A COMPARATIVE STUDY OF TWO 47 Tuc GIANT STARS WITH DIFFERENT s-PROCESS ENRICHMENT

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ABSTRACT

Here we aim to understand the origin of 47 Tuc’s La-rich star Lee 4710. We report abundances for O, Na, Mg, Al, Si, Ca, Sc, Ti, V, Cr, Co, Ni, Zn, Y, Zr, Ba, La, Ce, Pr, Nd, and Eu and present a detailed abundance analysis of two 47 Tuc stars with similar stellar parameters but different slow neutron-capture (s-)process enrichment. Star Lee 4710 has the highest known La abundance ratio in this cluster ([La/Fe] = 1.14), and star Lee 4626 is known to have normal s-process abundances (e.g., [Ba/Eu] < 0). The nucleosynthetic pattern of elements with Z ≥ 56 for star Lee 4710 agrees with the predicted yields of a 1.3M⊙ asymptotic giant branch (AGB) star. Therefore, Lee 4710 may have been enriched by mass transfer from a more massive AGB companion, which is compatible with its location far away from the center of this relatively metal-rich ([Fe/H] ∼ −0.7) globular cluster. A further analysis comparing the abundance pattern of Lee 4710 with data available in the literature reveals that nine out of the ∼200 47 Tuc stars previously studied show strong s-process enhancements that point toward later enrichment by more massive AGB stars.

Key words: globular clusters: individual (47 Tuc) – stars: abundances – stars: chemically peculiar

1. INTRODUCTION

The abundances of neutron-capture elements in globular clusters (GC) provide additional insight, beyond the light elements O, Na, and Al, into the origin of abundance anomalies found among stars in a given cluster. In particular, finding GC stars with unusual enhancements of elements produced by the s-process6 enables a direct comparison with theoretical yield predictions. For example, comparing the ratio of light (first peak) to heavy (second peak) s-process elements provides information about the mass and metallicity of the stars in which the s-process elements were produced. Most s-process elements are produced through one of two channels. The main channel takes place in ∼8M⊙ asymptotic giant branch (AGB) stars where neutrons are released in a 12C(p, γ)13N(β+, ν)13C(α, n) 16O reaction occurring in a 13C-enriched pocket. The size and efficiency of the 13C-pocket, and in turn the outcome of the main s-process, is not currently well-constrained, but the 13C-pocket is likely located in the He-intershell region and driven by carbon created in the stellar interior and protons from the outer H-rich layers (e.g., Sneden et al. 2008; Käppeler et al. 2011; Karakas & Lattanzio 2014). Several theoretical studies have shown that M = 1–3M⊙ AGB stars may produce the largest fractional yield of main s-process material peaking around 2M⊙ (e.g., Bisterzo et al. 2010, 2014; Cristallo et al. 2011, 2015). In more massive stars, the weak s-process is thought to be the dominant slow neutron-capture process, and the neutron source is a 22Ne(α, n)25Mg reaction that is only activated at higher densities and temperatures (T ≥ 2.5 ·10^8 K; e.g., Pignatari et al. 2010). While the main s-process produces a larger fraction of second-peak neutron-capture elements (e.g., Ba and La), the weak s-process tends to produce a higher fraction of first-peak (e.g., Sr, Y, and Zr) s-process elements (Gallino et al. 1998; Busso et al. 1999; Bisterzo et al. 2010; Pignatari et al. 2010; Cristallo et al. 2011; Karakas & Lattanzio 2014).

The GC 47 Tuc is a useful candidate for analyzing neutron-capture production because it is nearby, massive, metal-rich ([Fe/H] ∼ −0.7), and has been spectroscopically studied in great detail. Previous analyses have found that 47 Tuc hosts at least three stellar populations that are distinguished as having unique Na and O abundance ratios (Carretta et al. 2013; Cordero et al. 2014, hereafter C14). However, similar to other GCs, 47 Tuc does not exhibit significant abundance variations of the iron-peak elements (Thygesen et al. 2014, hereafter T14 and references therein). Interestingly, although T14 and C14 found the cluster stars to have a mostly homogeneous heavy element composition, identical to the abundances observed in field stars at the same metallicity, T14 and Wylie et al. (2006, hereafter W06) found evidence indicating that some RGB and AGB stars may have enhancements of elements produced by the s-process.

