Differential chemical abundance analysis of a 47 Tucanæ asymptotic giant branch star with respect to Arcturus

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ABSTRACT
This study resolves a discrepancy in the abundance of Zr in the 47 Tucanæ asymptotic giant branch (AGB) star Lee 2525. This star was observed using the echelle spectrograph on the 2.3-m telescope at Siding Spring Observatory. The analysis was undertaken by calibrating Lee 2525 with respect to the standard giant star Arcturus. This work emphasizes the importance of using a standard star with stellar parameters comparable to the star under analysis rather than a calibration with respect to the Sun as in Koch & McWilliam. Systematic errors in the analysis process are then minimized due to the similarity in atmospheric structure between the standard and programme stars. The abundances derived for Lee 2525 were found to be in general agreement with the Brown & Wallerstein values except for Zr. In this study Zr has a similar enhancement ([Zr/Fe] = +0.51 dex) to another light s-process element, Y ([Y/Fe] = +0.53 dex), which reflects current theory regarding the enrichment of s-process elements by nuclear processes within AGB stars. This is contrary to the results of Brown & Wallerstein where Zr was underabundant ([Zr/Fe] = −0.51 dex) and Y was overabundant ([Y/Fe] = +0.50 dex) with respect to Fe.

Key words: stars: abundances – stars: individual: Arcturus – globular clusters: individual: 47 Tuc.

1 INTRODUCTION
The globular cluster 47 Tucanæ (47 Tuc) has proven to be a rich source of study with regards to the structure and evolution of stars and stellar systems. Chemical abundance studies have indicated the presence of light-element abundance anomalies between the stars at all stages of stellar evolution. Recent advances in telescope and instrument sensitivity are providing observation of larger samples of stars within clusters at higher resolution enabling a more detailed investigation of the exact nature of the abundance anomalies. A significant advance has been the greater number of abundances derived for the elements heavier than iron. In particular, the light and heavy s-process elements which provide signatures of key stages in stellar evolution.

A well-studied phenomenon in 47 Tuc is the CN-weak, CN-strong bimodality which is seen at all stages of stellar evolution in 47 Tuc (Cannon et al. 1998). Internal mixing cannot solely explain this anomaly, and some primordial or pollution mechanism is required to account for it being observed on the main sequence and giant branches (Cannon et al. 1998; Briley et al. 2004). Also observed in 47 Tuc is a correlation of Na to CN strength (Cottrell & Da Costa 1981). However, there has been no observational evidence of a correlation of either Mg or Al with CN or Na as can be observed in more metal poor clusters though Na has been observed to anticorrelate with O in 47 Tuc (Carretta et al. 2004). As these anomalies have been observed in giants and dwarfs, it is theorized they are most likely due to primordial scenarios rather than solely due to internal mixing in globular cluster stars. For a complete summary of these anomalies in 47 Tuc and other globular clusters refer to the recent review paper, Gratton, Sneden & Carretta (2004).

Recent stellar studies have investigated the abundances of elements heavier than iron and have shown an enhancement in s-process elements in 47 Tuc. Brown & Wallerstein (1992) analysed four giant stars in 47 Tuc for their light and heavy-element abundances, determining for the s-process elements an average enhancement in Y ([Y/Fe] = +0.48 ± 0.11 dex) but a depletion in Zr ([Zr/Fe] = −0.22 ± 0.05 dex). Alves-Brito et al. (2005) analysed a sample of five 47 Tuc giant stars and found Zr to also be depleted ([Zr/Fe] = −0.17 ± 0.12 dex) though did not obtain abundances for Y. However, Wylie et al. (2006) found an overall enhancement in s-process elements, including Zr ([Zr/Fe] = +0.65 ± 0.16 dex) and Y ([Y/Fe] = +0.64 ± 0.20 dex), in seven giant branch stars in 47 Tuc. In a study of three turn-off and eight subgiants in 47 Tuc, James et al. (2004) found enhancements in Sr and Ba, but Y was depleted for the subgiants ([Y/Fe] = −0.11 ± 0.10 dex) and

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slightly enhanced for the turn-off stars ([Y/Fe] = +0.06 ± 0.010 dex). While the results are consistent within each study, the variation between studies is contradictory to the expected homogeneous distribution of heavy elements in globular cluster stars.

The primary source for s-process element production is nuclear reactions that occur during the asymptotic giant branch (AGB) stage of stellar evolution (Busso et al. 2001). AGB stars of mass greater than 1.5 M⊙ undergo third dredge up (TDU) during which seed nuclei (Fe) are exposed to neutron fluxes. This builds up heavier and heavier nuclei resulting in the observed enhancements in s-process element abundances in thermally pulsing AGB stars. Due to small reaction cross-sections, elements are first built up in the light s-process peak (ls = {Sr, Y, Zr}) then in the heavy s-process peak (hs = {Ba, La, Nd}) (Busso et al. 2001). The ratios of [ls/Fe], [hs/ls] and [hs/Fe] are used as indicators of the degree of s-process enhancement and neutron flux. A depletion in Zr coinciding with an enrichment in Y, as determined in Brown & Wallerstein (1992), is not a likely result in a scenario of enrichment due to AGB stars. There are other potential sources for the s-process elements. The AGB source is referred to as the ‘main’ s-process. The ‘weak’ s-process occurs during He-core burning in massive stars and can enhance light s-process elements such as Sr and Y (Arlandini et al. 1999). The r-process, rapid neutron exposures typically in supernovae, can also contribute to the abundances of s-process elements. The contributions from these different sources can be disentangled by comparing heavy elements whose abundances are mainly s-process (such as Y and Zr) to those who are mainly r-process, such as Eu, and to those who have contributions in different ratios from these sources (Travaglio et al. 2004).

While there are these different potential sources for each of the s-process elements, including contributions from the r-process, for the most part it is argued that the abundance of a heavy element is homogeneous within a cluster. The differing results for Zr (and Y) need to be resolved in order to pursue the connections between heavy- and light-element abundances. These connections provide clues as to the nature of primordial and mixing scenarios that could lead to chemical-abundance distributions that are seen in globular cluster stars.

