THE SUPER LITHIUM-RICH RED GIANT RAPID ROTATOR G0928+73.2600: A CASE FOR PLANET ACCRETION?

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ABSTRACT

We present the discovery of a super lithium-rich K giant star, G0928+73.2600. This red giant (Teff = 4885 K and log g = 2.65) is a fast rotator with a projected rotational velocity of 8.4 km s−1 and an unusually high lithium abundance of A(Li) = 3.30 dex. Although the lack of a measured parallax precludes knowing the exact evolutionary phase, an isochrone-derived estimate of its luminosity places the star on the Hertzsprung–Russell diagram in a location that is not consistent with either the red bump on the first ascent of the red giant branch or with the second ascent on the asymptotic giant branch, the two evolutionary stages where lithium-rich giant stars tend to cluster. Thus, even among the already unusual group of lithium-rich giant stars, G0928+73.2600 is peculiar. Using 12C/13C as a tracer for mixing—more mixing leads to lower 12C/13C—we find 12C/13C = 28, which is near the expected value for standard first dredge-up mixing. We can therefore conclude that “extra” deep mixing has not occurred. Regardless of the ambiguity of the evolutionary stage, the extremely large lithium abundance and the rotational velocity of this star are unusual, and we speculate that G0928+73.2600 has been enriched in both lithium and angular momentum from a sub-stellar companion.

Key words: stars: abundances – stars: chemically peculiar – stars: rotation

1. INTRODUCTION

The expected abundance of lithium, A(Li)5, in the stellar atmosphere of a red giant star depends on many factors, including the stellar mass and the current evolutionary stage. It is well understood that lithium should be destroyed as the deepening convective layers of evolving red giants mix the lithium into the hot interior of the star, diluting the surface abundance (Iben 1967). Depleted lithium is then expected throughout most of the red giant phase. In stars more massive than 1.5 M⊙ and more luminous than ∼104L⊙, temperatures at the base of the convection envelopes are hot enough for the nucleosynthesis of 7Li through the Cameron–Fowler chain, and if the convective mixing time is faster than the lithium destruction time, an abundance of lithium can be built up in the envelope (Scalo et al. 1975). Stars meeting these requirements are generally late in the second ascent, i.e., the asymptotic giant branch (AGB) stage.

Contradicting these theoretical expectations are the many red giant stars that show A(Li) values that either exceed or fall short of the anticipated value. First-ascent, low-mass stars, for example, generally show far more lithium depletion than the standard dilution models (Brown et al. 1989); the A(Li) in these stars point toward additional mixing processes beyond the standard model predictions. Even more surprising are the stars for which A(Li) exceeds not only the standard dilution model predictions, but also the upper limit of primordial abundance measured from the meteorites in our solar system—A(Li) = 3.28 (Lodders et al. 2009). These stars are difficult to account for, especially stars on the red giant branch (RGB), which have convection envelopes that are too cool to regenerate lithium. A special mixing mechanism, termed “cool-bottom processing” (CBP; Sackmann & Boothroyd 1999), is needed both to get material below the convection zone to layers hot enough for the Cameron–Fowler process to work and then to transport lithium back into the convection zone where regular convective mixing can rapidly distribute fresh lithium throughout the stellar envelope.

Clues to identifying the physical mechanism responsible for CBP can be found by looking at the properties of stars that show unusual lithium enhancements. Charbonnel & Balachandran (2000), hereafter C00, and Reddy & Lambert (2005) noted that super lithium-rich giants tend to cluster in the Hertzsprung–Russell (H–R) diagram in two groups. The first group is near the red bump (or luminosity bump), which is an evolutionary stage of low-mass stars on the RGB when the outward hydrogen-burning shell reaches the chemical discontinuity left behind by the convection zone at the peak depth of first dredge-up. C00 hypothesized that in this phase, low-mass stars may go through a short-lived burst of lithium production that is quickly diluted. The other lithium-rich group seen in the C00 study is on the early AGB, at log L/L⊙ ∼ 2.8. These AGB stars are more massive and did not go through a red bump stage while on the RGB.

