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LITHIUM IN A COOL RED GIANT MEMBER OF THE GLOBULAR CLUSTER NGC 362

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ABSTRACT

A surprisingly strong Li i λ6707 feature has been identified in a red giant member of the globular cluster NGC 362. This giant, V2, is located near the tip of the red giant branch and could be either a first-ascent red giant or on the asymptotic giant branch. An abundance analysis finds the lithium abundance to be log ϵ(Li) = 1.2 ± 0.2. Since almost all low-mass giants have destroyed and diluted their photospheric lithium abundances to much lower levels, the source of lithium in star V2 is a mystery. The solution to this mystery is suggested to reside in two possible mechanisms. The proposed deep-mixing mechanism called "cool bottom processing" can account for the observed lithium at this giant's luminosity [log $(L/L_\odot) = 3.3$] if the parameterized mixing speed, measured as log (dM/dt), is ∼−5.5 (in units of $M_\odot$ yr^{-1}). An alternative source of the excess lithium could be the ingestion, into the red giant's convective envelope, of an ∼0.04 $M_\odot$ object with an assumed undepleted, typical halo lithium abundance of log ϵ(Li) = 2.2.

Subject headings: Galaxy: general — globular clusters: individual (NGC 288, NGC 362) — stars: abundances

1. INTRODUCTION

Since the initial discovery of a K giant with a strong Li i λ6707 resonance line by Wallerstein & Sneden (1982), it has been found that ∼1% of field G and K giants possess relatively strong Li i features (Brown et al. 1989). A number of additional Li-rich red giants have been found in surveys by de la Reza et al. (1997). Standard red giant first dredge-up theory predicts substantial lithium depletion: for a recent review of this phase of stellar evolution, see Wallerstein et al. (1997). Many observations, of both Li and $^{12}C/^{13}C$ ratios in red giants, suggest that the mixing during and after first dredge-up is even more extreme than standard models predict, especially in the lower mass stars ($M \leq 2.5\ M_\odot$) (see, e.g., Gilroy 1989; Gilroy & Brown 1991; Suntzeff & Smith 1991; Shetrone, Sneden, & Pilachowski 1993). The extreme mixing observed in the lower mass red giants suggests that some type of extramixing, leading to the partial processing of the envelope, must occur in these stars during evolution on the red giant branch (RGB).

The suggestion of extramixing, along with the observed small percentage of Li-rich red giants, has led to the hypothesis that under certain conditions of extramixing, lithium production, not destruction, can occur. This production arises from a mechanism first suggested by Cameron & Fowler (1971) and involves the reaction $^3He(^4He, \gamma)^7Be$. In an environment in which the ^7Be can be rapidly convected outward and undergo an e^- capture to ^7Li, the resulting envelope lithium abundance can be increased. It is known that this type of reaction occurs in the most luminous asymptotic giant branch (AGB) stars and can result in substantial ^7Li production (Smith & Lambert 1989, 1990; Sackmann & Boothroyd 1992). Lithium 7 production via the "Cameron Fowler" mechanism requires temperatures of a few times 10^7 K. In a low-mass star on the RGB, regions that experience such high temperatures are not expected to be in contact with the surface. Extramixing mechanisms in low-mass RGB stars have been proposed and investigated by a number of authors, e.g., Sweigart & Mengel (1979), Charbonnel (1995), and Sackmann & Boothroyd (1999). Wasserburg, Boothroyd, & Sackmann (1995) also investigated extramixing in low-mass RGBs to explain carbon and oxygen isotopic ratios (but did not model Li) and coined the term cool bottom processing (CBP) as a label for this mixing; this term has since come into popular use.

In CBP, a certain fraction of envelope material is circulated at some mixing rate through to deeper layers of the red giant than predicted by standard models of convection. This deeper mixing can lead to ^7Li production under certain conditions and is a possible explanation for the Li-rich RGB stars. Important stellar parameters involved in CBP models include the red giant's luminosity, mass, and metallicity. A number of Li-rich field red giants are known; however, their intrinsic luminosities and masses are very uncertain. Red giant members of clusters (either open or globular) have much more accurately known masses and luminosities when compared to field giants, so any Li-rich RGB members of clusters would provide important tests to the CBP models. We report here on the detection and abundance analysis of a red giant member of the globular cluster NGC 362 that has a strong Li i λ6707 feature.