2 OBSERVATIONS AND PREVIOUS WORK

In 2007 November, the 47 Tuc giant branch star Lee 2525 was observed on the 2.3-m telescope at the Siding Spring Observatory by K. C. Freeman and E. C. Wylie-de Boer. It was observed using the échelle spectrograph, obtaining wavelengths from 4500 to 6500 Å. The spectrum had a resolution of R ~ 20000 with a signal-to-noise ratio (S/N) per resolution element of ~35. The spectrum was reduced in IRAF and the normalized spectrum underwent the same equivalent width analysis as the calibration star Arcturus (see Section 3.1). Lee 2525 had been observed previously in Brown & Wallerstein (1992), along with four other 47 Tuc giant branch stars. In Wylie et al. (2006), these stars were compared with seven more giant stars in 47 Tuc.

Fig. 1 shows the placement of the stars in both studies on the colour–magnitude diagram of 47 Tuc. Lee 2525 is also indicated on the diagram and all of the stars fall on the red giant branch (RGB) or AGB as indicated by the fiducial lines (Hesser et al. 1987).

Lee 2525 has been studied in a number of papers. As a bright giant, it was initially observed under this designation in Lee (1977). Subsequently, it was studied in Norris & Freeman (1979) where it was determined to be a CN-weak AGB star. It has also been part of a mass-loss rate study for giant stars in 47 Tuc where it was determined to have no infrared excess (Ramdani & Jorissen 2001). Lee 2525 was analysed in Brown & Wallerstein (1992) as the CN-weak star in a CN-weak–CN strong pair. Its counterpart was Lee 1513.

Worley, Cottrell & Wylie de Boer (2008) observed Lee 2525 as part of a study into the feasibility of medium-resolution surveys of globular cluster stars to determine their s-process elemental abundances using the Robert Stobie Spectrograph (RSS) on the Southern African Large Telescope. For Lee 2525, in particular, there was an indication of an enhancement in Zr, although this lies within the uncertainties of the model abundance. The resolution of the spectra in this study was determined to be too low (R ~ 5000) to determine absolute s-process element abundances, although upper limits of 0.5 dex may be possible in future higher resolution observations with RSS.

The average heavy-elemental abundances for the stellar samples reported in Brown & Wallerstein (1992) and Wylie et al. (2006) are listed in Table 1.

The sample in Wylie et al. (2006) show a general enhancement of the s-process elemental abundances across the sample, with the average enhancement for Zr being [Zr/Fe] = +0.65 dex. A similar abundance enhancement was found for several s-process elements in Brown & Wallerstein (1992), but Zr was found to be depleted with an average abundance of [Zr/Fe] = −0.22 dex. Y was enhanced in both studies as were La and Eu.

Table 1. Comparison of the mean heavy-elemental abundances from samples of AGB and RGB stars analysed in Brown & Wallerstein (1992) (BW92) and Wylie et al. (2006) (W06).

| No. of stars | BW92 | W06 |
|-------------|------|-----|
| ([Fe/H])    | −0.81| −0.63|
| ([Y/Fe])    | +0.48| +0.64|
| ([Zr/Fe])   | −0.22| +0.65|
| ([La/Fe])   | +0.18| +0.31|
| ([Eu/Fe])   | +0.25| +0.15|

Figure 1. Colour–magnitude diagram of 47 Tuc showing the placement of the giant stars observed in Brown & Wallerstein (1992) and Wylie et al. (2006). The fiducial lines indicating the RGB and AGB branches of 47 Tuc are from Hesser et al. (1987).
The goal of this analysis of Lee 2525 is to link these two studies in an effort to consolidate the reported abundances of heavy elements in 47 Tuc giant branch stars.

3 SPECTRAL DERIVATION OF STELLAR PARAMETERS

For sufficiently high-resolution observations, the determination of the spectral parameters of a star can be carried out using a curve of growth analysis. A curve of growth analysis allows the simultaneous determination of the effective temperature ($T_{\text{eff}}$), surface gravity ($\log g$), metallicity ([Fe/H]) and microturbulence ($\xi$) of a star. For both Arcturus and Lee 2525, the normalized spectrum was measured for the equivalent widths of selected Fe I and Fe II lines. Using MOOG (Sneden 1973), these equivalent widths were used to determine the best-fitting stellar model by balancing the derived abundances $[\log(\epsilon)]$ with excitation potential ($\chi$) to find $T_{\text{eff}}$, with reduced equivalent width $[\log(\frac{\lambda}{\xi})]$ to find $\xi$ and with wavelength $\lambda$. The derived $\log(\epsilon)$ values for Fe I and Fe II were required to balance in order to find the correct $\log g$.

3.1 Arcturus calibration

Deriving abundances relative to the Sun may not be appropriate for giant stars as so many features present in giant stars are not present in the solar spectrum. Deriving the abundances relative to Arcturus, a giant star of metallicity similar to 47 Tuc, is a more appropriate choice as the similarities in atmospheric structure will cancel out any systematic errors (Koch & McWilliam 2008).

The equivalent widths of spectral lines in Arcturus were measured in order to calibrate the analysis process used in this study. The equivalent widths of all possible Fe I and Fe II lines were measured from the high-resolution atlas of Arcturus (Hinkle & Wallace 2005).

Lines with equivalent width greater than 180 mÅ were rejected as they are saturated and also less accurate due to the assumption of a Gaussian profile fit in the determination of equivalent width. The stellar parameters for Arcturus were derived using the MOOG curve of growth analysis ABFIND function. The latest available published $\log g f$ values from VALD were used for this Fe line list (Kupka et al. 2000).