Sackmann & Boothroyd (1999) studied the effects of CBP on the surface abundances of light elements by including parameterized models of CBP in red giant stars at the red bump. They found that, depending on the mixing geometries, CBP can explain both the general destruction of light elements and the occasional creation of 7Li. However, they did not provide a physical mechanism behind their parameterized model. Rotation was thought to be a likely candidate mechanism until Palacios et al. (2006) found that a self-consistent model of rotational mixing could not generate enough circulation to be responsible for CBP. A recent paper by Palmerini & Maiorca (2010) summarized various mechanisms that have been explored as the physics of CBP and noted that the two current contenders are thermohaline mixing (Eggleton et al. 2006; Charbonnel &
Zahn (2007) and magnetic buoyancy (Guandalini et al. 2009). Because thermohaline mixing is a relatively slow process, it is generally invoked only to explain additional lithium depletion; the mixing may be too slow to bring fresh lithium to the stellar envelope. The magnetic buoyancy models are fast enough and can work both at the red bump and on the AGB; however, both the Guandalini et al. (2009) and Palmerini & Maiorca (2010) models have maximum lithium enrichments of $A$(Li) $\sim$2.5 dex—well short of the lithium abundances observed in the most lithium-rich red giants.

A useful tool for tracking the amount of mixing in a star that may have regenerated lithium is $^{12}\text{C}/^{13}\text{C}$ because both lithium and $^{12}\text{C}/^{13}\text{C}$ are reduced during mixing episodes in the absence of the Cameron–Fowler mechanism. Consequently, small values of $^{12}\text{C}/^{13}\text{C}$ are expected when extra mixing processes succeed in replenishing lithium in red giant atmospheres. In light of this expectation, the most unusual stars are those with relatively large values of $^{12}\text{C}/^{13}\text{C}$, which suggests standard mixing, and super Li-rich abundances (near or above the meteoritic value).

While much theoretical work on mixing processes focuses on trying to understand the two groups of lithium-rich giants identified in C00, it is worth noting that dividing the lithium-rich giants into two categories may still be too simple of a picture. A recent review of lithium in red giants by Smith (2010) highlights examples of lithium-rich giants at many different phases along the RGB; many physical processes may be contributing to the population of lithium-rich giants.

In this Letter, we announce a discovery of just such an unusual lithium-rich star, G0928+73.2600, which was originally selected from the Grid Giant Star Survey (Patterson et al. 2001) for a spectroscopic survey of slow and rapid rotator RGB stars collected for chemical abundance studies. This star has $A$(Li) $= 3.30$ dex and $^{12}\text{C}/^{13}\text{C} \sim 28$, and it does not fall into either of the lithium-rich groups identified in C00. The star also has enhanced rotation, with $v\sin i = 8.4$ km s$^{-1}$. We place this star in context of the other known lithium-rich giants and lithium-regeneration mechanisms. In Section 2, we describe the observations and stellar parameter/abundance analysis of G0928+73.2600. Section 3 provides a comparison of the evolutionary phase of G0928+73.2600 to other known Li-rich stars and discusses implications for the mechanism responsible for the excess lithium. Our conclusions are presented in Section 4.

2. OBSERVATIONS AND ABUNDANCE MEASUREMENTS

Two high-resolution spectra of G0928+73.2600 were obtained with the echelle spectrograph on the Kitt Peak Mayall telescope, at signal-to-noise ratio (S/N) $> 100$ per pixel and $R \sim 43,000$. The spectra were reduced using standard IRAF procedures and the echelle orders combined and continuum corrected to create two normalized one-dimensional spectra.

Stellar abundances were derived using the MOOG stellar line analysis program (Sneden 1973) and MARCS spherical stellar atmosphere models (Gustafsson et al. 2008). A set of 73 Fe I lines constrained the effective temperature and microturbulence at the point where there is no trend of iron abundance with either excitation potential or reduced equivalent width. Thirteen Fe II lines constrained surface gravity. The line list was compiled from a variety of sources including the Vienna Atomic Line Database (Piskunov et al. 1995) and Mandell et al. (2004). Table 1 shows the stellar parameters derived from each spectrum. The average solution for G0928+73.2600 is $T_{\text{eff}} = 4885 \pm 30$ K, $\log g = 2.65 \pm 0.1$ dex, $[\text{Fe/H}] = -0.25 \pm 0.03$ dex, and $\xi = 1.46 \pm 0.10$ km s$^{-1}$.

