further observations in both medium- and high- resolution will be made to further complete this picture.

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