Mem. S.A.It. Vol. 81, 1016

Memorie della

Neutron–capture element abundances of luminous giant stars in the Globular Clusters 47 Tuc, NGC 6388 and NGC 362

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Abstract. A spectroscopic study of neutron-capture element abundances has been carried out for giant stars in three globular clusters: 47 Tuc, NGC 6388 and NGC 362. These clusters range in metallicity from [Fe/H] = -0.60 ± 0.02 dex for NGC 6388, [Fe/H] = -0.88 ± 0.09 dex for 47 Tuc and [Fe/H] = -1.21 ± 0.09 dex for NGC 362, as derived in this study. The stars analysed here were all luminous giants located near the asymptotic giant branch for each cluster. The two stars analysed in NGC 6388 both showed enhancements in the light (l*s*: Sr, Y, Zr) and heavy (h*s*: La, Nd) *s*-process elements ([l*s*/Fe] = 0.58 ± 0.13 dex, [h*s*/Fe] = 0.39 ± 0.07 dex, [h*s*/l*s*] = -0.18 ± 0.06 dex). Six stars were analysed in 47 Tuc and similar enhancements were found ([l*s*/Fe] = 0.53 ± 0.02 dex, [h*s*/Fe] = 0.40 ± 0.06 dex, [h*s*/l*s*] = -0.13 ± 0.05 dex). The eleven stars analysed in NGC 362 also showed enhancements in the *s*-process elements. However the heavy *s*-process element abundances were more enhanced than the light *s*-process ([l*s*/Fe] = 0.32 ± 0.10 dex, [h*s*/Fe] = 0.46 ± 0.09 dex , [h*s*/l*s*] = +0.14 ± 0.03 dex). A comparison between the *s*-process element abundances of each cluster show a general trend of increasing [h*s*/l*s*] 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. Europium, the representative *r*-process element, is also enhanced, with a homogeneous distribution, in all three clusters.

Key words. Stars: abundances – Stars: atmospheres – Galaxy: globular clusters

1. Introduction

This research was motivated by recent work that found a scatter in *s*-process element abundances between giant stars in the globular cluster 47 Tuc (Wylie et al. 2006). The datasets available for the current research expanded the analysis to more luminous giants stars in 47 Tuc, as well as in NGC 6388 and NGC 362 (McDonald & van Loon 2007). The goal of this research was to investigate the nature of the *s*-process element abundance distribution in globular cluster giant stars.

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Table 1. Globular cluster characteristics and observation specifications including the sample number for each cluster from each observation dataset

Globular Cluster	[Fe/H] [a] (dex)	Age [b] (Gyr)	ANU 2.3 m échelle	VLT [d] UVES	Resolution	Wavelength (Å)
47 Tuc	−0.76	12.5	1	-	20,000	4500-6500
47 Tuc	−0.76	12.5	-	5	110,000	6100-9000
NGC 6388	−0.60	12.0 [c]	-	2	110,000	6100-9000
NGC 362	−1.16	9.9	-	13	110,000	6100-9000

a. Harris (1996) c. Catelan et al. (2006)
b. Carretta et al. (2000) d. McDonald & van Loon (2007)

There are two key sites of *s*-process production in late-type stars: asymptotic giant branch (AGB) stars (1 $M_\odot$<$M_\star$<8 $M_\odot$) and massive He-core burning stars (13 $M_\odot$>$M_\star$). For the former the onset of third dredge up (TDU), which mixes the products of hydrogen burning and *s*-process nucleosynthesis throughout the envelope of the star, does not occur for every star that ascends the AGB. Only AGB stars with an initial mass between 0.8 $M_\odot$ and 8 $M_\odot$ undergo a sufficient number of thermal pulses such that enhancements in light and heavy *s*-process element abundances are observed (Busso et al. 2001, Iliadis 2007). The heaviest of the *s*-process elements are thought to be produced in low mass (1 $M_\odot$≥$M_\star$≥3 $M_\odot$), low metallicity ([Fe/H] $\lesssim -1.5$ dex) thermally pulsing AGB (TP-AGB) stars (Gallino et al. 1998).

The second site of *s*-process element production, core He-burning in massive stars ($M_\star$ > 13$M_\odot$), produces a signature of *s*-process elements lighter than that of the signature in TP-AGB stars. There is only one neutron burst in these massive stars that allows the creation of *s*-process elements, hence elements beyond the light *s*-process peak are not produced (Arlandini et al. 1999; Iliadis 2007). Both the *s*-process elements and the products of H burning (C, N, O, Na, Mg, Al) are mixed through the atmosphere of these stars due to convection. Slow stellar winds are the mechanism by which the material from the atmosphere of these stars are injected into the interstellar medium (Prantzos & Charbonnel 2006).

