ON $^7$Li ENRICHMENT BY LOW-MASS METAL-POOR RED GIANT BRANCH STARS

RAMIRO DE LA REZA, 1 LICIO DA SILVA, 1 NATALIA A. DRake, 1, 2 AND MARCO A. TERRA 3

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ABSTRACT

First-ascent red giants with strong and very strong Li lines have just been discovered in globular clusters. Using the stellar internal prompt $^7$Li enrichment–mass-loss scenario, we explore the possibility of $^7$Li enrichment in the interstellar matter of the globular cluster M3 produced by these Li-rich giants. We found that enrichment as large as 70% or more compared to the initial $^7$Li content of M3 can be obtained during the entire life of this cluster. However, because M3 will cross into the Galactic plane several times, the new $^7$Li will be very probably removed by ram pressure into the disk. Globular clusters appear then as possible new sources of $^7$Li in the Galactic disk. It is also suggested that the known Na/Al variations in stars of globular clusters could be somehow related to the $^7$Li variations and that the cool bottom process mixing mechanism acting in the case of $^7$Li could also play a role in the case of Na and Al surface enrichments.

Subject headings: globular clusters: individual (M3) — ISM: evolution — stars: abundances — stars: mass loss — stars: Population II

1. INTRODUCTION

The main purpose of this Letter is to discuss the possibility of $^7$Li enrichment in some components of the Galactic halo in view of recent discoveries of very strong and moderately strong Li giant stars in globular clusters M3 (Kraft et al. 1999), NGC 362 (Smith, Shetrone, & Keane 1999), and M5 (Carney, Fry, & Gonzalez 1998). In general, Galactic chemical evolution models contain the following sources of $^6$Li and $^7$Li enrichment in the halo: Galactic cosmic ray $\alpha$-$\alpha$ nucleosynthesis, the Type II supernova (SN II) $\nu$-process, and the $^7$Be process in intermediate-mass ($3 M_\odot < M < 7 M_\odot$) asymptotic giant branch (AGB) stars (Deliyannis, Boesgaard, & King 1995; Boesgaard et al. 1998; D’Antona & Matteucci 1991; Romano et al. 1999). The $^7$Li detection in two stars, HD 84937 (Smith, Lambert, & Nissen 1993, 1998) and BD +26°3578 (Hobbs & Thorburn 1994, 1997), indicated for the first time that a Galactic source other than a cosmological one was at play, at least in the metallic range of the interstellar matter preceding the formation of stars having [Fe/H] $\sim -2.4$. Cosmic rays have produced $^7$Li in a prestellar interstellar medium by the $\alpha$-$\alpha$ process or directly on stars. This last possibility has been shown, however, to be inefficient (Lambert 1995). Also, the creation of Li on the surface of stars appears to be uncertain (Montes & Ramsey 1998). Difficulties related to $^7$Li formation by SN II $\nu$ and AGB giants are discussed by Boesgaard et al. (1998). They concern the absence of spectral signatures in the Li-enriched dwarf and subgiant stars proving the action of these processes such as the absence of excesses of Mg in the case of SN II and of the $s$-elements in the case of AGB stars. These Li-rich objects, such as the field star BD +23°3912 (King, Deliyannis, & Boesgaard 1996), present an overabundance with respect to the mean $^7$Li abundance of the Spite plateau (Spite & Spite 1982). Observational $^7$Li enrichment in AGB giants that have been discovered in the LMC (Smith & Lambert 1989, 1990) are, however, on a much sounder theoretical basis (Sackmann & Boothroyd 1992; Mazzitelli, D’Antona, & Ventura 1999). It appears interesting to explore the possibilities of a new source of $^7$Li enrichment in systems of Population II stars. This source is the metal-poor low-mass ($M < 2.5 M_\odot$) first-ascent red giant branch (RGB) stars.