MOOG derives abundances based on local thermodynamic equilibrium calculations and assumes the model has a plane-parallel geometry for the structure of the stellar atmosphere. Spherical geometry stellar models are more representative of the atmospheric structure of giant stars and can be used in MOOG with the above codicil in mind. The stellar parameters for Arcturus were derived using a MARCS spherical geometry model (Gustafsson et al. 2008) and an Kurucz/Atlas9 plane-parallel model (Kurucz 1979, 1995).

Table 2 compares the Arcturus stellar parameters derived here using plane-parallel and spherical geometry with the values obtained in Fulbright, McWilliam & Rich (2006).

The best-fitting stellar parameters for both the spherical and plane-parallel geometry models are in close agreement with each other and with that derived in Fulbright et al. (2006).

The determination of the remaining element abundances proceeded by two methods. For the light elements (O through Zn), which have sufficiently isolated lines, equivalent widths were measured and used with the best-fitting model and ABFIND in MOOG to derive abundances. For the weaker lines and those of the heavy elements (Y to Eu) in more crowded spectral regions, abundances were derived by comparing synthesized and observed spectra. The spectrum synthesis line lists in key $s$-process regions were calibrated to the observed Arcturus spectrum using SYNTH in MOOG. The $\log g f$ values for the key $s$-process lines were taken from the latest published laboratory values: Lawler, Bonvallet & Sneden (2001); Biemont et al. (1981); Den Hartog et al. (2003); Hannaford et al. (1982).

An abundance analysis of the light elements in Arcturus was carried out in Fulbright, McWilliam & Rich (2007), and the values derived here are compared with that study in Table 2. There is very little change between the light-element abundances derived using the spherical model compared with the plane-parallel model. Comparing the spherical model to the Fulbright et al. (2007) values, there is reasonable agreement ($\pm 0.1$ dex) between the two sets of abundances. Given the close agreement between the derived abundances of the spherical and plane-parallel models, and the good agreement

| Geometry | Plane-parallel | Spherical | Plane-parallel |
|----------|----------------|-----------|----------------|
| $T_{\text{eff}}$ | 4290K | 4300K | 4270K |
| $\log g$ | 1.55 | 1.6 | 1.7 |
| [Fe/H] | $-0.5$ dex | $-0.6$ dex | $-0.60$ dex |
| $\xi$ | 1.67 km s$^{-1}$ | 1.50 km s$^{-1}$ | 1.50 km s$^{-1}$ |

| X | [Fe/Fe] | $\sigma$ | $N$ | [Fe/Fe] | $\sigma$ | [Fe/Fe] | $\sigma$ | $N$ |
|---|--------|-------|---|--------|-------|--------|-------|---|
| O | 0.48 | – | 1 | 0.57 | 0.02 | 0.56 | 0.03 | 2 |
| Na | 0.09 | – | 1 | 0.15 | 0.04 | 0.14 | 0.04 | 2 |
| Mg | 0.39 | 0.06 | 5 | 0.34 | 0.15 | 0.32 | 0.15 | 8 |
| Al | 0.38 | 0.03 | 3 | 0.25 | 0.07 | 0.24 | 0.07 | 4 |
| Si | 0.35 | 0.05 | 15 | 0.24 | 0.14 | 0.21 | 0.14 | 10 |
| Ca | 0.21 | 0.01 | 2 | 0.19 | 0.06 | 0.19 | 0.06 | 12 |
| Ti | 0.26 | 0.04 | 24 | 0.34 | 0.15 | 0.34 | 0.11 | 29 |

| [X/H] | $\sigma$ | [X/H] | $\sigma$ | $N$ |
|---|---|---|---|---|
| Fe | – | – | – | $-0.59$ | 0.12 | $-0.62$ | 0.11 | 40 |
with Fulbright et al. (2007), the spherical model was selected as the stellar model for Arcturus in this analysis.

The derived Arcturus abundances for the light and heavy species, and uncertainties associated with changes in $T_{\text{eff}}$, log $g$ and $\xi$, are listed in full in Table 3.

The uncertainties associated with changes in $T_{\text{eff}}$, log $g$ and $\xi$ are sufficiently greater than the abundance differences between the spherical and plane-parallel models that the stellar parameter selection can be considered to introduce a more significant error than the geometry upon which the model is based. The parameter uncertainties can account for differences in the light-element abundances between this study and Fulbright et al. (2007), except for the Al I which is due to different line selection between the studies. With regard to the heavy elements, the neutral species are most affected by changes in $T_{\text{eff}}$, while the ionized species are more affected by changes in log $g$. The Ba II abundance varies greatly with all three parameters which can be explained due to it being derived from two strong lines that are sensitive to variations with $\xi$ and $T_{\text{eff}}$, and, as an ionized species, a large variation with log $g$.

### Table 3. Derived element abundances for Arcturus with uncertainties in [Fe/H] and [X/Fe] associated with changes in $T_{\text{eff}}$, log $g$ and $\xi$ using spherical geometry stellar models.