Heavy element production also occurs in supernova via the *r*-process, where high neutron fluxes allow the rapid build up of seed nuclei to create the heaviest elements. Type II supernovæ are theorised to be the most likely sites for *r*-process production. The exact circumstances that result in a Type II supernova are still unclear but the progenitors are thought to be massive stars of $M > 8\ M_\odot$ whose explosive death results in the creation of O, Na, Al, the α and the *r*-process elements (Edvardsson et al. 1993; Sneden et al. 2008).

The origin of the chemical composition of globular clusters can be traced using the chemical signatures of explosive stellar death, combined with the chemical signatures of pollution by TP-AGBs and massive stars.

2. Observations

These results are based on observations using the échelle spectrograph on the Australian National University (ANU) 2.3 m telescope (R~20,000) and from the Ultra-Violet Échelle Spectrograph (UVES) on the Very Large Telescope (VLT). The observations from the VLT were part of a programme investigating mass-loss rates in luminous giants (McDonald & van Loon 2007). The characteristics of the globular clusters in which the stars were observed, the sample sizes and observation details are listed in Table 1.

3. Derivation of stellar parameters

The effective temperature ($T_{\rm eff}$), surface gravity ($\log g$), microturbulence (ξ) and metallicity ([Fe/H]) were derived from the measurement of the equivalent widths of Fe I and Fe II lines in each of the stellar spectra using the spectrum synthesis programme MOOG (Sneden 1973) and the MARCS stellar atmosphere models for cool stars (Gustafsson et al. 2008). The heavy element abundances were derived using the spectrum synthesis routines in MOOG.

The analysis was carried out initially on the standard K giant Arcturus. The derived parameters were found to be in reasonable agreement with previous studies (Fulbright et al. 2006; Worley et al. 2009). The analysis of the single star, Lee 2525 in 47 Tuc, which was observed on the ANU 2.3 m, also resulted in stellar parameters that were in good agreement with previously determined values (Brown & Wallerstein 1992; Worley et al. 2009).

The low effective temperatures (~ 3900 K) and low surface gravities (~ 0.0) of the UVES 47 Tuc stars exposed an issue with the derivation of the stellar parameters. It was observed that the abundances derived from the low excitation potential (χ) Fe I lines were enhanced significantly compared to the abundances derived from the high χ Fe I lines. This effect was seen in all the UVES 47 Tuc stars, as well as the NGC 362 and NGC 6388 stars (Worley et al. 2010; Worley & Cottrell 2010). The observation of Lee 2525 had significantly lower signal to noise and no such discrepancy was observed. However, the high resolution atlas of Arcturus (Hinkle & Wallace 2005) provided sufficient precision that a review of the measured equivalent widths showed the same effect, although much less significant due to the higher temperature and gravity of Arcturus. The effect was attributed to departures from local thermodynamic equilibrium (LTE) in the extended atmospheres of the luminous giants where the low χ lines are formed. Consequently attempting to derive abundances using assumptions of LTE, as are used in MOOG, led to artificially high abundances being derived from these lines. The analysis was repeated for the low gravity giants, but the parameters were based on the equivalent widths of the high χ Fe I and Fe II lines only.

4. Heavy element abundances

Abundances were derived for Fe, the light s- (l*s*) process elements (Sr, Y, Zr), the heavy *s*-process (h*s*) elements (Nd, La) and the *r*-process element, Eu. Figure 1 shows the trend

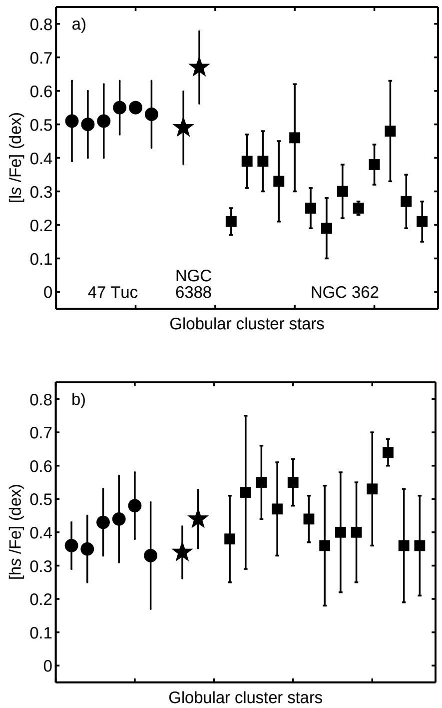

Fig. 1. Element abundances for each star in the 47 Tuc (circle), NGC 6388 (star) and NGC 362 (square) samples. a) [l*s*/Fe] for each star, and b) [h*s*/Fe] for each star.

of the l*s* and h*s* abundances for the individual stars in each globular cluster as indicated.

