ON A RAPID LITHIUM ENRICHMENT AND DEPLETION OF K GIANT STARS  

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ABSTRACT

A model scenario has recently been introduced by de la Reza and colleagues to explain the presence of very strong Li lines in the spectra of some low-mass K giant stars. In this scenario all ordinary, Li-poor, K giants become Li rich during a short time (∼10^7 yr) when compared to the red giant phase of 5 × 10^7 yr. In this “Li period,” a large number of the stars are associated with an expanding thin circumstellar shell supposedly triggered by an abrupt internal mixing mechanism resulting in a surface new ^7Li enrichment. This Letter presents nearly 40 Li-rich K giants known up to now. The distribution of these Li-rich giants, along with 41 other observed K giants that have shells but are not Li rich, in a color-color IRAS diagram confirms this scenario, which indicates, also as a new result, that a rapid Li depletion takes place on a timescale of between ∼10^3 and 10^4 yr. This model explains the problem of the presence of K giants with far-infrared excesses presented by Zuckerman and colleagues. Other present and future tests of this scenario are briefly discussed.

Subject headings: infrared: stars — stars: circumstellar matter — stars: evolution — stars: late-type — stars: mass loss

1. INTRODUCTION

Since the discovery in the 1980s of some K giant stars showing strong lines of Li in their spectra, the main tendency has been to consider these stars as peculiar. This was because, following classical first dredge-up theory (Iben 1967), all K giants would have their surface Li depleted owing to convective mixing with internal material devoid of this element or through direct Li destruction by inward transport. In fact, this Li depletion has actually been observed for a large part of the K giants, and in several cases, as in the stars with masses lower than 2.5 M⊙, Li depletions are larger than those indicated by theory, which suggests that an additional mixing mechanism could be present (Gilroy 1989). Some hypotheses have been formulated to try to explain the apparently anomalous presence of Li in the Li-rich giants. These are (1) maintenance during the giant phase of a pre-main-sequence large Li abundance, (2) engulfing orbiting planets and/or brown dwarfs, (3) Li production by a nearby nova companion, and (4) internal production of fresh ^7Li.

The maintenance hypothesis is very improbable owing first, to main-sequence depletion and second, to the first dredge-up action. Also, the measured isotope ratios of ^12C/^13C, which indicate the degree of mixing, appear not to be correlated with strong Li lines; these lines must then be the result of recent Li production (da Silva, de la Reza, & Barbuy 1995). In the engulfing as in the maintenance mechanisms, there is no new Li production; Li contained in the planets or in the brown dwarfs (Rebolo et al. 1996) is introduced in the newly formed giant. This mechanism could gain new impetus owing to the recent discoveries of extrasolar “51 Peg”–type hot planets (Mayor & Queloz 1995). Nevertheless, we know neither if the Li contained in these planets is sufficient to contaminate a star nor what the proportions of these kinds of planets are when compared to the more distant “cool” planets also recently discovered. These more external planets are not efficient sources for Li in the engulfing process because, owing to stellar mass loss, these planets will escape being swallowed (Sackmann, Boothroyd, & Kraemer 1993). Concerning novae, even if these objects can eventually produce nearly 15% of the Galactic Li (Hernanz et al. 1996), there is no observational support for the presence of white dwarfs as hot companions to the Li K giants. This is based on IUE observations (de la Reza & da Silva 1995) and on the absence of companions indicated by the lack of variations of radial velocities in Li K giants at the 1 km s⁻¹ level (de Medeiros, Melo, & Mayor 1996). Recently detected variations at the 20 m s⁻¹ level in the K giant β Ophiuci appear to be due rather to nonradial pulsations (Hatzes & Cochran 1996).

We remain then with the internal production mechanism, and the main purpose of this Letter consists of presenting observations supporting the idea that Li K giants are not peculiar K giants but, rather, normal giants going through a short Li-rich period, presented for the first time in de la Reza, Drake, & da Silva (1996, hereafter Paper I).