| Species | X | N | [X/H] | $\sigma$ | $\Delta T_{\text{eff}}$ | $\Delta \text{log } g$ | $\Delta \xi$ |
|---------|---|---|--------|---------|-----------------|-----------------|--------|
| Fe I    | 29 | −0.61 | 0.12 | 0.06 | 0.13 | −0.29 | 0.07 |
| Fe II   | 11 | −0.56 | 0.05 | −0.20 | 0.21 | −0.13 | 0.01 |
| O I     | 2  | 0.57  | 0.02 | −0.01 | 0.20 | −0.02 | 0.07 |
| Na I    | 2  | 0.15  | 0.04 | 0.09 | 0.01 | −0.10 | 0.02 |
| Mg I    | 8  | 0.34  | 0.15 | 0.01 | 0.03 | −0.04 | 0.02 |
| Al I    | 4  | 0.25  | 0.07 | 0.07 | 0.01 | −0.07 | 0.01 |
| Si I    | 10 | 0.24  | 0.14 | −0.06 | 0.13 | −0.06 | 0.10 |
| Ca I    | 12 | 0.19  | 0.06 | 0.12 | −0.03 | −0.26 | 0.02 |
| Sc II   | 2  | 0.24  | 0.01 | −0.02 | 0.22 | −0.18 | 0.04 |
| Ti I    | 24 | 0.35  | 0.12 | 0.17 | 0.04 | −0.15 | 0.02 |
| Ti II   | 5  | 0.33  | 0.10 | −0.04 | 0.22 | −0.15 | 0.02 |
| Zn I    | 2  | −0.04 | 0.09 | −0.07 | 0.14 | −0.26 | 0.02 |
| Y I     | 3  | 0.07  | 0.24 | 0.21 | 0.03 | −0.07 | 0.07 |
| Y II    | 5  | 0.12  | 0.11 | 0.02 | 0.22 | −0.04 | 0.02 |
| Zr I    | 7  | 0.01  | 0.07 | 0.13 | 0.07 | 0.00  | 0.04 |
| Zr II   | 3  | 0.12  | 0.10 | −0.01 | 0.24 | −0.01 | 0.06 |
| Ba II   | 2  | −0.19 | 0.08 | 0.27 | 0.26 | −0.16 | 0.04 |
| La II   | 6  | 0.04  | 0.08 | 0.04 | 0.19 | −0.02 | 0.02 |
| Nd II   | 4  | 0.10  | 0.07 | 0.03 | 0.17 | −0.09 | 0.04 |
| Eu II   | 2  | 0.36  | 0.04 | −0.02 | 0.23 | −0.01 | 0.02 |

3.2 Lee 2525 stellar model

As part of an ongoing programme of research into the nature of s-process elemental abundances in globular cluster giant stars, the Zr discrepancy between the studies of Brown & Wallerstein (1992) and Wylie et al. (2006) needed to be addressed. This motivated the high-resolution observation and analysis of Lee 2525. The stellar parameters derived for Lee 2525 in Brown & Wallerstein (1992) were $T_{\text{eff}} = 4225$ K, log $g = 1.3$, [Fe/H] = −0.82 dex and $\xi = 2.0$ km s$^{-1}$.

Figure 2. Fe I line at 6127.906 Å in the Lee 2525 stellar spectrum. The dotted line is the observed spectrum. The black square line segments are the continuum regions used to normalize the spectrum locally about the line. The solid line is the line profile used to determine the equivalent width for this line where the continuum has been placed so as to account for the low S/N of the spectrum. The dashed line is the line profile where the S/N has not been taken into account.

Equivalent widths from the Lee 2525 spectrum were measured for each of the Fe I and Fe II lines that were used in the analysis of Arcturus. Due to the much lower resolution and S/N of this spectrum compared with the Arcturus atlas, careful selection of the best-fitting lines was made with which to determine the stellar parameters for Lee 2525. This reduced the list from 40 to 22 lines in total. Local normalization about each Fe line in the stellar spectra was necessary to ensure the correct location of the continuum. Fulbright et al. (2006) defined continuum regions that were clear of molecular bands about each of the Fe lines in Arcturus. These regions were used in the local normalization about each of the Fe lines measured in Lee 2525. An example of the normalization and measurement of equivalent width process for the Fe I line at 6127.906 Å in the Lee 2525 stellar spectrum is shown in Fig. 2.

The normalization was made by finding the mean intensity and wavelength of each of the Fe lines’ two continuum regions. The mean was calculated iteratively, discarding points that lay outside $2\sigma$ of the mean and then recalculating until less than 5 per cent of the remaining points lay outside the $2\sigma$ limit. A linear relation between the two mean points was then divided out from the spectrum resulting in the required normalization. If only one continuum region was available, the mean intensity of that region was divided out of the spectrum to effect the normalization. Given the low S/N of the spectrum, this continuum placement was considered to be too high (see dashed line profile in Fig. 2). A further downward vertical shift of 0.03 (as the noise per pixel was equivalent to ±3 per cent of the signal) was applied in order to take account of the high degree of noise in the spectrum (solid line profile in Fig. 2).

Fig. 2 clearly shows that a much larger equivalent width would be measured if the noise was not taken into account. For the Fe I line at 6127.906 Å, the equivalent width for which the S/N was accounted for in the continuum placement was measured to be 98.8 mÅ. If the S/N was not accounted for in the continuum placement, the equivalent width was measured to be 119.4 mÅ. Similar measurements were carried out for each of the Fe lines. This shows that the
Table 4. Stellar model parameters and resulting values of [Fe/H] and [Fe II/H] for Arcturus and range of models for Lee 2525. Values at two different ξ values are also compared. The first model for Lee 2525 uses the Brown & Wallerstein (1992) parameters. The final model for Lee 2525 is the best-fitting determined in this study.

| Star          | Arcturus       | Lee 2525     |       |
|---------------|----------------|--------------|-------|
|               | T eff (K)      | 4300         | 4225  | 4050  | 4225  |
|               | log g          | 1.6          | 1.3   | 0.8   | 1.2   |
| [Fe/H] (dex)  | −0.60          | −0.82        | −0.65 | −0.70 |
| ξ (km s⁻¹)    | 1.5            | 1.5          | 1.5   | 1.8   |
| [Fe I/H]      | −0.64 ± 0.17   | −0.72 ± 0.16 |       |       |
| [Fe II/H]     | −0.56 ± 0.05   | −0.60 ± 0.02 |       |       |
| ξ (km s⁻¹)    | 2.0            | 2.0          | 2.0   | 2.0   |
| [Fe I/H]      | −0.90 ± 0.13   | −0.98 ± 0.20 |       |       |
| [Fe II/H]     | −0.69 ± 0.10   | −0.72 ± 0.06 |       |       |

Figure 3. Comparison of [Fe/H] versus χ derived from Fe I (×) and Fe II (●) lines. (a) [Fe I/Fe II]/H] derived for Arcturus using the measured Arcturus equivalent widths. (b) As for (a) but for the Brown & Wallerstein (1992) model and the Lee 2525 measured equivalent widths. (c) As for (b), but for a high-metallicity model and the Lee 2525 equivalent widths. (d) As for (b), but for the best-fitting stellar model determined for Lee 2525 in this study and the Lee 2525 equivalent widths. The figures in the left-hand column show the derived [Fe I/Fe II]/H] values for the specified stellar atmosphere models at ξ = 2.0 km s⁻¹. The figures in the right-hand column are the same but for ξ = 1.5 km s⁻¹ except for the best-fitting model in (d).

