THE LITHIUM IN WEAK G-BAND STARS

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Abstract. The lithum abundance in weak G-band stars is found to be linearly correlated with CH deficiency. Weak G-band stars with a high Li abundance are found to show relatively least carbon deficiency, while the stars with a relatively low Li abundance show a high under-abundance of carbon.

1. Introduction

Weak G-band stars are carbon-deficient giants with spectral types between G and K (Bidelman, 1951; Greenstein and Keenan, 1958; Bidelman and MacConnell, 1973; Dean *et al.*, 1977). These stars show substantial carbon deficiencies and nitrogen enhancements (Hartoog *et al.*, 1977; Rao, 1978), and the weak G-band phenomenon also exists in globular cluster stars (Zinn, 1973). However, weak G-band stars in globular clusters are found to show varying degrees of nitrogen enhancement and do not seem to show any correlation with the degree of carbon depletion (Carbon *et al.*, 1977).

Recently, Rao (1978) made scanner observations of ten field weak G-band stars of Bidelman and MacConnell (1973). He found that the weakness of the G-band is linearly related to the enhancement of NH band strength, thus suggesting that the atmospheres of weak G-band stars is severely mixed with material which has been exposed to the CN cycle. A detailed analysis of the spectrum of HR 6766 by Sneden *et al.* (1978) and HD 91805 by Cottrell and Norris (1978) shows that these stars have an under-abundance of carbon, an over-abundance of nitrogen and a normal abundance of oxygen and iron peak elements. Sneden *et al.* (1978) examined four weak G-band stars for ^{13}C and found $^{12}C/^{13}C \sim 4$.

The presence of lithium in weak G-band stars was first noted by Dean *et al.* (1977). Recently, Hartoog (1978) derived an Li abundance for ten weak G-band stars. He found that the Li abundance in these stars ranges from log ϵ(Li) of 0.7 to 3.0. For two stars – HR 1023 (HD 21018) and HD 120170 – Hartoog (1978) found an abundance of lithium equal to the cosmic value of log $\epsilon(\mathrm{Li}) = 3.0$. More recently, Lambert *et al.* (1980) confirmed the Li abundances derived by Hartoog (1978) for HD 21018 and HD 120170. Sneden *et al.* (1978) derived a lithium abundance for HR 6766 and estimated tentatively an upper limit to the isotope ratio $^6\mathrm{Li}/^7\mathrm{Li} < 0.25$; however, they concluded that the presence of ^{6}Li cannot be definitely established in HR 6766.

Several hypotheses have been advanced to explain the weak G-band

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phenomenon: Sneden *et al.* (1978) and Hartoog (1978) suggested meridional currents in a rapidly rotating Main-Sequence star as the responsible agent. If these complex meridional currents could mix most of the envelope except for the outer few per cent of the mass (Maheswaran, 1968), the star as a red giant will show a normal Li abundance (initial Main-Sequence abundance possibly depleted by a factor of 60), a low C abundance and a high N abundance. Sweigart and Mengel (1979) proposed that meridional circulation due to internal rotation might mix the CNO-processed material from the vicinity of the hydrogen shell into the envelope of a red giant star. The resulting red giant could be a weak G-band star with a low Li abundance. Hartoog's (1978) discovery of an almost cosmic abundance of Li in HR 1023 and HD 120170 indicates that meridional circulation on the Main-Sequence or in the red giant phase alone cannot explain the Li abundance and weak G-band phenomenon. The predicted upper limit for Li in normal red giants is $\log \epsilon(\text{Li}) = 1.2$ (Boesgaard, 1976). Thus, in weak G-band stars, Li production appears to be necessary. In order to define the production phase of Li, a search for correlations with an abundance of ^{12}C, ^{13}C and ^{14}N, etc., are of interest. In this paper an attempt is made to see whether a correlation exists between carbon depletion and Li abundance in weak G-band stars.

2. Observations

Rao (1978) derived the strengths of the G-band of CH at λ4300 for ten field weak G-band stars with a photoelectric spectrum scanner (Bappu, 1977) attached to the Cassegrain focus of the 1-metre telescope at Kavalur. G-band strengths are determined for a further six weak G-band stars (Table I). Observations were made with the instrumental set up described above. The bandwidth (25 Å) of the observations of G-band is same as that used by Rao (1978). The band strength parameter I_{CH} is observed as the ratio of the counts in the feature (λ4300) to the continuum at the feature as obtained from two continuum points 50 Å away on either side of the feature (i.e., λ 4250, λ 4350). The band strength I_{CH} not only reflects the absorption of the molecular bands of CH but also includes other atomic lines occurring in the 25 Å bandwidth centred on the feature. Because of the similarities between the spectra of weak G-band stars and those of normal field giants of the same spectral type, the difference in I_{CH} values between normal and weak G-band giant stars are indicative of the differences of molecular band strength. The observed I_{CH} and ΔI_{CH} values (CH band strength in weak G-band star minus CH band strength in normal giant of similar $R-I$ colour) for the ten weak G-band stars for which Li abundance are known (Hartoog, 1978; Sneden *et al.*, 1978; and Lambert *et al.*, 1980) are given in Table I together with the ^{12}C/^{13}C ratio (Lambert *et al.*, 1980). Of the ten stars listed in Table I, the I_{CH} and Δ_{ICH} values for five are from Rao (1978). The $R-I$ values given in Table I are from Dean *et al.* (1977), and when the observed $R-I$ colour is not available,