In Fig 1a, 47 Tuc shows the clearest uniformity in the enhancement of the l*s* elements between the stars. The two stars analysed in NGC 6388 are also enhanced in l*s* but are disparate in values. The NGC 362 sample also shows enhancement but at a lower level. They are in good agreement within the uncertainties.

All three samples show a similar degree of enhancement in the h*s* elements in Fig 1b. Again the two large samples show uniformity in the abundances within the uncertainties. For the two metal-rich clusters, 47 Tuc and NGC 6388, the l*s* are more enhanced than the h*s* elements in the stellar samples. However, the metal poor cluster, NGC 362, is slightly more enhanced in the h*s* elements than in the l*s* elements. This is expected as for metal-poor AGB

Table 2. Mean [Fe/H] and heavy element abundances for the three globular cluster samples

	NGC 6388		47 Tuc		NGC 362	
X	⟨[X/H]⟩	σ	⟨[X/H]⟩	σ	⟨[X/H]⟩	σ
Fe I	−0.65	0.05	−0.90	0.09	−1.22	0.09
Fe II	−0.55	0.01	−0.88	0.08	−1.20	0.09
	⟨[X/Fe]⟩	σ	⟨[X/Fe]⟩	σ	⟨[X/Fe]⟩	σ
Eu II	+0.57	0.09	+0.46	0.08	+0.78	0.05
X/Y	⟨[X/Y]⟩	σ	⟨[X/Y]⟩	σ	⟨[X/Y]⟩	σ
l*s*/Fe	+0.58	0.13	+0.53	0.02	+0.32	0.10
h*s*/Fe	+0.39	0.07	+0.40	0.06	+0.46	0.09
h*s*/l*s*	−0.18	0.06	−0.13	0.05	+0.14	0.03

[X/H] = log(X/H)$_\star$ - log(X/H)$_\odot$, l*s* = ⟨ Sr, Y, Zr ⟩, h*s* = ⟨ La, Nd ⟩

stars undergoing third dredge up there are less seed nuclei (Fe) available and so the l*s* peak is built up first but then the l*s* elements are used as the seeds with which to build up the h*s* peak.

Table 2 lists the derived mean metallicities and heavy element abundances for each of the globular cluster samples. There is a very small spread in [Fe/H] values for each cluster indicating the homogeneous distribution of that element as is expected. The mean [Fe/H] for NGC 6388 and NGC 362 derived from this study are in reasonable agreement with the values derived from other studies (NGC 6388: Carretta et al. 2007, Wallerstein et al. 2007; NGC 362: Shetrone & Keane 2000, Caldwell & Dickens 1988, Gratton 1987). The mean [Fe/H] for 47 Tuc was found to be more metal poor in this study than in previous studies (Wylie et al. 2006, Wallerstein et al. 1997).

The mean values for [Eu/Fe] in all three clusters show enhancements with respect to Fe. The uncertainties are also very small, of the same order as [Fe/H]. Eu is created by the *r*-process during supernovæ in which Fe is also created, and both are then distributed throughout the interstellar medium. The stars in the globular clusters then form from this polluted material.

For the two metal rich clusters with comparable mean [Fe/H] values, 47 Tuc and NGC 6388, both the mean [l*s*/Fe] and mean [h*s*/Fe] values are similar within each cluster. The derived [h*s*/Fe] is less enhanced than the [l*s*/Fe] in these clusters. For the metal poor cluster, NGC 362, the derived [h*s*/Fe] is more enhanced than the [l*s*/Fe], although the actual [h*s*/Fe] is similar in value to the those in both 47 Tuc and NGC 6388. All the values in each cluster have small uncertainties comparable to those of the mean [Eu/Fe] and mean [Fe/H] values for each cluster. The uniform distribution of these elements implies that the *s*-process element enhancements in all three clusters occurred in a pollution event prior to the formation of these stars.