In this study, the Brown & Wallerstein (1992) values of T eff and log g (4225 K and 1.3 respectively) for Lee 2525 were used as the starting point for determining the spectroscopic stellar model. An exploration in stellar parameter space was carried out in order to determine the best-fitting model. Table 4 lists the stellar parameters and resulting [Fe I, Fe II/H] values for each model permutation. Fig. 3 compares [Fe/H] against χ for Arcturus, the Brown & Wallerstein (1992) model for Lee 2525 and two prospective models for Lee 2525 derived in this study.

[Fe I, Fe II/H] refers to the Fe abundance derived from Fe I and Fe II lines, respectively.
In Fig. 3(a), the small spread in values is obvious for Arcturus due to the much greater resolution and high S/N of that spectrum. The Arcturus models at $\xi = 2.0$ and 1.5 km s$^{-1}$ are compared showing that Arcturus clearly falls in the $\xi = 1.5$ km s$^{-1}$ regime, illustrated by the smaller spread in [Fe/H] values (see Table 4).

The stellar model matching the Brown & Wallerstein (1992) parameters for Lee 2525 (Fig. 3b) show good agreement between the derived Fe I and Fe II abundances in the $\xi = 2.0$ km s$^{-1}$ regime. For the $\xi = 1.5$ km s$^{-1}$ regime, the [Fe I,Fe II/H] values are out of equilibrium and the [Fe I/H] disagrees with the model [Fe/H] by $\approx 0.2$ dex (see Table 4). Fig. 3c uses a model for Lee 2525 at [Fe/H] = $-0.65$ dex which returns [Fe/H] = $-0.62$ dex for $\xi = 1.5$ km s$^{-1}$. The spread in values are reasonable and tighter than the spread in the $\xi = 2.0$ km s$^{-1}$ regime.

Ultimately, the best-fitting model shown in Fig. 3(d) resides closer to the $\xi = 2.0$ km s$^{-1}$ regime at $\xi = 1.8$ km s$^{-1}$ where the spread in values is reasonable for both the Fe I and Fe II abundances. Hence, the best-fitting model for Lee 2525 derived in this study returned values of $T_{\text{eff}}$ = 4225 K, log $g$ = 1.2, [Fe/H] = $-0.70$ dex and $\xi$ = 1.8 km s$^{-1}$ (see Table 4), which are in reasonable agreement with the values derived in Brown & Wallerstein (1992).

The Fe abundances derived from the Fe I and Fe II lines using the best-fitting stellar atmosphere model were $-0.72 \pm 0.16$ and $-0.74 \pm 0.08$ dex, respectively. These values were derived from the equivalent widths measured such that the continuum placement took account of the low S/N of the Lee 2525 spectrum, as outlined above. Using the best-fitting Lee 2525 stellar model, Fe abundances were rederived from the equivalent widths measured without taking the S/N into account. The respective values were determined to be [Fe I/H] $-0.37 \pm 0.17$ and $-0.29 \pm 0.10$ dex. These values are considerably more metal rich and reflect an increase in derived abundance of $\sim 0.3$ dex from the Fe I lines and $\sim 0.4$ dex from the Fe II lines due to the increased equivalent width values. The weaker Fe II lines show a larger change in the increase in equivalent width is proportionally greater than for the strong Fe I lines. These values reflect the maximum possible uncertainty introduced by the spectrum's low S/N. However, the equivalent width measurements and abundance analysis were carried out in a consistent manner with careful inspection of the lines to ensure the best placement of the continuum in order to minimize this uncertainty.

The best-fitting stellar model for this study returned an average [Fe/H] of $-0.73$ dex which is slightly more metal rich than the Brown & Wallerstein (1992) value of $-0.82$ dex. Comparing these values to previous studies of RGB and AGB stars in 47 Tuc, both are more metal poor than Alves-Brito et al. (2005), which found an average [Fe/H] of $-0.68$ dex, Carretta et al. (2004) ([Fe/H] = $-0.67$ dex) and Wylie et al. (2006) ([Fe/H] = $-0.60$ dex). However, a more recent paper, Koch & McWilliam (2008), derived an [Fe/H] of $-0.76$ dex for 47 Tuc with their stars having a range of values from $-0.82$ to $-0.72$ dex. This is significantly more metal poor than previous studies and in better agreement with the derived metallicities of Lee 2525 found in this study and Brown & Wallerstein (1992).

### 4 ELEMENT ABUNDANCES IN LEE 2525

Table 5 lists the light- and heavy-elemental abundances derived in this study for two models for Lee 2525 as well as the results from Brown & Wallerstein (1992). As outlined in Section 3.1, the light-elemental abundances were derived using ABBIND in MOOG, while heavy-elemental abundances were derived using MOOG's spectrum synthesis function, SYNTH.

Given the similar nature of the stellar parameters for Lee 2525 derived in this study to those derived in Brown & Wallerstein (1992), elemental abundances using both models were calculated for a complete comparison. In Table 5, the abundances derived in Brown & Wallerstein (1992) are quoted in Column 2 with associated uncertainties and the number of lines used. Column 5 lists the abundances derived in this study using the Brown & Wallerstein (1992) stellar model parameters, and Column 7 lists the abundances derived using the best-fitting model determined in this study. Columns 10–12 list the changes in abundance with associated changes in $T_{\text{eff}}$, log $g$ and $\xi$.