2. THE METAL-DEFICIENT GIANT $^7$Li ENRICHMENT PROCESS

Low-metallicity RGB stars are expected to lose a reasonable quantity of mass (0.1–0.2 $M_\odot$) during their first ascent on the giant branch. Considering a timescale to reach the tip of this branch as $2 \times 10^4$ yr (Rood 1972; Kraft et al. 1993), we obtain mean stellar mass losses of the order of $5 \times 10^{-4}$ to $10^{-3} M_\odot$ yr$^{-1}$. It is interesting to note that the same mass-loss rates are present, nevertheless in a discontinued way, in the mass-loss–$^7$Li enrichment scenario proposed by de la Reza, Drake, & da Silva (1996) and de la Reza et al. (1997). In this scenario, all low-mass giants ($M < 2.5 M_\odot$) suffer a prompt $^7$Li enrichment in the upper part of the RGB, after the first dredge-up and before the RGB tip. The internal mechanism producing new $^7$Li forms a circumstellar shell (CS) enriched with $^7$Li, which detaches from the star when the internal process ceases. In this way, the interstellar medium is enriched with $^7$Li. The synchronized expansion of the dusty CS enriched with $^7$Li and the subsequent $^7$Li depletion in star photospheres can be followed by means of closed loops in an IRAS color-color diagram and compared with observed positions of the stars following these loops (de la Reza et al. 1996, 1997). These times measure the “lithium cycles,” which are the periods when strong Li lines are observed. Li cycles of the order of $10^3$–$10^4$ yr have been estimated for a CS expanding velocity of 2 km s$^{-1}$ (de la Reza et al. 1997). Maybe the best mechanism for producing the $^7$Li photospheric enrichment from internal origin for these low-mass giants is the “cool bottom process” (CBP; Sackmann & Boothroyd 1999) based on the $^7$Be production by means of the excess of $^7$He in the H-burning shell characteristic of these low-mass stars. The fresh $^7$Be is transported by a conveyor circulating mechanism up to the base of the convective layer to be then taken to the stellar surface, where it is transformed into $^7$Li. Because the mentioned conveyor mechanism attains deeper and hotter regions in the case of metal-deficient giants, very large $^7$Li surface abundances ($\log \epsilon_7 \sim 4.2$) have been obtained for [Fe/H] $\sim -2.3$ in a short episode (see Fig. 10 in Sackmann...
be presented in the next section, we have calculated the Li abundance of IV-101 in non-LTE (NLTE) by means of the Li i λ6708, λ6104 lines using a new self-consisting methodology for treating chromospheres. Details of this method can be found in Terra (1997) and will be submitted elsewhere (M. A. O. Terra, R. de la Reza, & C. Batalha 2000, in preparation). The obtained $^{7}$Li abundance for IV-101 is log $\epsilon_{Li}$ = 4.0. This NLTE value is an order of magnitude larger than the LTE Li abundance proposed by Kraft et al. (1999) based on the resonant Li i λ6708 line alone.

3. IS THERE A $^{7}$Li–Na/Al ENRICHMENT CONNECTION?

An extensive literature exists on the CNO, Na, and Al variations among globular cluster stars (for a review see, for instance, Kraft 1994). The most remarkable are the Na and Al versus O anticorrelation and the Na and Al versus N correlation. These variations indicate that relatively rapid mixing is taking place. Considering this, we can ask if there is an $^{7}$Li–Na and $^{7}$Li–Al simultaneous surface enrichment. Kraft et al. (1999) have suggested that an Li–Al correlation could be present in some giants of metallicity $[\text{Fe/H}] = -1.5$ in M3. We did not find a similar correlation for mild deficient giants having extremely high $^{7}$Li abundances, as is the case of the high-velocity star PDS 68 ($[\text{Fe/H}] = -0.4$) where no substantial Na enrichment was found (Drake 1998). Substantial Li–Al/Na correlations must exist in very low metal RGB stars because at [Fe/H] $\sim -2.3$ relatively similar internal star regions produce large increases of $^{23}$Na and $^{27}$Al (from the seed elements $^{20}$Ne and $^{28}$Mg, respectively; Cavallo, Sweigart, & Bell 1996) and that of $^{7}$Li (from the seed element $^{3}$He; Sackmann & Boothroyd 1999). The cool bottom processing proposed by Sackmann & Boothroyd for low-mass giants producing the large surface Li enrichments could also play an important role concerning the Na and Al enrichment variations. If this is the case, an $^{7}$Li–Al/Na connection will be independent from any stellar interactions owing to high stellar density in globular clusters and will also be valid for field stars. Fujimoto, Aikawa, & Kato (1999) have suggested another scenario to explain Na/Al variations (not $^{7}$Li) in globular cluster stars by means of shell flashes induced by deep H mixing provoked by star-star interactions in a dense cluster.

4. ON THE $^{7}$Li PRODUCTION IN M3

We calculate here the enrichment of new $^{7}$Li in the interstellar matter of M3 produced by low-mass giant stars ($M < 2.5$ $M_{\odot}$). These stars are considered to be second-generation stars formed by matter already enriched in a large part of heavy elements by a first generation of high-mass, short-life stars. The prompt $^{7}$Li enrichment–mass-loss scenario used here will enter into action only when the first giants of mass $\sim 2.5$ $M_{\odot}$ appear in M3; that is after 10$^{7}$ yr, which is a small fraction of the lifetime of the globular cluster. Afterward, the $^{7}$Li production will increase owing to the rise of low-mass giants of $\sim 1.0$ $M_{\odot}$. It is then clear that, because of time evolution constraints, the $^{7}$Li prompt enrichment–mass-loss mechanism will very probably never be able to operate during any initial self-enrichment of the gas cloud from which the present M3 cluster is formed. Some recent results (Drake 1998) indicate that $^{7}$Li photospheric depletion, following a strong enrichment, depends on the value of the stellar mass for masses less than 2.5 $M_{\odot}$. RGB stars with masses $\sim 2$ $M_{\odot}$ have larger depletion times (10$^{7}$ yr) than those of stellar masses of $\sim 1$ $M_{\odot}$ ($\sim 3 \times 10^{7}$ yr). These results were obtained for mass losses between 10$^{10}$ and 10$^{8}$ $M_{\odot}$ yr$^{-1}$ and CS expansion velocities equal to 2 km s$^{-1}$ and for [Fe/H]...
between ~0.5 and 0.2. In the case ($M < 2.5 \, M_\odot$) of Population II giants, where stellar masses around 1 $M_\odot$ are of interest, we obtain short Li cycles resulting in lower probabilities of detection. Considering the time to reach the RGB tip as $2 \times 10^7$ yr, the probability of detecting a Li-rich RGB star will be $\sim 3 \times 10^{-2}$, that is 0.15%. However, if the Li enrichment process is repeated by a recurrence factor of 10, for example, we obtain 1.5%. A similar result is found by Kraft et al. (1999) considering that already two Li-rich RGB giants have been found among near 100 observed globular cluster giants. We must note that the physical basis for the actual value of the recurrence factor depends on the quantity of $^3$He that remains to be burned.