The rotational broadening was derived from the Fe I line at 6750.15 Å, which was chosen because it is in the same spectral order as the Li I line and is free from blending. Instrumental broadening was measured from the ThAr spectrum. The macroturbulent broadening, $\xi = 5.62$ km s$^{-1}$, comes from the temperature relation of Hekker & Meléndez (2007) for class III giants. With $\xi$ and instrumental broadening fixed, we used a $\chi^2$-minimization routine to find the rotationally broadened synthetic spectrum that fit best, yielding $v\sin i = 8.4$ km s$^{-1}$ for G0928+73.2600.

Finally, to measure the lithium abundance, we used spectral synthesis to fit the spectral region around the Li I line region at 6707 Å, as illustrated in Figure 1, using the line list published in Ghezzi et al. (2009). Free parameters in the fit include $A$(Li) and small adjustments in the overall continuum level, velocity solution, and broadening to get the best fit. From this analysis, we find an LTE solution of $A$(Li) = 3.62 $\pm$ 0.07 dex for G0928+73.2600, which required reducing $\xi$ to 3.0 km s$^{-1}$. The quoted error in $A$(Li) includes contributions from both the fitting procedure and variations within the errors of the stellar parameters. The latter were computed by holding the equivalent width associated with the lithium abundance constant and adjusting the stellar parameters within the error bars to see how $A$(Li) varied. We found that temperature introduced the largest error at 0.04 dex. Finally, we computed non-LTE corrections to the lithium abundance by interpolating the Lind et al. (2009) grid of corrections to our stellar parameters. These corrections yield a non-LTE Li abundance of 3.30 dex.

Table 1

| Obs. Date | $T_{\text{eff}}$ (K) | $\log g$ | $[\text{Fe/H}]$ | $\xi$ (km s$^{-1}$) | $v\sin i$ (km s$^{-1}$ m) | $A$(Li)$_{\text{LTE}}$ | $A$(Li)$_{\text{NLTE}}$ |
|-----------|---------------------|---------|----------------|---------------------|------------------------|---------------------|------------------------|
| 2007-03-06 | 4900.2 | 2.7 | -0.26 | 1.51 | 8.4 | 3.62 | 3.296 |
| 2008-01-11 | 4870.2 | 2.6 | -0.23 | 1.41 | ... | 3.61 | 3.308 |
| Mean | 4885 | 2.65 | -0.245 | 1.46 | 8.4 | 3.62 | 3.30 |

Figure 1. Fit from MOOG to the lithium resonance lines at 6707.8–6707.9 Å in the 2007 spectrum. The data are the small circles, and the lines show the best-fit $A$(Li) (dotted) and 0.1 dex above (dashed) and below (solid) the best fit.
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Figure 2. Fit to CN lines in the G0928+73.2600 spectrum. The observed data, a sum of the 2007 and 2008 spectra, are plotted as circles. The lines show synthetic spectra for carbon ratios of 28 (solid, the best fit), 20 (dotted), and 50 (dashed). The gray dash-dot lines show an atlas telluric spectrum shifted in velocity to the stellar rest frame. Note that the $^{13}$CN lines are free of telluric contamination.

We measured $^{12}$C/$^{13}$C using spectral synthesis of the CN features between 8001 and 8006 Å. Because of the lower S/N in this part of the spectrum, we added the two observations together to increase the S/N. Our fitting routine allows for variations in the carbon ratio, C and N abundances (keeping C/N fixed at 1.5), velocity, and overall scaling. Figure 2 shows the summed spectrum of G0928+73.2600. The lines between 8003 and 8004.3 Å are $^{12}$CN features, whereas $^{13}$CN forms the lines near 8004.7 Å. We measure a best-fit $^{12}$C/$^{13}$C of 28 ± 8 from this spectrum. The weak $^{13}$CN lines are responsible for the large error bars.

3. DISCUSSION

As mentioned earlier, $^{12}$C/$^{13}$C can be used as a tracer for mixing in giant stars. Early stellar models predict post first dredge-up carbon ratio values near 23 (Sweigart et al. 1989). More recent models of mixing in red giant stars indicate that post first dredge-up values of $^{12}$C/$^{13}$C for 1 and 2 $M_\odot$ stars range from 29.5 to 22.3, respectively (Eggleton et al. 2008). Empirical measurements verify these models; Gilroy & Brown (1991) found $^{12}$C/$^{13}$C ~ 22 for giants at the end of first dredge-up, and even lower values near the RGB tip. Therefore, G0928+73.2600 has a measured $^{12}$C/$^{13}$C that is comparable, though slightly higher than model predictions and empirical values for giants, suggesting that this particular star may not have completed the first dredge-up. However, we note that the error bars make it difficult to be certain of these conclusions. The carbon ratio is certainly not very low.

