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ON THE SERENDIPITOUS DISCOVERY OF A LI-RICH GIANT IN THE GLOBULAR CLUSTER NGC 362*

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ABSTRACT

We have serendipitously identified the first lithium-rich giant star located close to the red giant branch bump in a globular cluster. Through intermediate-resolution FLAMES spectra we derived a lithium abundance of $A(\text{Li}) = 2.55$ (assuming local thermodynamical equilibrium), which is extremely high considering the star’s evolutionary stage. Kinematic and photometric analysis confirm the object as a member of the globular cluster NGC 362. This is the fourth Li-rich giant discovered in a globular cluster, but is the only one known to exist at a luminosity close to the bump magnitude. The three previous detections are clearly more evolved, located close to, or beyond, the tip of their red giant branch. Our observations are able to discard the accretion of planets/brown dwarfs, as well as an enhanced mass-loss mechanism as a formation channel for this rare object. While the star sits just above the cluster bump luminosity, its temperature places it toward the blue side of the giant branch in the color–magnitude diagram. We require further dedicated observations to unambiguously identify the star as a red giant: we are currently unable to confirm whether Li production has occurred at the bump of the luminosity function or if the star is on the pre-zero-age horizontal branch. The latter scenario provides the opportunity for the star to have synthesized Li rapidly during the core helium flash or gradually during its red giant branch ascent via some extra mixing process.

Key words: globular clusters: individual (NGC 362) – stars: abundances – stars: Population II

1. INTRODUCTION

Lithium is one of the most fragile elements, promptly consumed by (p, α) reactions when the temperature in stellar interiors reaches $T \approx 2.5 \times 10^6$ K. According to standard stellar evolution theory, when a star leaves the main sequence and experiences the first dredge-up (Iben 1967), the convective envelope penetrates into hot internal layers, mixing the outer zones with matter that has undergone partial H-burning. The main surface abundance changes are increases in ^4He , ^{14}N , and ^{13}C and a decrease in the ^{12}C abundance (e.g., Karakas & Cosmochemistry 2010). The initial Li content is reduced by factors of 15–20 in Population II stars, reaching typical values of $A(\text{Li}) \leq 1.5$ dex. Observations of Li abundances in low-mass red giant branch (RGB) stars have indeed provided strong and unambiguous confirmation to these theoretical predictions (e.g., Lambert et al. 1980; Gratton et al. 2000). Yet, approximately between 1% and 2% of K giants have been found to exhibit significantly higher Li abundances, and they are thus referred to as Li-rich giants (Brown et al. 1989; Kumar et al. 2011; Monaco et al. 2011; Lebzelter et al. 2012 and references therein). Interestingly, this fraction might be even lower, that is, $0.56\% \pm 0.16\%$, as recently emphasized by Zhang et al. (2015). A clear explanation for this rare phenomenon is still wanting and different mechanisms have been suggested. They envisage contamination from ejecta of nearby novae (Martin et al. 1994), accretion of planets and/or brown dwarfs (Siess & Livio 1999), as well as freshly

synthesized Li in the stars themselves (see e.g., Sackmann & Boothroyd 1999). The physical process responsible for Li production is the well-known Cameron & Fowler (1971) mechanism: the fusion sequence is $^3\text{He}(\alpha, \gamma)^7\text{Be}(e, \nu)^7\text{Li}$, with the requirement that the astrated ^7Be is quickly transported to the cooler envelope so that the eventual ^7Li produced will not be destroyed by proton captures. Charbonnel & Balachandran (2000) proposed two distinct episodes of Li production depending upon the mass of the star. In low-mass RGB stars, with degenerate helium cores, Li production may be associated with the bump in the luminosity function; alternatively, intermediate-mass stars can synthesize Li once the core-He burning has ceased and they ascend the early asymptotic giant branch (AGB; see that paper for details).

The preliminary observational detections of Li-rich giants seemed to suggest that these stars occupy only specific regions of the Hertzsprung–Russel diagram (such as the RGB bump, tip, and/or the red clump). However, several studies (e.g., Monaco et al. 2011; Lebzelter et al. 2012) have recently identified Li-rich stars at magnitudes that span the red giant branch. Their results indicate that the formation of Li-rich giants might not be limited to the aforementioned specific evolutionary events.