2. OBSERVATIONS AND REDUCTION

Observations were conducted at Cerro Tololo Inter-American Observatory using the 4 m Blanco telescope with the echelle spectrograph and the long focal length camera. The resulting spectra have a resolution of $R = 30{,}000$. Three 1200 s exposures of NGC 362 V2 (Sawyer 1931; also known as Tuc 281 [Tucholke 1992] and A129 [Alcaino 1976]) were taken on 1996 September 25. Three 1200 s exposures of NGC 288 531 (Olszewski, Harris, & Canterna 1984; also known as A260 [Alcaino 1975] and V1 [Hogg 1973]), obtained on 1995 October 10, were also included in the analysis since this star has

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a similar color, luminosity, and metallicity to NGC 362 V2. Overscan, bias and dark removal, flat-field correction, scattered light removal, sky subtraction, extraction, and wavelength calibration were done in the standard IRAF NOAO.IMRED.ECHELLE package. The resulting combined spectra have signal-to-noise ratios of 74 and 60 at 6708 Å for 531 and V2, respectively.

Both NGC 288 531 and NGC 362 V2 are known variables. Sawyer (1931) found a period of 105.2 days, and Eggen (1972) found a period of 90 days (with an amplitude of ∼0.8 mag in *B*) for NGC 362 V2. Hogg (1973) found NGC 288 531 to be a semiregular variable with a period of 103 days. Photometry for NGC 362 V2 is available in the literature: $(B-V)_0 = 1.56$ and $(V-K)_0 = 3.90$ (Table 3 of Frogel, Persson, & Cohen 1983). Corresponding photometry for NGC 288 531 in the literature has $(B-V)_0 = 1.87$ and $(V-K)_0 = 3.97$ (Table 2 of Frogel et al. 1983). Both of these stars lie near the tip of the red giant branch in their respective clusters. The major spectral differences between these two stars is that NGC 362 V2 has a strong Li I λ6707 line and very strong Hα and Hβ emission, while NGC 288 531 does not. This difference between the Li I lines is illustrated in Figure 1, where spectra of both red giants near the Li I region are shown. The very strong Li I line in V2 is obvious.

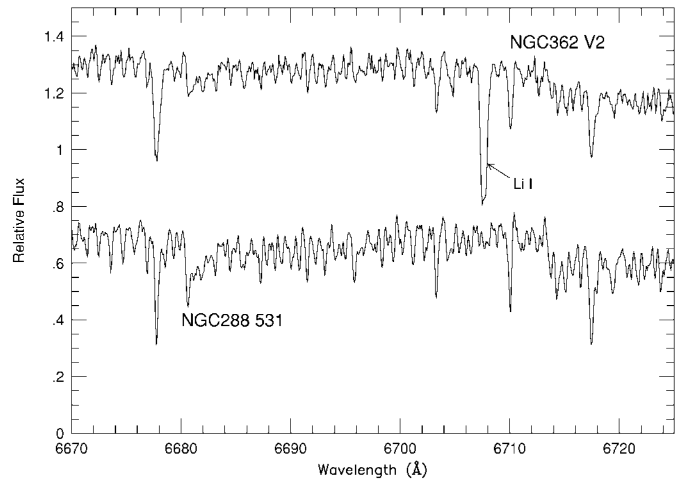

FIG. 1.—Spectra of the red giants V2 in NGC 362 and 531 in NGC 288 are compared. The strong Li I line in V2 is indicated. The spectra have been normalized and offset from each other in relative flux for clarity.

3. THE ABUNDANCE ANALYSIS

An abundance analysis was carried out for stars V2 in NGC 362 and 531 in NGC 288 under the usual assumption of LTE using the most recent version of the spectral analysis program MOOG, first introduced by Sneden (1973). Model atmospheres were interpolated within the standard grid of MARCS models produced by Gustafsson et al. (1975). For red giants, such an abundance analysis is now quite standard and a careful selection of spectral lines can typically produce abundances that are accurate, on an absolute scale, to within about 0.1–0.2 dex.

The first step in this analysis was the determination of the appropriate stellar parameters: effective temperature ($T_{\rm eff}$), surface gravity (parameterized by log g), overall stellar metallicity, and the atmospheric microturbulent velocity (ξ). The effective temperature and surface gravity were derived from a combination of photometry and spectroscopy: the spectroscopic analysis used Fe I and Fe II lines with well-determined laboratory *gf*-values. Using the photometry for star V2 discussed in § 2 from Frogel et al. (1983), we estimate $T_{\rm eff} = 3750$ K using the Ridgway et al. (1980) temperature-($V-K$) calibration. Its $(B-V)_0$ color indicates an estimated $T_{\rm eff} = 3850$ K from our own calibration of published $(B-V)$'s and $T_{\rm eff}$'s for red giants with metallicities of [Fe/H] ~ -1.0 to -1.5. Frogel et al. (1983) derive their own value of $T_{\rm eff} = 3850$ K: all of these determinations are in quite reasonable agreement. The luminosity of V2 is also derived by Frogel et al. with $M_{\rm bol} = -3.52$ or $\log (L/L_\odot) = 3.29$. With an assumed mass of ∼0.8 $M_\odot$ for V2, the expected surface gravity is then $\log g \sim 0.3$.