In our previous spectroscopic study of 47 Tuc (C14), we found one s-process rich giant out of a sample of ∼160 stars. In addition to the s-process rich stars found by W06 and C14, D’Orazi et al. (2010) have found five Ba-rich stars ([Ba/Fe] > 0.51) in a sample of 1200 GC stars, and Cohen & Meléndez (2005) found a Y-rich star in M13. Thus, s-process enhanced stars are relatively rare in monometallic GCs. Interestingly, these s-process rich stars tend to be found in the external regions of GCs, which could be a consequence of less efficient binary disruption, assuming these s-process rich stars formed in binary systems. Therefore, in the present work

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6 Slow neutron-capture process.
we perform a detailed abundance analysis of Lee 4710, an s-process enhanced star in 47 Tuc. We aim to assess whether or not the star’s heavy element composition can be modeled by theoretical AGB yields, and also explore possible formation modes.

2. DATA REDUCTION AND ABUNDANCE ANALYSIS

The stars Lee 4710 and Lee 4626 were observed with FLAMES at VLT (ID: 088.D-0026(A)), using the gratings HR13, HR14, and HR15, which offer moderate to high spectral resolving power ($R = 22,500, 17,700$, and $19,300$, respectively) and a wavelength coverage ranging from $6100$ to $6800 \AA$ (including gaps). The data reduction was carried out with the girBLDRS pipeline (http://girbldrs.sourceforge.net/), which performs bias subtraction, flat-fielding, wavelength calibration, and object extraction. Sky subtraction and telluric contamination removal were performed using the IRAF tasks skysub and telluric. Multiple exposures taken a few days apart were combined using the IRAF task scombine, achieving a signal-to-noise ratio of $\sim 75$ at $6200 \AA$. Two sample spectral regions of Lee 4710 and the comparison star Lee 4626, which has similar atmospheric parameters, are contrasted in Figure 1.

Atmospheric parameters were adopted from C14, which employed 40 Fe i and 6 Fe ii lines. A more detailed description of the parameter determinations can be found in C14. The radial velocities of both stars are given in Table 1. The velocity values are in agreement with the systemic velocity and dispersion found by Koch & McWilliam (2008), which suggests that both stars are true cluster members.

The abundance analysis was performed using the LTE line analysis code MOOG (Sneden 1973, version 2014) and plane parallel, $\alpha$-enhanced 1D ATLAS9 model atmospheres. The abundance of all elements except Fe were computed using spectrum synthesis. The line list was downloaded from VALD (Kupka et al. 2000) and updated with atomic data from NIST (http://www.nist.gov/pml/data/ asd.cfm) and the Kurucz database (http://kurucz.harvard.edu). A molecular CN line list from Sneden et al. (2014) was also included. Since we could not measure C or N independently, we assumed [C/Fe] = −0.5 and [N/Fe] = +0.7 following Carretta et al. (2013), and adjusted the [N/Fe] to match the strength of nearby CN features in our spectra.

The full wavelength range was inspected for lines useful for the chemical analysis, with an emphasis on identifying lines of elements predominantly produced by the s-process. Only clean CN features in our spectra.

Table 1

| Element | Lee 4626 | Lee 4710 |
|---------|----------|----------|
| O       | 0.40 ± 0.14 | 0.35 ± 0.17 |
| Na      | 0.60 ± 0.14 | 0.13 ± 0.17 |
| Mg      | 0.30 ± 0.14 | 0.30 ± 0.13 |
| Al      | 0.59 ± 0.15 | 0.38 ± 0.15 |
| Si      | 0.3 ± 0.14  | 0.28 ± 0.14 |
| Ca      | 0.39 ± 0.16 | 0.30 ± 0.19 |
| Sc      | 0.23 ± 0.13 | 0.17 ± 0.16 |
| Ti      | 0.42 ± 0.15 | 0.33 ± 0.18 |
| V       | 0.37 ± 0.15 | 0.35 ± 0.17 |
| Cr      | 0.20 ± 0.14 | 0.20 ± 0.15 |
| Co      | 0.40 ± 0.14 | 0.30 ± 0.14 |
| Ni      | 0.07 ± 0.16 | 0.02 ± 0.19 |
| Zn      | <0.85      | <0.95     |
| Y       | …          | 0.75 ± 0.18 |
| Zr      | 0.37 ± 0.14 | 0.83 ± 0.17 |
| Ba      | 0.35 ± 0.24 | 1.03 ± 0.20 |
| La      | 0.35 ± 0.19 | 1.14 ± 0.14 |
| Ce      | …          | 1.00 ± 0.17 |
| Pr      | <0.6       | <0.9      |
| Nd      | …          | <1.1      |
| Eu      | 0.50 ± 0.19 | 0.50 ± 0.17 |

Notes.

a Values from C14.

b Uncertain due to line blends. These measurements were given half weight in the final averaged abundance listed.

c Solar abundances from Asplund et al. (2009).
the two stars have very similar stellar parameters and lighter element \((Z < 30)\) abundances. However, the two stars have significantly different heavy element \((Z \gtrsim 30)\) abundances. This effect is illustrated in Figure 1. From C14 and current measurements, we know that Lee 4710 is a primordial and Lee 4624 an intermediate population star. Like most GC stars, Lee 4626 shows a \([\text{Ba/Eu}] < 0\) and \(\alpha\)-element enhancement of \(\sim 0.4\) dex, which is consistent with enrichment by SNe II.