Given how rare these stars are, large surveys are required (and underway) to increase the number of observed Li-rich objects. More detections are necessary to improve our understanding of the physical phenomena involved and provide empirical constraints on their formation. Many stellar environments, within and beyond the Milky Way, have been scrutinized for the presence of Li-rich giants (thin/thick disk,

* Based on observations taken with ESO telescopes under program 094.D-0363(A).

bulge and halo in the Milky Way, dwarf galaxies, open clusters, and globular clusters (GCs; e.g., Pilachowski et al. 2000; Monaco et al. 2011; Kirby et al. 2012; Lebzelter et al. 2012; Martell & Shetrone 2013; Monaco et al. 2014). Clusters (either open or globular) offer an obvious advantage in that they host mono-metallic, almost coeval, stellar populations and hence represent an excellent target for this kind of investigation; their masses and luminosities are also much more accurately determined with respect to field stars. To date, only three Li-rich giants have been reported in GCs: V42 in M5 (Carney et al. 1998), V2 in NGC 362 (Smith et al. 1999), and IV-101 in M3 (Kraft et al. 1999). All of them are located in the upper part of the RGB; V2 and IV-101 lie at the tip of the RGB, while V42 is actually a W Vir post-AGB star. We present in this Letter the serendipitous discovery of a Li-rich giant close the RGB bump in the globular cluster NGC 362, a relatively metal-rich cluster ($[\text{Fe}/\text{H}] = -1.26$ dex, 2011 update of the Harris catalog), characterized by chaotic and unusual orbital parameters (Dinescu et al. 1999). This is the first time that a Li-rich giant is detected at this evolutionary stage in a GC.

2. OBSERVATIONS AND ANALYSIS

Observations were conducted in visitor mode with FLAMES (Pasquini et al. 2002) mounted at ESO VLT on 2014 December 11–13, under program 094.D-0363(A). Spectra were collected with the scientific aim of inferring Li and Al abundances for large samples of RGB stars in several GCs, as part of our dedicated survey (see D'Orazi et al. 2014, hereinafter Paper I). We utilized the HR15N setup that provides a nominal resolution of $R = 17\,000$ and a spectral coverage from 6470 \AA to 6790 \AA , allowing the simultaneous inclusion of the strong doublets for Li I (6708 \AA) and Al I ($6696/6698\text{ \AA}$). The data were reduced using the dedicated ESO software (version 2.12.2, available at <http://eso.org/sci/software/pipelines>) and resulting in bias-subtracted, flat-fielded, wavelength-calibrated, one-dimensional spectra. Sky subtraction and rest-frame shift were then carried out within IRAF.⁸ As with Paper I, stellar parameters were derived in the following manner: effective temperatures (T_{eff}) are inferred from V and K_s photometry (from Momany et al. 2004 and Skrutskie et al. 2006, respectively) and the calibration by Alonso et al. (1999). The reddening and metallicity values are adopted from the Harris (1996) catalog, that is, $E(B - V) = 0.05$ and $[\text{Fe}/\text{H}] = -1.26$ dex. Surface gravities were computed from the standard formula relating luminosities, temperatures, and masses,⁹ adopting $M = 0.85 M_{\odot}$ and a bolometric solar magnitude of $M_{\text{bol},\odot} = 4.75$. Microturbulence velocities (ξ) are from the relation by Gratton et al. (1996). Abundances were obtained via spectral synthesis for both Li and Al using the local thermodynamical equilibrium (LTE) code MOOG (Snedden 1973, 2014 version); interpolated Kurucz model atmospheres based on the ATLAS9 code with α -enhancement and

no convective overshooting (Castelli & Kurucz 2004) were used throughout this study.¹⁰

We adopted the same line list as in Paper I, performing the comparison between synthetic and observed spectra between 6696 and 6720 \AA (exploiting the Ca I line to evaluate the spectral broadening). Errors related to best-fit determination and uncertainties in stellar parameters were consistently calculated as for Paper I and then added in quadrature, given their independence. The total internal random error results in 0.09 dex and 0.12 dex for Li and Al, respectively. Finally, non-LTE corrections were applied to Li abundances, following prescriptions by Lind et al. (2009).