As described in Section 3.2, the placement of the continuum for the measurement of the equivalent widths introduced a key source of uncertainty for the abundances measured in this analysis. This is likely to be the main source of discrepancy between this analysis and the element abundances determined in Brown & Wallerstein (1992). While the spectra in both studies were of similar resolution ($R \approx 20000$), the S/N in this study was considerably lower. It must also be noted that Brown & Wallerstein (1992) used a mixture of solar and laboratory log $gf$ values, but only laboratory log $gf$ values were used in this analysis. Also, Brown & Wallerstein (1992) used the solar abundances reported in Anders & Grevesse (1989) while those of Lodders (2003) were used here.

#### 4.1 Light elements: O to Zn

Comparing the abundances we derived using the Brown & Wallerstein (1992) parameters with the Brown & Wallerstein (1992) results, there is reasonable agreement (to within 1σ) for the majority of the light elements. The key differences were: Al I, which was less abundant in this study by 0.19 dex; Ti II, which was less abundant by 0.23 dex; Zn I, which was less abundant by 0.10 dex, and Sc II, which was over abundant by 0.10 dex.

Comparing the best-fitting model of this study with Brown & Wallerstein (1992), similar comments can be made. In general, the light-elemental abundances agree within 1σ. Sc II and Zn I are also enhanced using this model compared to Brown & Wallerstein (1992), while Ti II is still significantly depleted. However, of the three sets of stellar atmosphere models, the best-fitting model derived in this study provided the best agreement between Ti I and Ti II abundances indicating a better choice of log $g$, at least in terms of Ti.

The error analysis in Table 5 shows that the strong lines of Sc II and Zn I used in this study are highly sensitive to changes in $\xi$ as is the case of strong lines. Also, both Sc II and Ti II are sensitive to changes in gravity as is expected for ionized lines.

This study confirms the abundance correlations previously observed for this star in Brown & Wallerstein (1992), namely a correlation of Al and Na abundance with CN strength. Another key abundance anomaly is the Na–O anticorrelation observed in 47 Tuc (see Carretta et al. 2004 and references therein). An O abundance was not measured in Brown & Wallerstein (1992). However, it was obtained in this study using the forbidden O I line at 6300 Å. Lee 2525 is enhanced in O ([O/Fe] = 0.40 dex), while Na is not ([Na/Fe] = 0.05 ± 0.05 dex). These values fall clearly within the anticorrelated trend of [Na/Fe] to [O/Fe] shown in fig. 5 of Carretta et al. (2004).

The abundances of Mg and Al are both enhanced in agreement with previous studies. There is no indication of an anticorrelation between Mg and Al (Carretta et al. 2004; Koch & McWilliam 2008). As 47 Tuc is a metal-rich globular cluster, this anomaly is not expected (Gratton et al. 2004).
With regard to Ca, previous studies have shown enhancements in 47 Tuc stars (Carretta et al. 2004; Koch & McWilliam 2008). However, the analysis of this star found a Ca abundance of [Ca/Fe] = 0.00 dex, in agreement with the value determined in Brown & Wallerstein (1992) ([Ca/Fe] = −0.03 dex).

The Ti abundance is slightly enhanced (∼ +0.15 dex) in this study for both Ti I and Ti II. In Brown & Wallerstein (1992), Ti I was enhanced at this same level while Ti II was greatly enhanced (∼ +0.42 dex). This implies that there is a log g determination issue in their study due to the neutral and ionized species being out of equilibrium.

For a sample of five red giants, Alves-Brito et al. (2005) found the mean abundances for Ca to be [Ca/Fe] = 0.00 dex and Ti to be [Ti/Fe] ∼ 0.25 dex. The Ca and Ti abundances derived in this study agree with Alves-Brito et al. (2005) within the uncertainties.

In Alves-Brito et al. (2005), a comparison of Ca abundances was made between Brown & Wallerstein (1992) and Carretta et al. (2004). The lack of enhancement in Ca in Brown & Wallerstein (1992) was noted. The stellar sample in Carretta et al. (2004) all had enhancements in Na and Ca, while the Alves-Brito et al. (2005) sample showed no enhancements in the mean abundances of both Na and Ca. While the correlation of Na with CN can be explained as leakage from the CNO cycle, a variation of Ca with Na or CN is not expected. Further investigation of Ca abundances is needed in order to clarify the reported abundances for this element in 47 Tuc.

Overall, this analysis of Lee confirms previous abundance anomalies within 47 Tuc giant branch stars with regard to CN, Na and O.

### 4.2 Heavy elements: Y to Eu

The comparison of the heavy-elemental abundances show that the current analysis of Lee 2525 carried out using the Brown & Wallerstein (1992) stellar atmosphere model returns slightly higher abundances than the values found in the paper itself. Zr and La show enhancements relative to Brown & Wallerstein (1992), while Ba is depleted.

The best-fitting stellar model in this study also shows Zr and La are enhanced compared with the Brown & Wallerstein (1992) values. However, there is a better agreement between the Y I values and the Y II abundance values. There is also a large uncertainty in the Brown & Wallerstein (1992) La abundance within which the value from this study resides. While Ba is depleted here with respect

### Table 5.

The light- and heavy-elemental abundances derived in this study from two stellar models for Lee 2525 compared with the values derived in Brown & Wallerstein (1992). The uncertainty on the mean (σ) and number of lines used to derived the abundance (N) are included. The variation in abundances due to changes in stellar parameters corresponding to ΔTeff = +100 K, Δ log g = +0.5 and Δξ = +0.5 km s⁻¹ are also shown.