### 2.1. Abundance Uncertainties

The abundances and number of measured lines are listed in Table 1. To assess the fitting uncertainties, all abundances have been measured separately by the authors, and we generally obtained a good agreement \((\pm 0.05 \text{dex})\) on a line-by-line basis. This uncertainty in the profile fitting is propagated together with uncertainties stemming from stellar parameters and the line list. The uncertainties of the abundances from individual lines were calculated by varying each star’s parameters by the model atmosphere uncertainties reported in C14 and Table 1. The final uncertainty in \([\text{X}/\text{Fe}]\) stems from the stellar parameters added in quadrature together with the uncertainty from line fitting and atomic data \((\pm 0.05 \text{dex})\).

### 3. DISCUSSION AND CONCLUSION

Although most GC stars, including those in 47 Tuc, tend to show a heavy element composition that is dominated by the \(r\)-process, previous studies have found that 47 Tuc stars exhibit some s-process enrichment as well. Furthermore, 47 Tuc’s s-process abundances are similar to the values found in halo stars with comparable metallicity (James et al. 2004). However, since the majority of 47 Tuc stars are not strongly s-process enhanced and do not show significant star-to-star scatter for the neutron-capture elements (T14; C14), the high \([\text{X}/\text{Fe}]\) ratios exhibited by Lee 4710 for elements heavier than the Fe-peak make the star a clear outlier in the cluster distribution. The low occurrence of s-process enhanced stars in 47 Tuc favors an event such as binary mass transfer as the preferred enrichment scenario for Lee 4710.

According to Bisterzo et al. (2014), more than 70\% of Y, Zr, Ba, La, and Ce are created by the s-process, and 94\% of Eu is created by the \(r\)-process at the time the solar system formed. Therefore, finding a low-mass star with enhanced \([\text{Ba}/\text{Eu}]\), in systems with \([\text{Fe}/\text{H}] > \sim 2\), suggests that a significant fraction of the star’s heavy elements were produced by the s-process. Similarly, the large \([\text{X}/\text{Fe}]\) ratios found for elements with \(Z \gtrsim 30\) in Lee 4710 (see Table 1) lead us to believe that this star experienced significant s-process pollution from an external source. Since most GCs exhibit \([\text{Ba}/\text{La}/\text{Eu}] < 0\) (e.g., see Gratton et al. 2004, their Figure 6), the heavy elements in these clusters were likely dominated by \(r\)-process enrichment from supernovae. Thus, GC stars such as Lee 4710 are relatively rare to find among monometallic GCs.

#### 3.1. A New s-process Rich Star in 47 Tucanae

47 Tuc is one of the most metal-rich clusters in which s-process dominated stars have been found. Here, we report the detection of significant enrichment \((|s\text{-process}/\text{Fe}| \approx 0.96)\) of several elements in the RGB star Lee 4710 that are likely produced by an s-process site in 47 Tuc. Lee 4710 is the most s-process-rich star yet found in 47 Tuc. In this section, we compare the abundance of neutron-capture elements in Lee 4710 to other red giants in the cluster (e.g., W06; D’Orazi et al. 2010) and to the barium star HD 5424. Figure 2 compares the scatter of heavy element abundances derived from single stars to the scatter of the cluster average abundances determined in different studies. Figure 2 also includes a comparison with the similar metallicity \(([\text{Fe}/\text{H}] = −0.55)\) Ba-star HD 5424 from Allen & Barbuy (2006). We find most analyses to be in agreement that the average \([\text{Eu}/\text{Fe}]\) abundance \((\sim\) r-process\) is similar to that of \([\text{Ba}/\text{Fe}]\) and \([\text{La}/\text{Fe}]\) \((s\text{-process})\). These data suggest that, at least on average, stars in 47 Tuc are not strongly s-process enhanced. Figure 2 indicates that some star-to-star scatter might exist for the lighter s-process elements (e.g., Y and Zr spanning 1.2 dex). While the cluster average abundance of \([\text{Zr}/\text{Fe}]\) from Brown & Wallerstein (1992), Alves-Brito et al. (2005), W06, and T14 varies by nearly a factor of 10, a close examination of the individual star abundances in their samples does not support an intrinsic dispersion in \([\text{Zr}/\text{Fe}]\). Within each study, the star-to-star \([\text{Zr}/\text{Fe}]\) scatter is comparable to that of the heavier neutron-capture elements for which the averages between studies are in better agreement.