3. RESULTS AND DISCUSSION

Stellar parameters, kinematics, and abundances for Li and Al are reported in Table 1 for our target star. We inferred a Li abundance of $A(\text{Li}) = 2.55 \pm 0.09$ (0.13 dex lower when departures from LTE are taken into account), which is significantly higher than our determined average for the cluster ($A(\text{Li}) = 0.90 \pm 0.02$ rms = 0.15 , 66 RGB stars; V. D'Orazi et al. 2015, in preparation). Thus, star #15370 joins the small family of Li-rich giants in GCs whose other members include a star in M3, M5 as well as a neighbor also in NGC 362. Star #15370 distinguishes itself because it is the first Li-rich giant discovered in a GC near the luminosity of the RGB bump (roughly 0.12 magnitudes brighter than $V_{\text{bump}} = 15.40$; from Nataf et al. 2013). Its siblings all sit close to the tip of their giant branches. There is little doubt that the star is Li rich; the intrinsic strength of the 6708 \AA doublet is evident from Figure 1, where we show the observed spectrum along with synthetic profiles calculated for different Li abundances. The equivalent width (EW), measured using the IRAF task *splot* and a Gaussian profile, is $\text{EW} = 250\text{ m\AA}$. Unfortunately, our spectral coverage does not include the other Li I feature at 6104 \AA , thus we cannot utilize this line as a secondary indicator.

Kinematic information confirms cluster membership. The star's radial velocity $V_{\text{rad}} = 222.68 \pm 1.02\text{ km s}^{-1}$ is consistent with the cluster average we derived from our sample of 71 RGB stars, i.e., $V_{\text{rad}} = 222.78 \pm 0.62\text{ km s}^{-1}$. This value agrees very well with $V_{\text{rad}} = 223.5 \pm 0.5\text{ km s}^{-1}$, as given by Harris (1996). Moreover, the position on the color-magnitude diagram (Figure 2) as well as the spectral comparison with another cluster member with almost identical stellar parameters (see Figure 3, namely, star #2213, $T_{\text{eff}} = 4821\text{ K}$, $\log g = 2.19\text{ cm s}^{-2}$, $\xi = 1.51\text{ km s}^{-1}$) further advocate that this Li-rich giant belongs to NGC 362.

We find an Al abundance of $[\text{Al}/\text{Fe}] = 0.08$ dex, which according to the definition by, e.g., Carretta et al. (2009) and Paper I suggests that our Li-rich giant is a member of the first generation of the cluster population.¹¹ A similar result was found by Smith et al. (1999), who derived high O and low Na and Al abundances for their Li-rich giant V2. Both IV-101 and V42 seem to show a (modest) Na enrichment and probably belong to the second generation of their respective clusters. Given the quite limited sample we are currently dealing with, statistics on the occurrence of Li-rich stars among the different

⁸ IRAF is the Image Reduction and Analysis Facility, a general purpose software system for the reduction and analysis of astronomical data. IRAF is written and supported by National Optical Astronomy Observatories (NOAO) in Tucson, Arizona.

⁹
$$\log \frac{g}{g_{\odot}} = \log \frac{M}{M_{\odot}} - \log \frac{L}{L_{\odot}} + 4 \log \frac{T_{\text{eff}}}{T_{\text{eff},\odot}}$$

¹⁰ <http://kurucz.harvard.edu/grids.html>

¹¹ A discussion on the multiple population phenomenon in GCs is not the purpose of the current manuscript; we refer the reader to recent reviews by Gratton et al. (2012) and Piotto et al. (2012) for spectroscopic and photometric perspectives, respectively.

Table 1
Stellar Parameters, Kinematics, and Chemical Information for Star #15370

Star ID	R.A. (hh:mm:ss)	Decl. (°:':")	B (mag)	V (mag)	K_s (mag)	V_{rad} (km s ⁻¹)	S/N (@6708 Å)	T_{eff} (K)	log g (cm s ⁻²)	ξ (km s ⁻¹)	A(Li) _{LTE} dex	A(Li) _{NLTE} dex	[Al/Fe] dex
15370	01:03:43.9	-70:52:20.9	16.052	15.233	12.944	233.47	190	4812	2.18	1.52	2.55	2.42	0.08

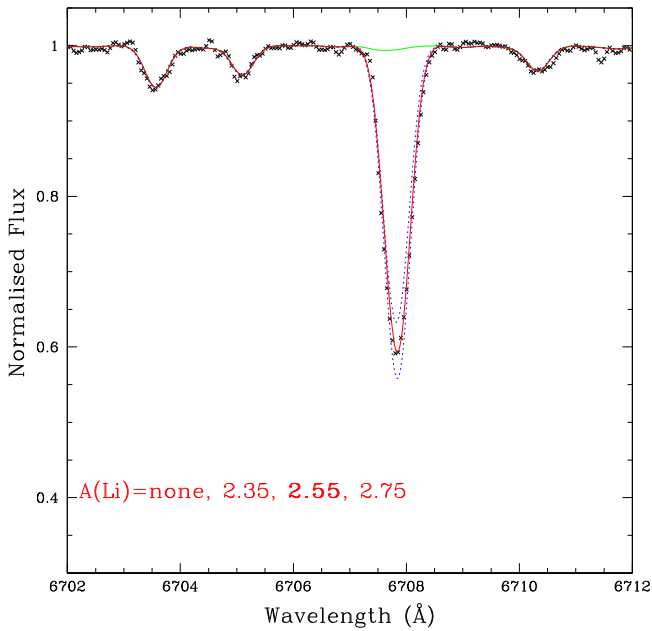


Figure 1. Spectral synthesis of the Li I line at 6707.78 Å for our target star.