The above stellar parameters were "fine-tuned" using the numerous Fe I and Fe II lines from the high-resolution spectra. These Fe lines were chosen to be relatively unblended and have accurate laboratory *gf*-values: lines were taken from the critical compilation included in Lambert et al. (1996) and included 28 Fe I and four Fe II lines. Demanding the simultaneous conditions of no slope in plots of Fe abundance (from Fe I) versus both excitation potential and equivalent width yield the effective temperature and microturbulent velocity: $T_{\rm eff} = 3900$ K and $\xi = 2.5$ km s^{-1}. Enforcing ionization equilibrium, such that both Fe I and Fe II yield the same abundance, provides a surface gravity of $\log g = 0.70$. The spectroscopic stellar parameters are not significantly different from those derived from the photometry, and we adopted the spectroscopic parameters for the abundance analysis: using the photometric parameters would not change the derived abundances in any significant way. The final derived Fe abundance is $\log \epsilon({\rm Fe}) = \log [N({\rm Fe})/N({\rm H})] + 12.0 = 6.28$, or [Fe/H] $= -1.23$.

As a check on the analysis, additional elements were analyzed from spectral lines consisting of [O I], Na I, Mg I, Al I, Si I, K I, Ca I, Sc II, Ti I, Ti II, V I, Ni I, Cu I, Zr I, Mo I, Ba II, La II, Ce II, Nd II, and Eu II. The list of lines is too long to include and discuss at length in the format of a Letter, but none of the above listed elements displayed unusual abundances: all were within 0.5 dex of Fe in terms of [X/H]. Star V2 thus does not display an unusual abundance pattern except for the presence of a rather strong Li I λ6707 feature. We do note that the O, Na, and Al abundances in star V2 ([O/Fe] $= +0.25$, [Na/Fe] $= -0.38$, and [Al/Fe] $= -0.50$) are typical of field halo stars at this metallicity and do not show the sometimes large enhancements, which can result from very deep mixing, found in many globular cluster giants (e.g., Kraft 1994).

A similar analysis was conducted on NGC 288 531 as a test of the analysis techniques for these rather cool giants. In this case, $T_{\rm eff} = 3750$ K and $\log g = 0.5$ were derived for star 531 from the Fe I/Fe II analysis (again, in reasonably good agreement with the initial estimates from the photometry). The derived iron abundance for NGC 288 531 is $\log \epsilon({\rm Fe}) = 6.23$ ([Fe/H] $= -1.28$), very similar to NGC 362 V2. As with V2, no apparent extreme abundance peculiarities were noted in the elements mentioned above, with the key deep-mixing indicators O, Na, and Al having [O/Fe] $= +0.30$, [Na/Fe] $= +0.12$, and [Al/Fe] $= +0.06$. It is worth noting that although carbon abundances were not measured in either star, any extramixing could severely deplete the C abundance without affecting significantly the O, Na, or Al abundances (Kraft 1994).

The Li I spectral region was synthesized with a line list compiled for the analysis of M and S stars with lithium (Smith et al. 1995), and this line list includes the numerous TiO lines found in this region. The TiO line list was kindly provided by