Interestingly, Figure 2 shows that Lee 4710 is the most s-process enhanced star yet found in the cluster. It seems unlikely that any intrinsic heavy element dispersion in 47 Tuc is due entirely to binary mass transfer. Instead, the star-to-star \([\text{Ba}/\text{La}/\text{Fe}]\) dispersion found for stars with generally low \([\text{Ba}/\text{La}/\text{Eu}]\) ratios may be a reflection of primordial variations and/or incomplete mixing of gas within the early cluster environment. In fact, heavy element dispersions ranging from a factor of \(\sim 2–6\) due to primordial r-process inhomogeneities alone have already been detected in some clusters (Roederer 2011). However, it is interesting to note that our observations of Lee 4710 increase the number of 47 Tuc stars with some s-process enhancement to nine stars, and all of them are located \(> 9\) core radii from the cluster center\(^7\) (see Figure 3).

\(^7\)Only 10/170 stars studied are located inside 9 core radii. Therefore, the lack of s-rich stars \(< 9r/\epsilon\) may not be significant.
3.2. The s-process Origin of Lee 4710

Since Lee 4710 exhibits larger [Ba/La/Fe] excesses compared to [Y,Zr/Fe], we expect that the star was polluted by the main s-process operating in a low to intermediate mass AGB star. We can rule out that Lee 4710 is a thermally pulsing AGB star given both its location on the color—magnitude diagram (2.5 mag. below the RGB-tip) and the fact that as a co-eval cluster member it would not have a high enough mass to be an intrinsic Ba-star. Thus, we believe that the s-process enrichment originates from a former AGB binary companion (see also Section 3.3). In order to better trace the possible origin of the s-process enrichment of Lee 4710, we can compare the star’s stellar abundance pattern to theoretical yields from similar metallicity AGB stars of different masses. In this connection we note that detailed, isotopic abundances of C and N in Lee 4710 would help us unveil the nature of its enrichment or mixing events, since dredge-up episodes would increase the $^{13}$C and N abundances and lead to a low C/N-ratio.

Figure 4 shows a comparison of the heavy element abundances derived for Lee 4626 (s-process poor) and Lee 4710 (s-process rich) against theoretical yields from the F.R.U. I.T.Y database (Cristallo et al. 2011) for $M_{1.3}$, 1.5, 2.0, and 3.0 $M_{\odot}$ AGB stars. Using these data, we find that for Lee 4710 the abundance pattern of elements with $Z > 40$ is best fit by the 1.3 $M_{\odot}$ model. The 1.5, 2.0, and 3.0 $M_{\odot}$ AGB models produce [X/Fe] ratios that are >0.5 dex too large to match the observations. Although we note that the present-day surface composition of Lee 4710 may not entirely reflect the abundance pattern of the material accreted while the star was on the main-sequence, any dilution of accreted material due to RGB evolution is unlikely to change the heavy element abundances by 0.5 dex or more, and we therefore believe that a low-mass AGB star ($<1.5M_{\odot}$) is most likely to provide the best fit (even after some pollution or dilution of the transferred material). The [Y/Fe] and [Zr/Fe] abundances are also enhanced in Lee 4710 compared to Lee 4626, and these elements are better fit by the 1.5 $M_{\odot}$ AGB model compared to the more massive AGB models. However, these elements may also have a production component from the weak neutron-capture processes and therefore, at least in 47 Tuc, the lighter elements may not be as useful for constraining the masses of individual AGB polluters.

3.2.1. Light versus Heavy s-process Abundances

A simple tracer of s-process production is the ratio of the heavy-to-light elements, which is annotated as $[\text{hs}/\text{ls}]$, where $[\text{hs}]$ is the average of [Ba/Fe], [La/Fe], [Nd/Fe], and [Sm/Fe] and $[\text{ls}]$ is the average of [Sr/Fe], [Y/Fe], and [Zr/Fe]. As a rule of thumb, the lighter s-process elements, such as Sr–Zr, can be created by the weak s-process (e.g., Pignatari et al. 2010) in more massive stars. The weak s-process is predicted to produce moderate amounts of light s-nuclei and only a small amount of the heavy s-elements. This in turn results in a negative $[\text{hs}/\text{ls}]$. However, such a negative ratio can also be produced by AGB stars if they have not undergone many pulses or if the seed-to-neutron ratio is high (i.e., a high metallicity). Similarly, an AGB star that experiences many thermal pulses and dredge-up episodes or has a low seed-to-neutron ratio (low metallicity) will produce a positive $[\text{hs}/\text{ls}]$ ratio.