5. Pollution by TP-AGB stars

Figure 2 compares theoretical predictions from Busso et al. (2001) with the [h*s*/l*s*] values for each star in each globular cluster, and the mean values for each cluster. Three theoretical predictions are shown for an AGB star of an initial mass of 3.0 M$_\odot$. The ^{13}C pocket parameter, which is a measure of the neutron efficiency for the star, is varied for each prediction with respect to the standard (ST) case (see Busso et al. 2001). The homogeneous distribution of the *s*-process elements in these clusters indicates that the observed stars are not creating the elements internally, hence the signature that is being matched to these predictions is that of the previous generation of AGB stars that polluted the star forming material.

Assuming only AGB stars are responsible for the observed enhancements in the *s*-

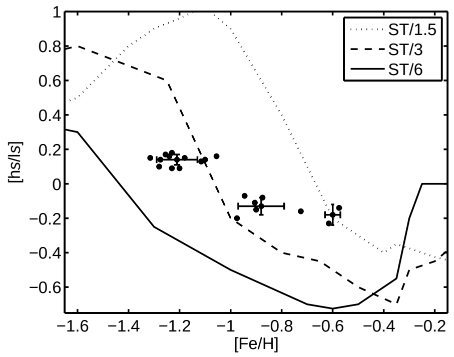

Fig. 2. [h*s*/l*s*] against [Fe/H] for the NGC 362, 47 Tuc and NGC 6388 stellar samples including the mean and uncertainty. Three theoretical predictions for AGB stars with initial mass of 3.0 $M_\odot$ are shown for comparison at ^{13}C pocket parameters of ST/1.5, ST/3 and ST/6.

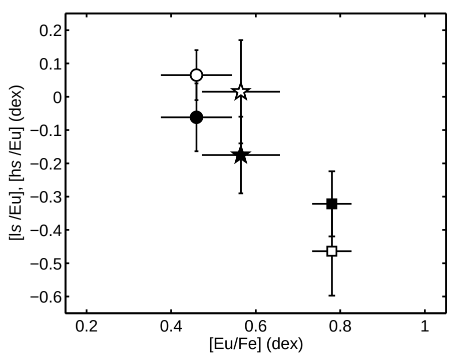

Fig. 3. [l*s*/Eu] (white) and [h*s*/Eu] (black) against [Eu/Fe] for 47 Tuc (circle), NGC 6388 (star) and NGC 362 (square). Both l*s* and h*s* are depleted with respect to Eu for NGC 362, while h*s* is depleted and l*s* is enhanced with respect to Eu for both 47 Tuc and NGC 6388.

process elements, the signatures in 47 Tuc and NGC 362 are best matched by the ST/3 prediction, while NGC 6388 is better matched by the ST/1.5 prediction. Overall there is a trend of increasing [h*s*/l*s*] with decreasing [Fe/H] which confirms the trend shown in the theoretical predictions that for fewer seed nuclei the h*s* elements are built up from the l*s* elements. This confirms that low-mass AGB stars are potential sources of the heavy element pollution in these clusters.

6. Pollution by supernovæ

The elements included in the definition of l*s* and h*s* can also be produced by the *r*-process and so when considering the sources of pollution the quantity of the *s*-process elements that have been produced by the *r*-process must be taken into account. Eu is predominantly formed in the *r* process (supernovæ) and can be used as the gauge for contributions from the *r* process. In all three globular clusters Eu was found to be significantly enhanced. However the effects of hyperfine splitting were not taken into account in the analysis and once they are in the follow up analyses of these stars, the derived abundances are likely to be reduced. With this caveat in mind the following discussion considers the relative abundances of *s*-process elements to that of Eu.

Figure 3 shows the ratio of the mean values of [l*s*/Fe] and [h*s*/Fe] to [Eu/Fe] for each cluster. The white symbols are the calculated [l*s*/Eu] ratios and the black symbols are the calculated [h*s*/Eu] ratios both against [Eu/Fe]. Considering first the NGC 362 values (squares), the negative values of [h*s*/Eu] and [l*s*/Eu] indicates that Eu is much more enhanced than the *s*-process elements and so the contribution from the *r* process is very great. It could be interpreted that all of the *s*-process elements in this cluster are actually created in supernovæ and not from TP-AGBs. Hence the chemical signature of the heavy elements in that cluster may be solely due to supenovæ.

For both 47 Tuc and NGC 6388 the [h*s*/Eu] is negative while the [l*s*/Eu] is slightly positive. This would suggest that the h*s* elements are more likely to have been produced as a consequence of the *r* process in supernovæ rather than within TP-AGB stars. However, the residual of the l*s* elements could be the signature of an alternate pollution source, such as massive core He-burning stars which produce this type of heavy element chemical signature, or intermediate mass TP-AGB stars.