How unusual is the combination of both high lithium and a $^{12}$C/$^{13}$C of 28? To answer this question, we plot literature values of red giant stars (and some main-sequence stars) in Figure 3. To properly compare these data to our own, we remove any previous NLTE corrections made to the lithium measurements and apply the Lind et al. (2009) corrections ourselves. We also plot two standard models of lithium dilution and decreasing $^{12}$C/$^{13}$C in RGB evolution; these models are adapted from Figure 9 of Lambert et al. (1980). Most of the giant stars fall in the lithium–carbon ratio space delimited by the two models. For lithium levels exceeding the primordial abundance of 3.28 dex, all but two stars have $^{12}$C/$^{13}$C lower than 20; G0928+73.2600 and HD 9746.

To gain a deeper understanding of the evolutionary stage of G0928+73.2600, we plot its stellar parameters together with Girardi et al. (2000) isochrones in Figure 4. Of the isochrones plotted, the one most consistent with the location of G0928+73.2600 is log $t$ = 9; note that this isochrone has no red bump (marked by the filled circles) because the stars are of relatively higher mass than the older isochrones. Because of the error bars on G0928+73.2600’s stellar parameters, it is uncertain whether the star is on the RGB, horizontal branch, or AGB. Nevertheless, we can use the isochrones to estimate a reasonable range of luminosity despite not knowing the distance. The ranges of stellar masses and luminosities overlapping the
temperature and gravity of G0928+73.2600 in the upper panel of Figure 4 are 2.0–2.2 $M_\odot$ and $\log L/L_\odot \sim 1.6$–1.9. Using these estimates, we plot G0928+73.2600 on the H-R diagram in the bottom panel of Figure 4 together with the same isochrones. For stars in the estimated mass range of G0928+73.2600, lithium dilution is expected to begin at $T_{\text{eff}} \gtrsim 5000$ K, first dredge-up ends at $\sim 4600$ K, and the red bump for stars just below our estimated mass range occurs at $\sim 4400$ K (see C00, particularly Figure 1). Consequently, G0928+73.2600 is an oddity; it is cool enough that it should be well into its lithium dilution stage, yet it is either too massive to even evolve through the red bump or too hot to have reached the red bump if it is less massive than our estimate. The star’s $^{12}$C/$^{13}$C combined with the mass estimate suggests that G0928+73.2600 has not yet completed first dredge-up—Eggleton et al. (2008) predict $^{12}$C/$^{13}$C = 22.3 for a 2 $M_\odot$ star. This fact places the likely evolutionary stage on the first ascent RGB star before the red bump.

Recalling HD 9746, the other star sharing a similar position in Figure 3 as G0928+73.2600, we find that G0928+73.2600 is again the odd-star out. HD 9746 is listed in C00 as one of the red bump lithium-rich stars, whereas G0928+73.2600 cannot be part of this group. We must therefore consider anew the possible explanations for enhanced lithium in giant stars. We already know that G0928+73.2600 should be well into the phase of lithium dilution, yet the lithium abundance is near its main-sequence value (see, for example, Figure 6 of Luck & Heiter 2006).

Generally, large lithium abundances in giant stars can be explained by suppressed lithium dilution, lithium regeneration, and lithium replenishment. The first scenario is ruled out by the $^{12}$C/$^{13}$C; mixing on the level of standard first dredge-up has occurred, i.e., $^{12}$C/$^{13}$C $\ll$ 89, the main-sequence value. Lithium regeneration has been explored by Sackmann & Boothroyd (1999); their model of parameterized CBP can regenerate lithium at this level. Figure 9 of their paper shows predictions for $A$(Li) as a function of RGB luminosity for a number of their models; however, lithium enhancements of the level seen in G0928+73.2600 occur in their models for only the most luminous RGB stars—higher than that of G0928+73.2600. Admittedly, their predicted luminosities for the lithium-rich stars also exceed that of observed stars in C00. The magnetic buoyancy models of both Guandalini et al. (2009) and Palmerini & Maiorca (2010) can also regenerate lithium, but their models predict a maximum $A$(Li) of about 2.5 dex—much lower than what is found in G0928+73.2600.