Wylie et al. (2006) find a $[\text{hs}/\text{ls}]$ of −0.4 to −0.09, which on our abundance scale (and [Fe/H]) corresponds to −0.35 to +0.05. These values match those we derive for Lee 4626, which shows a normal La abundance. On the other hand, Lee 4710 has a $[\text{hs}/\text{ls}]$ of +0.33. This large value almost matches the total $[\text{hs}/\text{ls}]$-ratio of a 1.3 $M_{\odot}$ AGB star ($Z=0.006$) after all dredge-ups (a total of four episodes) have been completed. We note that if the metallicity was slightly higher, then the observed $[\text{hs}/\text{ls}]$ of Lee 4710 would agree with the 1.3 $M_{\odot}$ AGB ($Z=0.003$) yield after just two dredge-up episodes. With the high $[\text{hs}/\text{ls}]$ of Lee 4710, the weak s-process is therefore not likely to explain the formation of this star, whereas a few or even all dredge-up episodes of a 1.3 $M_{\odot}$ AGB can plausibly explain the heavy element enrichment found in Lee 4710.

3.3. Binarity in GCs

Understanding the mechanism responsible for the s-process pattern of star Lee 4710 will shed light on its chemical enrichment and indirectly may provide some insight regarding dynamical differences between the inner and outer regions of 47 Tuc. A commonly adopted explanation for the creation of extrinsic Ba-stars is mass transfer in a binary system (e.g., McClure et al. 1980; D’Orazi et al. 2010; W06). In this scenario, a more massive companion produces s-process elements through third dredge-up episodes that are later accreted onto the surface of the lower mass, and more slowly.
evolving, companion. The old age of 47 Tuc (11.75 ± 0.25 Gyr; Vanden-Berg et al. 2013) stars provides more than enough time for a 1.3\(M_\odot\) star to evolve through the AGB phase and be responsible for the heavy element abundance pattern of Lee 4710.

As noticed by D’Orazi et al. (2010), four out of five Ba-rich stars in their sample (∼1200 stars) are primordial population stars, similar to Lee 4710. This finding is consistent with the greater predicted survival rates for binaries in the primordial population of 47 Tuc, and would allow the binary system to survive long enough for the original primary star to reach the AGB phase and transfer s-process enhanced material onto its companion. The fact that all nine s-process enriched stars found in 47 Tuc are far from the center of the cluster suggests that the outer regions may provide more favorable conditions for binary systems to survive and for mass transfer to occur. This scenario is supported by Hong et al. (2015), who claims that at an age of 5 Gyr, when the putative AGB companion transferred mass, 75% of the binaries in the first generation population survived. At 47 Tuc’s current age, ∼60% of these still survive.

Although Omega Cen is known to have a large population of stars highly enriched in s-process elements, [s-process/Fe] > 1.0 (Johnson & Pilachowski 2010; Marino et al. 2011), large s-process enhancements are an uncommon characteristic among most GCs. Enhancements in s-process elements in GCs typically do not exceed [Ba,La/Fe] = 0.6 dex and have been found only in a limited number of more metal-poor clusters ([Fe/H] < −1.2): M4 (Shingles et al. 2014), NGC 1851 (Yong & Grundahl 2008), M22 (Marino et al. 2009), M2 (Yong et al. 2014), and NGC 6864 (Kacharov et al. 2013). From published samples of s-process elements (∼200 stars) we find that nine stars are s-process enriched in 47 Tuc, i.e., ∼4% ± 2%. Within the errors, this number is consistent with 47 Tuc’s small binary fraction (1.8% ± 0.6%: see Milone et al. 2012). However, there are two caveats that prevent assessing whether mass transfer in a binary system is the only mechanism responsible for the s-process rich stars in 47 Tuc. First, Milone et al. determined the fraction of binaries in 47 Tuc within 2.5 arcmin; therefore, in the outermost regions where the s-process rich stars have been found, the binary fraction could be different. Hong et al. (2015) suggest that the first generation binary fraction increases as a function of distance from the center. Second, the current binary fraction could be slightly smaller than it was when the s-rich stars were produced due to dynamical evolution of the cluster.

Multi-epoch spectroscopic follow-up with several months between the observation is needed to determine whether some of these nine s-process rich stars currently belong to a binary system with an unseen WD or post-AGB companion. These observations should also be accompanied by a determination of C, N, and 12C/13C abundances that may help to further constrain any AGB mass transfer scenarios.

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