2. THE SCENARIO

In Paper I, a scenario was proposed to explain the existence of Li K giant stars. This model was constructed based on the discovery that almost all Li K giants are optical counterparts of IRAS sources indicating the presence of dusty circumstellar shells (CSs). Nearly half of the known Li K giants indicated in this Letter were discovered as a subproduct of the search for new T Tauri stars, the Pico dos Dias Survey (PDS) made in Brazil (Gregorio-Hetem, et al. 1992; Torres et al. 1995; de la Reza et al. 1997). A survey for new Li K giants in IRAS color boxes other than that corresponding to T Tauri stars has been initiated by Gregorio-Hetem, Castilho, & Barbuy (1993). First, the presence of a CS region was believed to be, apart from Li, the main difference between Li K and normal K giants. However, Fekel et al. (1996) showed that some K giants could possess CSs without showing a strong Li feature. Also, Zuckerman, Kim, & Liu (1995) presented a list of nearly 90 stars,
the large part of which were K giants, with IRAS fluxes ratios compatible with the presence of CS regions. No explanation for the presence of large far-infrared excesses in these oxygen-type giants was found by these last authors. In this Letter, we report on observations of 27 stars from this list in order to insert them into our scenario. The main characteristics of the scenario are as follows:

1. All normal K giants (at least single field stars with masses between approximately 1.0 and 2.5 $M_\odot$) become Li rich during a short time of $\leq 10^7$ yr compared to the red giant phase duration ($5 \times 10^7$ yr).

2. An abrupt mixing mechanism producing a rapid surface injection of material with fresh internal $^7$Be, the only newly formed element at this stage via $^3$He $+ ^4$He and rapidly transformed to $^7$Li, produces the formation of a CS of gas and dust.

3. When this sudden mass loss stops, the CS detaches and is ejected into the interstellar medium. The best values for the CS, adjusted to observations (see Paper I), give an expansion velocity of $2$ km s$^{-1}$ and an equivalent mass loss of $2-5 \times 10^{-8} M_\odot$ yr$^{-1}$, which is 100 times the normal mass loss of ordinary K giants. The complete ejection of the CS up to the stage when it is no longer detectable lasts at least $8 \times 10^7$ yr.

4. The fresh $^7$Li that has not been ejected into the interstellar medium remains in the stars' photospheres. This surface Li will be depleted later in a time less than or equal to the total CS ejection time, depending on the stellar parameters. This depletion mechanism is probably related inversely to the additional mixing mechanism introduced to produce the Li enrichment.

3. OBSERVATIONS

The results presented in this paper were obtained from spectroscopic observations using the following telescopes: (1) the CTIO 4.0 m telescope in Cerro Tololo, Chile with an echelle spectrograph with 0.08 Å pixel$^{-1}$ (1996 April–May); (2) the 3.5 m telescope of the Calar Alto Observatory (Almeria, Spain) with the TWIN spectrograph with 0.88 Å pixel$^{-1}$ (1996 July); and (3) the 2.5 m Isaac Newton Telescope (La Palma, Spain) with the IDS spectrograph with 0.85 Å pixel$^{-1}$ (1996 November). The first main program stars consisted of a group of faint Li K and Li-poor K giants discovered in the PDS. These PDS observations were restricted to coudé spectra of a small spectral interval between Hα and the Li I resonance line. The main interest in obtaining echelle spectra was to perform a detailed analysis in order to derive the main stellar parameters. The second program stars consisted of a group of relatively bright K giants from the list of Zuckerman et al. (1995). Bearing in mind that these stars have IRAS colors indicating the presence of CS regions, these objects were potential candidates for new Li K giants. The observed results presented in this Letter are limited to the presence, or lack, of strong Li lines. A subsequent paper will be devoted to the determinations of the masses and metallicities of these objects.

4. DISCUSSION OF THE RESULTS AND TESTS OF THE MODEL

The most complete list of observed Li K giants known up to now is presented in Table 1, which lists K giants with spectral type limits between G8 and M0. In this table, numbers with an asterisk indicate the Li K giants that are represented in Figure 1 with their respective labels. From the observational point of view, we considered as Li K giant stars those presenting the resonance Li I line at 6708 Å with intensities comparable to or higher than the neighbor Ca I at 6718 Å. When the Li abundance is known, “Li K giants” are stars with Li abundances larger than $\log e$(Li) = 1.2 [$\log e$(H) = 12.00]. K giants presenting no strong Li lines and having far-infrared excesses are from the list of Zuckerman et al. (1995) (with HD numbers) and to the PDS list (with IRAS numbers). Apart from the bright and already known Li K giants discovered by several authors and resulting in 21 objects, we have added 20 new Li K giants discovered in the PDS (Gregorio-Hetem et al. 1992; de la Reza et al. 1997) at fainter visual magnitudes. These groups, bright ($m_V$ of 3–8 mag) and faint (9–14 mag), are located in different places in a color-color diagram with IRAS fluxes at 12, 25, and 60 μm (see Fig. 1). The explanation of this separation in apparent magnitudes appears naturally in the model of Paper I. That paper considers the existence of three regions in the diagram of [60 μm] versus [25 μm] labeled I, II, and III (see Fig. 1). In region I are the bright, commonly called normal K giants with IRAS colors of photospheric origin that show the absence of CS regions. It is in this region that almost all the Li-poor giants are found. Region II corresponds to the color box used in the PDS to discover new T Tauri stars. It is in this region that the new, faint, recently discovered Li K giants are placed. In region III are found all the previously known visual bright Li K giants. Some of the curves resulting from the model of Paper I are presented in Figure 2. They represent the evolutionary paths of the ejections of the CS regions. Beginning in region I, they go to region II and then to region III before returning to region I. This loop takes at least $8 \times 10^7$ yr. The stars remain for a long time in region I during the red giant phase.