| Species | [X/H] | σ | N | [X/H] | σ | N | ΔTeff | Δ log g | Δξ |
|---------|-------|---|---|-------|---|---|-------|-------|---|
| Fe I    | −0.83 | 0.16 | 22 | −0.85 | 0.18 | 19 | 0.01 | 0.11 | −0.23 |
| Fe II   | −0.82 | 0.17 | 5  | −0.81 | 0.09 | 3  | −0.12 | 0.32 | −0.06 |
| [X/Fe]  |       |     |   |       |     |   |       |       |   |
| O I     | −      | 0   | 0.45 | −      | 0.40 | − 1 | 0.01 | 0.18 | −0.01 |
| Na I    | −0.01 | 0.06 | 2  | 0.15  | 0.06 | 0.05 | 2    | 0.09 | 0.01 |
| Mg I    | −      | 0   | 0.43 | −      | 0.34 | 0.04 | 2    | 0.01 | 0.05 |
| Al II   | 0.51  | 0.23 | 2  | 0.32  | 0.02 | 0.21 | 0.03 | 0.08 | 0.02 |
| Si II   | 0.21  | 0.14 | 6  | 0.43  | 0.20 | 0.36 | 0.20 | 0.07 | 0.14 |
| Ca I    | −0.03 | 0.06 | 9  | 0.04  | 0.21 | 0.00 | 0.23 | 0.11 | 0.00 |
| Sc II   | −0.04 | 0.06 | 2  | 0.06  | 0.07 | 0.05 | 0.08 | −0.03 | 0.22 |
| Ti I    | 0.17  | 0.09 | 7  | 0.24  | 0.19 | 0.14 | 0.18 | 0.17 | 0.05 |
| Ti II   | 0.42  | −    | 1  | 0.19  | 0.06 | 0.17 | 0.04 | −0.05 | 0.23 |
| Zn I    | 0.14  | 0.03 | 2  | 0.04  | 0.15 | 0.05 | 0.16 | −0.08 | 0.16 |
| Y I     | 0.58  | −    | 1  | 0.60  | 0.25 | 0.51 | 0.28 | 0.25 | 0.09 |
| Y II    | 0.41  | 0.47 | 2  | 0.44  | −    | 0.54 | −1   | 0.07 | 0.20 |
| Zr I    | −0.51 | 0.24 | 3  | 0.37  | 0.04 | 0.36 | 0.04 | 0.15 | 0.03 |
| Zr II   | −      | 0   | 0.70 | −    | 0.65 | −1   | 0.05 | 0.25 | −0.03 |
| Ba II   | −0.15 | 0.21 | 3  | −0.32 | 0.02 | −0.21 | 0.01 | 0.06 | 0.27 |
| La II   | 0.10  | 0.40 | 2  | 0.34  | 0.01 | 0.31 | 0.03 | 0.04 | 0.24 |
| Nd II   | −      | 0   | 0.40 | −    | 0.41 | −1   | 0.11 | 0.31 | 0.05 |
| Eu II   | 0.44  | −    | 1  | 0.48  | −    | 0.40 | −1   | 0.12 | 0.38 |
| [X/Y]   |       |     |   |       |     |   |       |       |   |
| ls/Fe   | 0.16  | 0.50 | 0.53 | 0.20 | 0.51 | 0.22 | 0.13 | 0.14 | −0.16 |
| hs/Fe   | 0.10  | 0.40 | 0.37 | 0.01 | 0.36 | 0.03 | 0.08 | 0.27 | 0.00 |
| hs/lS   | −0.06 | 0.64 | −0.16 | 0.15 | −0.16 | 0.18 | −0.05 | 0.13 | 0.16 |
Figure 4. Wavelength region about 6140 Å showing the observed spectrum overlaid with spectra synthesized at different specified Zr abundances: (a) Arcturus spectrum where [Zr/Fe] = +0.00 dex provides the best fit to the Zr i lines; (b) Lee 2525 spectrum using the stellar model based on the stellar parameters specified in Brown & Wallerstein (1992). [Zr/Fe] = −0.51 dex is the best-fitting Zr abundance found in Brown & Wallerstein (1992). [Zr/Fe] = +0.33 dex is the best-fitting Zr abundance for this model in the current analysis; (c) Lee 2525 spectrum using the best-fitting stellar model parameters determined in this study. [Zr/Fe] = +0.35 dex is the best fit to the Zr abundance.

With Zr now similar to Y, these heavy-elemental abundances fall within the spread of values determined for the s-process elemental abundances obtained in Wylie et al. (2006) confirming an enhancement of s-process elements in 47 Tuc (see Table 1).

4.3 Lee 2525 abundances with respect to Arcturus

In light of this result for Lee 2525, the [Fe/H] and [X/Fe] relative to the Sun listed in Table 5 were recalculated relative to Arcturus and are listed in Table 6. This was carried out in order to remove any systematic errors within the analysis process by restating the abundances in Lee 2525 relative to a star of similar metallicity and atmospheric structure on which the process has been calibrated (Koch & McWilliam 2008).

While Arcturus and Lee 2525 have similar stellar parameters, Table 6 shows the clear differences in their chemical make up. For the most part, Lee 2525 is less abundant in the light elements than Arcturus and more abundant in the heavy elements. Si and Zn are both enhanced in Lee 2525 compared to Arcturus. However, the derived uncertainties of Si and Zn in this study bring them in line with the other light-element abundances.

Of the heavy elements, Ba ii and Eu ii show abundances similar to Arcturus. The strength of the Ba ii lines and their sensitivity to $\xi$ make the Ba ii less reliable. As Eu is predominantly an r-process element, its abundance is a useful indication of how much pollution by supernovae the gas clouds underwent prior to the formation of stars. The similar value between Lee 2525 and Arcturus could imply some similar degree of exposure. The similarity in Eu abundances between globular cluster stars and field stars has been noted previously (James et al. 2004).

The comparison between the Lee 2525 and Arcturus abundance results is a natural consequence of undertaking a differential...
analysis with a standard star. However, as Lee 2525 is a globular cluster star and Arcturus is field star, the comparison being made is really between two distinct stellar environments which is beyond the scope of this paper. The key adjustments due to differencing Lee 2525 with Arcturus is a reduction in the scatter of the s-process element abundances. For Zr and Y, there is a better agreement between their neutral and ionized abundances, and a better agreement between these two light s-process peak elements overall. The abundances of the heavy s-process elements (La and Nd) are also brought in line. These effects are reflected in the [hs/Fe] and [ls/Fe] ratios although the [hs/ls] ratio is only adjusted by 0.02 dex. These improvements imply the reduction of systematic errors in the results due to the analysis process. In the case of a larger set of stars within a globular cluster, a similar differential analysis would be useful to reduce systematic errors within a study and thereby to produce more consistent results.