7. Conclusion

The results of this analysis show a homogeneous distribution of the heavy elements in the three globular cluster stellar samples. The small uncertainties in the mean abundances of Fe, l*s*, h*s* and Eu indicates that these elements were created prior to the formation of the stars that are currently observed in these globular clusters. The source of these elements polluted the star forming material and it is the chemical signature of this source that the heavy element abundance distribution represents.

The potential sources of the pollution are TP-AGB stars, massive core-He burning stars and supernovæ. A comparison of the globular cluster [h*s*/l*s*] and [Fe/H] values to theoretical predictions (Busso et al. 2001) shows that low mass TP-AGB stars can replicate the enhancements in both l*s* and h*s* abundances at the respective [Fe/H] values. The trend of increasing [h*s*/l*s*] with decreasing [Fe/H] that was predicted was also confirmed.

However the significantly enhanced Eu in each cluster, particularly NGC 362, indicates a significant contribution of the heavy element abundances from the *r*-process via supernovæ. The negative values for the ratios [l*s*/Eu] and [h*s*/Eu] for NGC 362 may suggest all the heavy elements in that cluster were created from supernovæ, and that there has been very little, if any, contribution from the *s*-process. The [h*s*/Eu] was negative for both 47 Tuc and NGC 6388 also implying those elements were predominantly formed in supernova. However, the [l*s*/Eu] values were positive for both clusters and therefore could be interpreted as a residual signature of another pollution source. Both massive, core He-burning stars and intermediate mass TP-AGB stars could be responsible for a l*s* chemical signature.

Acknowledgements. The authors would like to acknowledge financial support from the NZ Marsden Fund and the Department of Physics and Astronomy at the University of Canterbury.

References

Arlandini, C., Käppeler, F., Wisshak, K., et al. 1999, ApJ, 525, 886
Brown, J. A. & Wallerstein, G. 1992, AJ, 104, 1818
Busso, M., Gallino, R., Lambert, D. L., Travaglio, C., & Smith, V. V. 2001, ApJ, 557, 802
Caldwell, S. P. & Dickens, R. J. 1988, MNRAS, 234, 87
Carretta, E., Bragaglia, A., Gratton, R. G., et al. 2007, A&A, 464, 967
Carretta, E., Gratton, R. G., Clementini, G., & Fusi Pecci, F. 2000, ApJ, 533, 215
Catelan, M., Stetson, P. B., Pritzl, B. J., et al. 2006, ApJ, 651, L133
Edvardsson, B., Andersen, J., Gustafsson, B., et al. 1993, A&A, 275, 101
Fulbright, J. P., McWilliam, A., & Rich, R. M. 2006, ApJ, 636, 821
Gallino, R., Arlandini, C., Busso, M., et al. 1998, ApJ, 497, 388
Gratton, R. G. 1987, A&A, 179, 181
Gustafsson, B., Edvardsson, B., Eriksson, K., et al. 2008, A&A, 486, 951
Harris, W. E. 1996, AJ, 112, 1487
Hinkle, K. & Wallace, L. 2005, ASPC, ed. T. G. Barnes, III & F. N. Bash, 336, 321
Iliadis, C. 2007, Nuclear Physics of Stars (Wiley-VCH)
McDonald, I. & van Loon, J. T. 2007, A&A, 476, 1261
Prantzos, N. & Charbonnel, C. 2006, A&A, 458, 135
Shetrone, M. D. & Keane, M. J. 2000, AJ, 119, 840
Sneden, C. 1973, PhD thesis, University of Texas at Austin
Sneden, C., Cowan, J. J., & Gallino, R. 2008, ARA&A, 46, 241
Wallerstein, G., Iben, I. J., Parker, P., et al. 1997, RvMP, 69, 995
Wallerstein, G., Kovtyukh, V. V., & Andrievsky, S. M. 2007, AJ, 133, 1373
Worley, C. C. & Cottrell, P. L. 2010, MNRAS, submitted
Worley, C. C., Cottrell, P. L., Freeman, K. C., & Wylie-de Boer, E. C. 2009, MNRAS, 400, 1039
Worley, C. C., Cottrell, P. L., McDonald, I. C., & Van Loon, J. T. 2010, MNRAS, 402, 2060
Wylie, E. C., Cottrell, P. L., Sneden, C. A., & Lattanzio, J. C. 2006, ApJ, 649, 248