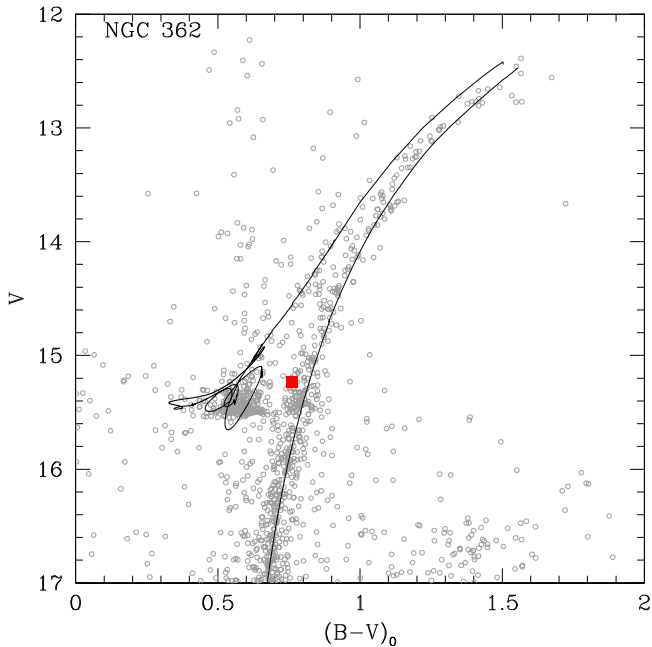


Figure 2. Color-magnitude diagram for NGC 362 (Momany et al. 2004). The target star is emboldened.

stellar populations in GCs are not meaningful. We hope that the dedicated surveys will lead to a higher number of detections and help with such analyses.

One possible explanation for the formation of Li-rich K giants is by accretion of planets and/or brown dwarfs (Siess & Livio 1999). Given the high Li abundance of $A(\text{Li}) \approx 2.5$ dex, this scenario seems unlikely for our star because it would require the ingestion of a very massive companion. Giants during this phase of evolution typically have a convective envelope of $\sim 0.5 M_{\odot}$. To account for the observed Li abundance, star #15370 needs to have engulfed a companion with a mass of at least $\approx 1.0 M_{\odot}$ (using Equation (2) given by Siess & Livio 1999 and adopting a Li content for the donor star

of 2.55 dex, which is already an unusually high value with respect to the Spite plateau). Such a big accretion event should also result in increased rotational velocity and/or an enhanced level of chromospheric activity (see, e.g., Drake et al. 2002; Hurley et al. 2002), which is not evident from our spectra (at least within the limits imposed by the quality of our data).

de La Reza et al. (1996, 1997) proposed a model connecting the high Li abundances observed in K giants to the evolution of circumstellar shells. In this framework, the internal mechanism responsible for the Li enrichment will initiate a prompt mass-loss event. Empirical evidence for this paradigm has not been forthcoming (e.g., Fekel & Watson 1998). We inspected our spectra around the $H\alpha$ feature, looking for possible blueshifted asymmetry as a hint of enhanced (gas) mass loss. Within the limit of our signal-to-noise ratio (S/N) and resolution, we did not discover any asymmetry in the $H\alpha$ profile of star #15370 compared to other Li-normal giants with similar atmospheric parameters. In this respect, we confirm results published by Monaco et al. (2011) and Lebzelter et al. (2012).

The literature offers two alternative scenarios that are consistent with our object.