When stars become $^7$Li enriched in a rapid episode, a CS is formed. When the mass loss (and the associated Li enrichment) stop, the CS detaches from the star ejecting its matter into the interstellar medium. In this way, $^7$Li surface enrichment and subsequent depletion are time adjusted with the expansion of the CS. Any expansion time can then be used to measure the $^7$Li depletion during the loops shown in Figure 2.

There are no observed stars between regions I and II owing to the very short corresponding evolutionary times (order of hundreds of years). In region II, only faint giants are observed. Even if the corresponding times are longer in this part of the diagram (more than 1000 yr), they are too short to observe objects in region II among the nearby stars. We must then survey a larger region consisting of more distant and faint giants. In region III, the crossing times are nearly 10,000 yr, and these longer times allow for the possibility of observing some Li K giants among the bright and nearby stars.

Paper I mentions that Li K giants contain a large majority of CS stars. This gives us the idea that normally Li-poor K giants have no CS regions and that the Li depletion times were of the order of 80,000 yr or somewhat larger. The possibility that some K giants having a CS region without high Li could exist was pointed out by Fekel et al. (1996). They suggested that Li depletion times could be smaller than 10$^7$ yr or even that CS could be formed without Li enrichment. The most important result of this Letter is to show that the first conclusion is the most probable. This can be seen very clearly in Figures 1 and 2. There is a group formed of Li K giants only in the lower part of region II, having the largest [25 – 12] and lowest [60 – 25] values. Those stars would be the most recently formed Li K giants! During the PDS, we found some faint K giants without high Li; however, these were less numerous than the Li K
giant, and the LiK giant HD 95799 detected by Luck (1994) is the only Li K that is not an $^{7}\text{Li}$ source. The explanation is not detected by IRAS because it is more distant than they are. In fact, the visual magnitude of HD 95799 is $m_v = 8.01$, whereas those of HD 39853 and HD 787 are, respectively, 5.66 and 5.25.

Li enrichment and depletion in K giants appears then to be the explanation to the problem posed by Zuckerman et al. (1995) with respect to the existence of oxygen giants with strong far-infrared excesses. Is stellar mass the factor that determines a shorter or longer depletion time? Determination of the main stellar parameters of these CS stars, with and without high Li, could give an answer to this question. Other important parameters, such as a strong differential rotation (Fekel et al. 1996) or metallicity, could, however, have a significant part in this rapid enrichment-depletion process.

Some questions have no answer as yet. Can stars become Li rich several times during the giant phase? This, in principle, depends on the quantity of available $^7\text{He}$, which acts as a fuel for the production and enrichment of $^7\text{Be}$, subsequently transformed into $^7\text{Li}$. Direct observational evidence of this could be shown by the eventual detection of double-detached CSs. Another question refers to the internal nature of these stars. Are they first-ascent red giant or clump giants? We do not propose an answer to this yet, owing to uncertainties related to the positions of these stars in the H-R diagram. As can be seen