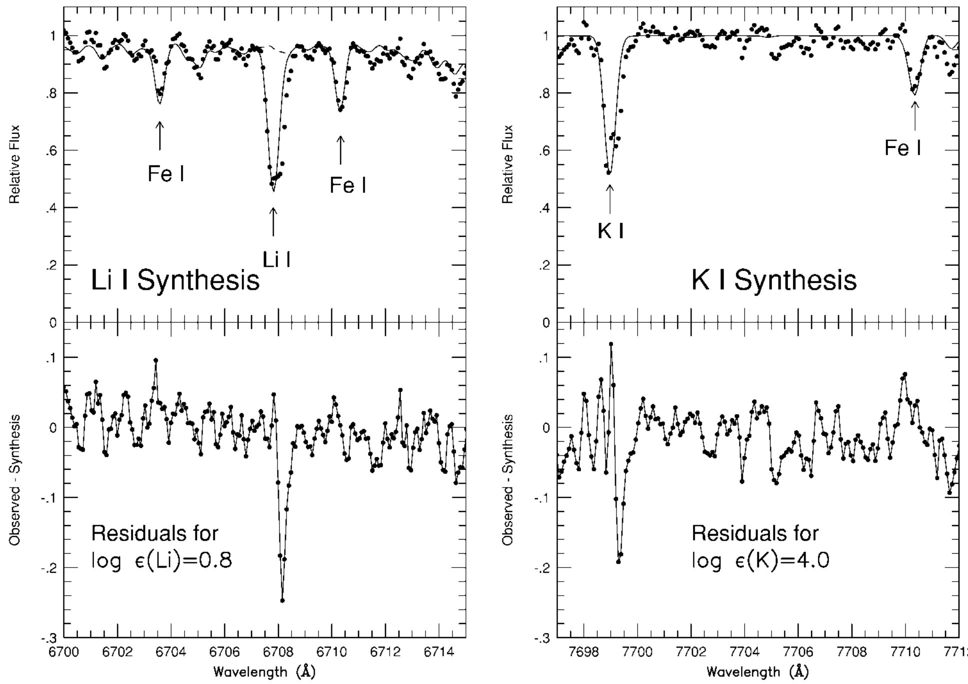

FIG. 2.—Synthetic spectral fits to the Li I region. The observed spectrum is indicated by the circles, while the various syntheses are shown as smooth curves. A best-fit LTE Li abundance is log ϵ(Li) = 0.80, while the other synthesis curve is for no Li.

M. M. Briley and R. A. Bell (1992, private communication). Weak TiO features (less than 10% deep) run through the Li I region in star V2. The observed and synthetic spectra for Li I are shown in the top left-hand panel of Figure 2: continuous curves are the syntheses, and the circles are the observations. In the bottom left-hand panel are shown the residuals (observed − synthesis), and an extra Li I component is obvious: inspection of the observed spectrum itself shows this additional red component. This component is not an artifact of the analysis, as shown in the right-hand panels of Figure 1, in which we show the analogous observed, synthetic, and residual spectra for K I at 7700 Å. The K I resonance line also shows this extra component. We have modeled these spectra as to reveal a slight redshifted component (almost certainly circumstellar) in both K I and Li I. Evidence for circumstellar material and activity is also revealed by the presence of Hα and Hβ emission in the spectra.

Equally good fits to the K I and Li I lines could also be obtained if the respective Li and K abundances were increased so as to broaden the lines. In this case, upon subtraction of the synthesis from the observed spectrum, a near zero-velocity (with respect to the photosphere) emission component can be made to appear. Such a fit, however, would require a large K abundance (such that [K/Fe] = +1.2); since we have no astrophysical reason to expect such a large K overabundance, we accept the smaller K and Li abundances, and the resulting Li abundance is log ϵ(Li) = 0.80. No Li is detected in the comparison star 531 in NGC 288, and the derived upper limit to the abundance is log ϵ(Li) ≤ -0.70.

Modest non-LTE corrections are predicted to LTE lithium abundances derived from the Li I resonance doublet in cool, low-gravity giants (Carlsson et al. 1994). Their non-LTE corrections do not include giants as cool as NGC 362 V2, but an estimated extrapolation of their model calculations indicate that a correction of $\sim+0.4$ dex should be applied to the LTE abundance, or log $\epsilon(\mathrm{Li})_{\mathrm{NLTE}} \sim 1.2$ for NGC 362 V2. The corresponding non-LTE upper limit for NGC 288 531 would then be log ϵ(Li) ≤ -0.30.

4. DISCUSSION

The presence of substantial Li abundances in red giants that are not luminous AGB stars requires a new physical mechanism to explain the lithium. One possible explanation put forth is the extramixing mechanism dubbed cool bottom processing (Wasserburg et al. 1995). Predictions of the Li abundances that result from CBP have been recently presented by Sackmann & Boothroyd (1999). Typically, this mixing is generalized as downward and upward streams of material carried to deeper and hotter layers in the star than predicted in models with standard convection. The speeds of the upward and downward streams might be different, and the mixing might be continuous or discontinuous, or perhaps episodic in nature. We compare our abundance results for Li in NGC 362 V2 with the simplest models, in which the mixing is assumed to be continuous along the RGB, being parameterized by a mixing rate dM/dt. Depending on the mixing rate, the abundance of Li changes with the stars position on the RGB: this RGB position corresponds to a particular luminosity for a given stellar model.