- (i) Star #15370 belongs to the class of Li-rich giants described by Charbonnel & Balachandran (2000) that are synthesizing Li at the beginning of the RGB bump phase. After the hydrogen-burning shell removes the composition discontinuity left behind by first dredge-up, some extra-mixing process facilitates Li production via the Cameron & Fowler mechanism. Subsequently, once the mixing deepens enough to convert additional ^{12}C to ^{13}C , the surface material is exposed to temperatures that are too high, and the fresh Li is quickly destroyed. Thus, the Li-rich phase is swift and a star will not retain its peak Li abundance once the $^{12}\text{C}/^{13}\text{C}$ drops below the standard value (Charbonnel & Balachandran 2000). Parametrized analyses, unsurprisingly, require that these stars have unusually large diffusion coefficients to allow for the rapid transport of ^7Be (Sackmann & Boothroyd 1999; Denissenkov & Herwig 2004).
- (ii) A second possibility is that the production of Li might have occurred during the helium flash (Kumar et al. 2011) or gradually as the star approached the RGB tip due to some kind of extra mixing (Lattanzio et al. 2015). Asteroseismic analysis of KIC 5000307 by Silva Aguirre et al. (2014) has identified this Li-rich field star as clearly undergoing core helium burning. An analogous scenario for star #15370 would require that it is actually a pre-zero-age horizontal branch (ZAHB) star. A close inspection of the color-magnitude diagram indicates that the star is located on the blue side of the RGB and its position is not inconsistent with theoretical predictions of pre-ZAHB evolution published by Silva Aguirre et al. (2008).

As a further check, we have run evolutionary models using MONSTAR (Monash Version of the Mt. Stromlo evolution code; see Angelou et al. 2012). For our model we assumed a metallicity of $[\text{Fe}/\text{H}] = -1.26$ dex, an α -element enhancement of $[\alpha/\text{Fe}] = 0.2$, and initial mass of $0.81 M_{\odot}$ corresponding to a main-sequence turn off age of 11.5 Gyr (Dotter et al. 2011). As can be seen from Figure 2, the star's location is best explained by RGB evolutionary tracks. We note that although the star is (slightly) on the blue side of the giant branch it is still somewhat

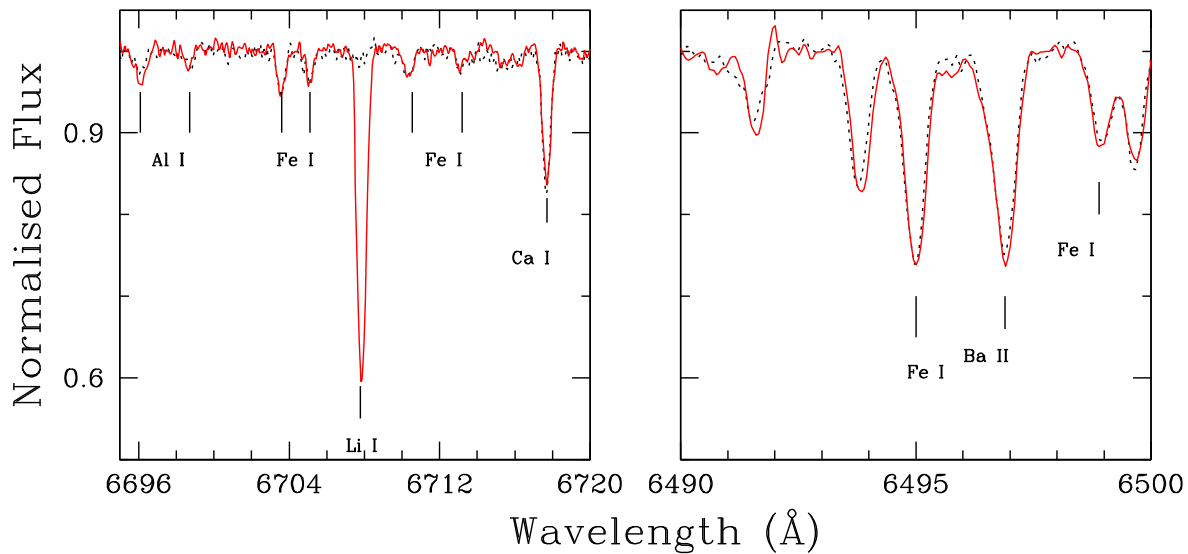


Figure 3. Spectral comparison for stars #15370 and #2213.

removed from the cluster HB. However, in order to unequivocally determine the evolutionary phase, we plan to acquire high-resolution ($R \approx 40\,000$), high S/N spectra (≥ 100) of our target star along with one of its siblings to derive their carbon isotopic ratios $^{12}\text{C}/^{13}\text{C}$. In principle, differences in Fe II lines would also provide us with evidence of a slightly different gravity for #15370—an indication that the star experienced mass loss at the tip of the RGB branch (a difference in mass of approximately $0.2 M_{\odot}$ implies a difference in gravity of about 0.10 dex).

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