### TABLE 1

**LIST OF K GIANTS OBSERVED IN THE LITHIUM SPECTRAL REGION**

| Number | Object   | Number | Object       |
|--------|----------|--------|--------------|
| 1°     | HD 787   | 42°    | IRAS 16086–5255 |
| 2°     | HD 9746  | 43°    | IRAS 16128–5109 |
| 3°     | CPD −53395 | 44°    | HD 146834    |
| 4°     | HD 19745 | 45°    | HD 146850    |
| 5°     | IRAS 03520–3857 | 46°    | HD 148293    |
| 6°     | HD 30238 | 47°    | IRAS 16227–4839 |
| 7°     | HD 30834 | 48°    | IRAS 16252–5440 |
| 8°     | HD 31993 | 49°    | IRAS 16514–4625 |
| 9°     | HD 39853 | 50°    | HD 153135    |
| 10°    | IRAS 06365+0223 | 51°    | HD 156061    |
| 11°    | IRAS 07227–1320 | 52°    | HD 156115    |
| 12°    | IRAS 07456–4722 | 53°    | IRAS 17102–3813 |
| 13°    | IRAS 07577–2806 | 54°    | IRAS 17120–4106 |
| 14°    | HD 69590  | 55°    | IRAS 17211–3458 |
| 15°    | HDE 233517 | 56°    | IRAS 17442–2441 |
| 16°    | HD 76066  | 57°    | HD 162298    |
| 17°    | HD 82227  | 58°    | IRAS 17576–1845 |
| 18°    | HD 82421  | 59°    | IRAS 17578–1700 |
| 19°    | IRAS 09553–5621 | 60°    | IRAS 17582–2619 |
| 20°    | HD 92253  | 61°    | IRAS 17590–2412 |
| 21°    | HD 95799  | 62°    | IRAS 17596–3952 |
| 22°    | IRAS 11044–6127 | 63°    | HD 164712    |
| 23°    | HD 96996  | 64°    | IRAS 18334–0631 |
| 24°    | HD 97472  | 65°    | IRAS 18397–0400 |
| 25°    | IRAS 12236–6302 | 66°    | IRAS 18559+0140 |
| 26°    | HD 108471 | 67°    | HD 176588    |
| 27°    | IRAS 12237–6523 | 68°    | IRAS 19012–0742 |
| 28°    | HD 111830 | 69°    | HD 177366    |
| 29°    | HD 112127 | 70°    | IRAS 19083+0119 |
| 30°    | IRAS 13313–5838 | 71°    | HD 181154    |
| 31°    | HD 118344 | 72°    | IRAS 19210+1715 |
| 32°    | HD 119853 | 73°    | HD 183202    |
| 33°    | HD 129802 | 74°    | PDS 100      |
| 34°    | PDS 68   | 75°    | HD 187114    |
| 35°    | HD 121710 | 76°    | HD 190299    |
| 36°    | HD 125618 | 77°    | HD 194317    |
| 37°    | HD 128309 | 78°    | HD 203251    |
| 38°    | HD 129955 | 79°    | HD 204540    |
| 39°    | HD 131530 | 80°    | HD 218527    |
| 40°    | IRAS 141948–6115 | 81°    | HD 219025    |
| 41°    | IRAS 14257–6023 | 82°    | HD 221776    |
in Paper I, these stars are somewhat grouped in the H-R diagram. Future accurate determinations of the stellar parameters will elucidate this question. Other considerations are important; this “Li phenomenon” has been observed only for single field giants spread overall Galactic latitudes. No clear identification of a Li K giant belonging to a cluster has yet been made. This will be important to determine the “Li age” for these stars. From the theoretical point of view, considerable advance has been made on the stellar internal \(^7\)Li production and surface enrichment in low-mass K giants (1–2.5 \(M_\odot\)) by means of an internal circulation mechanism (Sackmann & Boothroyd 1997). This one relates the base of the convective layer to a hot region producing the \(^7\)Be. Larger Li abundances can be obtained, depending upon certain values of the circulation mechanism, such as the mixing speed, the depth of mixing, the star’s metallicity, and possibly the star’s mass. For example, large Li abundances such as \(\log (e(Li)) = 4.2\) were obtained for a 1 \(M_\odot\) star of metallicity \(Z = 0.0001\) with a rapid mixing to greater depths.

Perhaps one of the most interesting points of the scenario of Paper I is that it can be tested by several means. One has already been made by Fekel et al. (1996) by means of the determination of the real nature of the star HDE 233517. This object was considered by Skinner et al. (1995) and Miroshnichenko, Bergner, & Kuratov (1996) to be a nearby K dwarf star of the “Vega” or “β Pictoris” type. Fekel et al. (1996) showed that this star is in reality a distant K giant with a large mass loss (object 15 in Fig. 1). According to its position in the color-color diagram, this star should be probably Li-rich, and, according to its corresponding mass loss and age of its shell, its CS should be of a specific size. Both points have been confirmed by observations (Fekel et al. 1996). Other general tests can be made, such as detection of the sizes and velocities of the CS and the presence of CS detachement and/or double shells. Also, observations of the presence of \(^{10}\)Be, \(^{11}\)B, and \(^{6}\)Li will give an insight into the rate of the \(^7\)Li enrichment process (Sackmann & Boothroyd 1997). A non-LTE Li abundance determination of several prototype stars in different regions of the color-color diagram is in progress. These determinations will help us to quantify their Galactic Li enrichment contribution.

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