4.4 The hs-to-ls ratio in 47 Tuc giant stars

The hs and ls indices derived for Lee 2525 in this study were compared with Brown & Wallerstein (1992) and Wylie et al. (2006). Fig. 5 shows the abundance ratio of the heavy to light s-process elements ([hs/ls]) for Lee 2525 as well as for the other studies.

Table 6. [Fe/H], [X/Fe] and s-process abundance ratios for Arcturus, and [Fe/H], [X/Fe] and s-process abundance ratios calculated relative to Arcturus for the Brown & Wallerstein (1992) and best-fitting Lee 2525 stellar models, where [X/Y]$_{Arcturus}$=[X/Y]$_{Arcturus}$- [X/Y]$_{Arcturus}$. The results from Brown & Wallerstein (1992) are also recalculated relative to Arcturus for comparison.

| Element | [X/H] | [X/H]$_{Arcturus}$ | [X/H]$_{Arc}$ | [X/H]$_{Arc}$ |
|---------|------|------------------|----------------|----------------|
| X       | -0.61| -0.22            | -0.24          | -0.11          |
| Fe i    | -0.56| -0.26            | -0.22          | -0.17          |
| O i     | 0.57 | -                 | -0.12          | -0.17          |
| Na i    | 0.15 | -0.16            | 0.01           | -0.10          |
| Mg i    | 0.34 | -                 | 0.08           | -0.01          |
| Al i    | 0.25 | 0.26             | 0.06           | -0.04          |
| Si i    | 0.20 | 0.01             | 0.23           | 0.16           |
| Ca i    | 0.19 | -0.22            | -0.15          | -0.19          |
| Sc i    | 0.24 | -0.28            | -0.18          | -0.20          |
| Ti i    | 0.35 | -0.18            | -0.11          | -0.21          |
| Ti ii   | 0.33 | 0.09             | -0.14          | -0.16          |
| Zn i    | -0.04| 0.18             | 0.07           | 0.09           |
| Y i     | 0.07 | 0.51             | 0.53           | 0.44           |
| Y ii    | 0.12 | 0.29             | 0.32           | 0.42           |
| Zr i    | 0.01 | -0.52            | 0.36           | 0.35           |
| Zr ii   | 0.12 | -                 | 0.58           | 0.53           |
| Ba ii   | -0.19| 0.04             | -0.13          | -0.02          |
| La ii   | 0.04 | 0.06             | 0.30           | 0.27           |
| Nd ii   | 0.10 | -                 | 0.31           | 0.32           |
| Eu ii   | 0.36 | 0.08             | 0.12           | 0.04           |

| Element | [X/Y] | [X/Y]$_{Arcturus}$ | [X/Y]$_{Arc}$ | [X/Y]$_{Arc}$ |
|---------|------|------------------|----------------|----------------|
| ls/Fe  | 0.08 | 0.09             | 0.45           | 0.44           |
| hs/Fe  | 0.07 | 0.06             | 0.30           | 0.29           |
| hs/ls  | -0.01| -0.03            | -0.14          | -0.14          |

Figure 5. The ratio of the heavy to light s-process element abundance ([hs/ls]) for each star against [Fe/H]. (•) Wylie et al. (2006), (♦) Brown & Wallerstein (1992) using ls = (Y i, Y ii) and (△) Lee 2525, this study.

The ls indices for the Brown & Wallerstein (1992) stars were recalculated to use only the Y i and Y ii abundances in light of the above analysis of Zr. Considering the sample as a whole, there appears to be no trend between the [hs/ls] ratio and [Fe/H] in Fig. 5. Given these stars all exist in the same cluster and therefore have the same metallicity within some variance, if there was a spread in [hs/ls] values greater than the systematic spread on the [Fe/H] values, it would indicate that s-process elements were being produced in these stars.

Observational and theoretical studies have shown that for AGB stars undergoing TDU the [hs/ls] ratio generally increases with decreasing metallicity, although the theoretical relations are naturally more complex (Busso et al. 2001). As the seed nuclei become fewer, there is greater enhancement in the heavy s-process peak compared with the light s-process peak. As no such trend exists in this sample of 47 Tuc stars, it implies that the s-process abundances observed here are primordial and are not being produced internally in these stars.

5 CONCLUSION

Studies to date of s-process element abundances in 47 Tuc stars have concluded that the observed s-process element abundances are due to the primordial chemical composition of the cluster or some pollution event early in the cluster’s history. While within each study there is agreement as to the magnitude of the s-process element abundances, the abundances differ between the studies. This analysis of Lee 2525 has resolved a discrepancy regarding the reported Zr abundance of the 47 Tuc stellar samples analysed in Brown & Wallerstein (1992) compared with Wylie et al. (2006). The current study found Lee 2525 to be enhanced in Zr at [Zr/Fe] = +0.51 dex which is in agreement with the enhancement found for Y at [Y/Fe] = +0.53 dex, another light s-process element. This is in line with s-process element enhancements found in 47 Tuc giant branch stars in Wylie et al. (2006). The Na–CN correlation reported in Brown & Wallerstein (1992) for Lee 2525 was also found here, as well as an Na–O anticorrelation in line with other studies of light elements in 47 Tuc stars (Carretta et al. 2004). These results support the premise that the abundance anomalies observed in 47 Tuc have a primordial or pollution-based origin.

While this study has resolved a discrepancy between two key papers, the overall s-process element abundance distribution within 47 Tuc is still not clear. It is necessary to expand the sample of 47 Tuc stars analysed for their s-process element abundances in order
to consolidate the results found here with those from other studies. This analysis was carried out differentially with respect to Arcturus in an effort to reduce systematic errors by calibrating the analysis process to a standard star of similar stellar parameters. This provides a solid framework for further study within this area.

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