Let us estimate the Li enrichment in the interstellar medium in the globular cluster M3 by means of mass loss of super-Li-rich RGB stars, following the scenario of de la Reza et al. (1996, 1997). Considering that all RGB stars are potential sources of Li during the short time in which they form and eject a Li-rich CS, the total production of Li will be

$$P_\text{Li} = N_{\text{RGB}} \times f_\text{Li} \times M_{\text{CS}} / M_{\odot}.$$ 

Here $N_{\text{RGB}}$ is the total number of RGB stars in the globular cluster M3, $N_{\text{CS}} = (n_{\text{Li}} / n_{\text{H}}) (m_{\text{Li}} / m_{\text{H}})$, where ($n_{\text{Li}} / n_{\text{H}}$) is the ratio of the number of Li and H atoms equal to $10^{-8}$ for log $e_\text{Li} = 4.0$ and $m_{\text{Li}} = 7$ amu. $f$ is the recurrence factor, $t_{\text{CS}} = 200$ yr is the time of CS formation (de la Reza et al. 1996), $M_{\odot}$ is the mass loss equal to $10^{-7} M_{\odot}$ yr$^{-1}$, and $t_{\text{CS}}$ is the time necessary to attain the RGB tip ($2 \times 10^6$ yr). The number of RGB stars ($N_{\text{RGB}}$) can be estimated in the following way: First, we consider that RGB stars have typical masses around the turn-off mass and similar to the one assumed by Kraft et al. (1999) for IV-101 (0.85 $M_\odot$). Then we assume that the present observed $N_{\text{RGB}}$ will represent a reasonable mean value of the number of RGB stars during the entire life of the globular cluster. Probably a better evaluation of the production of Li during the life of M3 can be made, if we are able to distinguish the stellar yields produced by giants with masses around $\sim 2.0 M_\odot$ to those with $\sim 1.0 M_\odot$: unhappily, this is not yet the case. Even in a crude way, $N_{\text{RGB}}$ can be estimated by extrapolating the already known number of RGB stars (424) counted among almost 19,000 stars in M3 (Ferraro et al. 1997). Maintaining the same proportion for the total estimated number of stars in M3 equal to $3.44 \times 10^6$ stars (Lang 1992), we obtain approximately 7700 RGB stars in M3. Taking first $f = 1$, we obtain $P_\text{Li} = 5.4 \times 10^{-15} M_{\odot}$ yr$^{-1}$ of new Li in the gas of the globular cluster interstellar medium. If we multiply this value by the mean age of the globular clusters (13 Gyr; Mould 1998) and if we consider this age to be that of M3, we obtain a total Li mass production of $7.0 \times 10^{-9} M_{\odot}$. To have a better idea of what represents this quantity of new Li, let us compare the latter with the initial content of Li in M3. To estimate this initial quantity of Li, we can consider a Jeans mass of $10^6 M_{\odot}$ at the earliest time of formation for M3 (Peebles 1993). Supposing for the sake of simplicity that almost all of the formed matter consists of H atoms and considering an initial Li abundance of $n_{\text{Li}} / n_{\text{H}} = 1.6 \times 10^{-10}$ corresponding to the Spite plateau (Molaro, Primas, & Bonifacio 1995; Bonifacio & Molaro 1997), we obtain an initial Li of $10^{-4} M_{\odot}$ in M3. The RGB production will represent only $\sim 7\%$ of this quantity. But if we consider $f = 10$, this value will increase to $\sim 70\%$. If we consider alternatively possible higher Li abundances as, as log $e_\text{Li} = 4.5$, as obtained for some giants such as PDS 68, and if we use a larger, but yet realistic, mass-loss value of $5 \times 10^{-6} M_{\odot}$ yr$^{-1}$, we will obtain increased enrichment factors. It is interesting to note that this new Li in the interstellar gas of M3 will, very probably, not be maintained for a long time in the cluster and will be transferred, by ram pressure, to the Galactic disk when M3 crosses this disk. Scholz, Odenkirchen, & Irwin (1993) have calculated that M3 crossed the plane nearly 34 times during the last 10 Gyr. Globular clusters appear then as new potential sources of Li enrichment in the Galactic disk!

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