We also note that G0928+73.2600 is rotating rapidly for a giant star, with $v\sin i = 8.4$ km s$^{-1}$ when most stars of this type generally rotate with $v\sin i < 2$ km s$^{-1}$ (de Medeiros et al. 1996). This enhanced rotation may be relevant to the lithium-regeneration models if it can create the favorable circumstances needed in the Sackmann & Boothroyd (1999) model by, for example, increasing the mixing speeds. On the other hand, recall that Palacios et al. (2006) found that rotational mixing is not efficient enough to create lithium-rich stars. In either case, one must consider the origin of the excess angular momentum implied by the moderately fast rotation.

We speculate that the increased angular momentum and the trigger for lithium regeneration could be related to the accretion of a planet. Siess & Livio (1999) computed detailed models of the effects of planets falling into their host stars and found that, if anything, lithium is depleted even more rapidly. However, Siess & Livio admit the possibility that planet accretion could trigger the de La Reza et al. (1996) model, where lithium regeneration is associated with a period of mass loss and ejection of a circumstellar shell.

The planet accretion line of reasoning naturally leads to the third scenario of creating lithium-rich giant stars: lithium replenishment. Planet accretion was first put forward by Alexander (1967) to explain lithium enrichment in giant stars and has been invoked by many authors since then to explain both lithium enhancements and rapid rotation in giant stars (see, e.g., Wallerstein & Sneden 1982; Reddy et al. 2002a; Drake et al. 2002; Carney et al. 2003; Denissenkov & Herwig 2004). On the main sequence, Israelian et al. (2001) found evidence of accreted planetary material in the detection of $^6$Li in HD82943 (although other authors, e.g., Reddy et al. 2002b; Ghezzi et al. 2009, cannot reproduce the detection).

G0928+73.2600’s evolutionary status is consistent with the models of Carlberg et al. (2009) that predicted that enhanced rotation from planet accretion is most likely found on the lower RGB. The rotation of G0928+73.2600 could be reproduced by a planet with $M_p\sin i$ as low as 2 $M_{\text{Jup}}$ for an initial orbital separation of 1 AU. An accreted planet can contribute lithium to the star from its own stores, but an expected upper limit to the planetary contribution is again the primordial lithium abundance of 3.28 dex. This limit can only be exceeded if the planet has undergone chemical fractionation and is therefore enhanced in lithium itself. To reach the lithium abundance seen in G0928+73.2600, we calculate that an accreted planet must have had $A$(Li)$_p = 3.30 + \log(1 + M_{\text{env}}/M_p)$. For a 2 $M_{\text{Jup}}$ planet and assuming 80% of the stellar mass is in the envelope, this equation gives $A$(Li)$_p = 6.23$, which implies 850 times more lithium per hydrogen in the accreted object compared with our solar system’s planets. A further test of this hypothesis would be to measure the abundance of other light elements, such as boron or beryllium. These elements should also be enriched if accreted planetary material is responsible for the lithium enhancement. Searches for beryllium enrichments were carried out for a small number of lithium-rich stars (Castilho et al. 1999; Melo et al. 2005), but no enhancements were found.

4. CONCLUSION

G0928+73.2600 joins the ranks of lithium-rich giant stars, and it may even be unique in this already unusual class. The near-primordial lithium abundance suggests that either lithium depletion never began or, more likely, some replenishment mechanism has taken place. However, this star’s stellar parameters put it outside of the other groups of lithium-rich stars—the red bump stars or the AGB stars—for which models of lithium regeneration exist. G0928+73.2600’s evolutionary stage is consistent with either the base of the RGB or the beginning of the AGB. It is unusual for lithium regeneration to have recently occurred at either phase. The star’s rotational velocity is higher than most red giant stars, and we suggest that this could be explained by the accretion of a planet. Planet accretion may have triggered the lithium regeneration needed to explain the lithium abundance observed in the star. Alternatively, the accretion of an extremely lithium-rich planet can account for the lithium enrichment of G0928+73.2600, its enhanced rotation, and its pre-bump evolutionary stage.

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