In Figure 3 are shown comparisons of the Li abundances derived for the two globular cluster red giants now known to exhibit strong Li I lines (V42 in M5 from Carney, Fry, & Gonzalez 1998 and V2 in NGC 362 presented here) as a function of luminosity, as well as the Li upper limit for NGC 288 531; predictions from Sackmann & Boothroyd (1999) for a 1 $M_{\odot}$ model with a metallicity 1/20 of solar ([Fe/H] = −1.3 if [O/Fe] is set to 0.0) are shown as the continuous curves. Theoretical predictions are plotted for two mixing rates. In general, the CBP models can successfully predict the Li abundances observed at luminosities corresponding to the globular cluster giants observed to date. Clearly, improved constraints on CBP models will result from Li detections in a number of

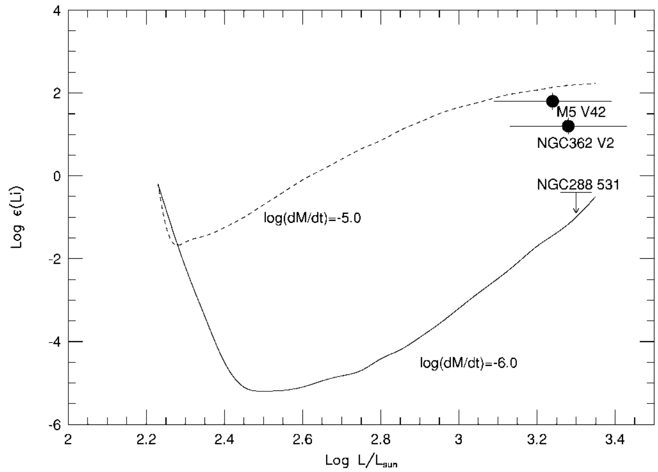

FIG. 3.—Theoretical Li abundances, as a function of luminosity, for low-mass ($M = 1.0\ M_\odot$), low-metallicity ([Fe/H] = −1.3) giant stars with cool bottom processing. The extramixing is parameterized by the different mixing speeds, with two different mixing speeds plotted; these models are from Sackmann & Boothroyd (1999). The Li abundance and luminosity of NGC 362 V2 is shown as well as star V42 from M5 (Carney et al. 1998). The upper limit to the Li abundance in NGC 288 531 is also shown. A mixing speed of about log (dM/dt) ∼ −5.0 to −5.5 can explain the observed lithium abundance under cool bottom processing.

cluster giants spanning a range in luminosity: even upper limits, from high-quality spectra of red giants at lower luminosities, will be of use. In addition, abundances from species involved in H burning (O, Na, Al, or Mg) can provide further constraints on the nature of the mixing in CBP. Star V2 does not show anomalous O, Na, Al, or Mg abundances, which would presumably limit the depth of the mixing necessary to create the Li to layers above the hottest H-burning regions. We point out also that star V2 might be an AGB star, since at these larger luminosities the AGB and RGB tracks are very close.

Although the observed Li abundances can be explained by CBP, the result from de la Reza, Drake, & da Silva (1996) of dust shells associated with the presence of Li in these giants remains something of a mystery. Clearly, the presence of extra Li I and K I absorption components in the spectra of NGC 362 V2 point to circumstellar material, as do the presence of strong Hα and Hβ emission. The origin of this material and its relation to the photospheric Li (if any) remains elusive. An alternative source of Li might be external to the red giant, such as the accretion or ingestion of a substellar mass object (a large planet or brown dwarf) into the red giant's envelope as it evolves up the RGB (at its luminosity, V2 has a radius of ∼0.5 AU). For example, if NGC 362 V2 began life with a halo Li abundance of log ϵ(Li) = 2.2, a substellar mass companion might be expected to have this same Li/H ratio (if it is a large unfractionated planet or brown dwarf; fractionation would complicate the details of the calculation, but not alter the physical picture). Assuming that V2 destroyed virtually all of its initial lithium on the RGB, an estimate of the mass necessary to increase its Li abundance to its currently observed value can be made. With log ϵ(Li) ∼ 1.2 being about 1/10 of the assumed initial (halo) value, V2 would have to ingest an object of roughly 1/10 of its convective envelope mass. If $M_{\rm envelope}$ is ∼0.4 $M_\odot$, then the mass of the accreted object would be of order 0.04 $M_\odot$, or about 40 Jupiter masses. In such a scenario, the accretion of an object of this mass might drive a mass-loss event which would explain the circumstellar material found around many of these Li-rich giants. Accretion might be tested by continuing and careful analyses of additional elements sensitive to mixing, such as C, N, and O, and comparing to other cluster members. We note that the very large Li abundance derived by de la Reza & da Silva (1995) for the K giant HD 19745 might rule out accretion, at least for that particular star. Clearly, extensive searches for Li-rich giants in clusters (both globular and open) is a priority in order to understand the fundamental processes at work here.

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