TABLE I

G-band strengths and Li abundances for weak G-band stars

HD	$R-I$	I_{CH}	ΔI_{CH}	Log ϵ(Li)	$^{12}C/^{13}C$
18474	(0.43)	0.968	−0.052	1.42	
21018	(0.40)	0.936	−0.006	2.93	
28932	(0.54)	0.888	−0.005	2.25	
94956	0.52	0.919	−0.034	≤1.07	
120170	(0.50)	0.902	−0.907	3.03	
165462	(0.52)	0.919	−0.034	2.05	
166208	0.472	0.944	−0.046	1.81	4.5
165634	0.52	0.965	−0.080	0.75	4.1
207774	(0.53)	0.909	−0.026	≤ 1.5	
BD + 5°593[a]		0.903		0.85	
67728[b]	0.60	0.891		0.76	

Notes: The $(R-I)$ values in parentheses are estimated from the method described by Rao (1978).

[a] BD + 5°593: This star is suspected to be of Population II by Cottrell and Norris (1978) from DDO photometry. It has the lowest CO index (−0.030) and large J–K colour (0.76) (Hartoog *et al.*, 1977).

[b] HD 67728: The spectral type is K1 IV. This star has the largest CO index (+0.055) and falls between the mean line for luminosity class III and V in the CO index and J–K plot (Hartoog *et al.*, 1977). It has small deficiency of CH band strength ($\Delta I_{CH} = -0.02$) when compared with δ Eri (K_0 IV), since the G-band strengths for IV stars are not calibrated and, secondly, the $R-I$ colour is 0.60.

it is obtained by the method mentioned in Rao (1978). The variation of I_{CH} with $R-I$ for giant stars becomes insensitive for $R-I \geqslant 0.55$ (Figure 2 of Rao, 1978). Thus, I_{CH} for giants with $R-I < 0.55$ most probably reflects the carbon abundance.

3. Discussion

Tsuji's (1964) calculations of molecular equilibria with different C and N abundances for log $Pg \sim 3$ and temperatures of 4200–5010 K indicate that the changes in the total abundances of carbon are almost directly proportional to the changes in the molecular abundances of CH. Since the weak G-band stars show normal Ca and Fe abundances, the difference ΔI_{CH} (difference in G-band strength between a normal giant and weak G-band giant of the same spectral type or $R-I$ colour) is an indicator of C deficiency. In Figure 1, the ΔI_{CH} values (Table I) are plotted against log ϵ(Li) (Hartoog, 1978) for nine field weak G-band stars. Two stars listed in Table I are not plotted in Figure 1 and the reasons for their omission are given in the notes to the table. From the variation of Li abundance with ΔI_{CH} values (Figure 1) we find that the C deficiency (relative to

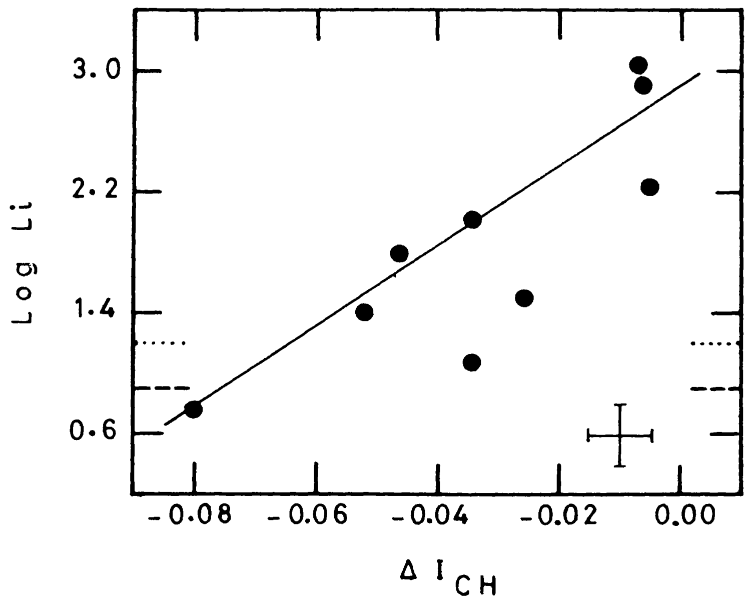

Fig. 1. ΔI_{CH} (CH band strength in weak G-band star minus CH band strength in normal giant of similar $R-I$ colour) values of weak G-band stars plotted against their log Li (in the log H = 12.0 scale) abundance. The dashed line on the y-axis indicates the average Li abundance in normal red giants in the same temperature range as that of weak G-band stars. The upper limit for Li abundance in normal red giants is indicated by the dotted line.

the normal field giants) in weak G-band stars is linearly related to the Li abundance. Weak G-band stars with a maximum amount of CH deficiency have a relatively low Li abundance. The average Li abundance for normal field giants (Lambert *et al.*, 1980) in the same effective temperature range as that of weak G-band stars listed in Table I is $\log \epsilon(\text{Li}) = 0.9 \pm 0.3$. However, the Li abundance in late-type stars is a function of temperature (Boesgaard, 1976; and Lambert *et al.*, 1980); the spread in T_{eff} of the weak G-band stars considered here is 4750–5000 K. In this temperature range the variation in $\log \epsilon(\text{Li})$ is small compared to the scatter around the average value. The two stars which seem to deviate from the mean line defined by seven stars are HD 94956 and HD 207774. Boesgaard (1976) has discovered Be deficiencies for the Main-Sequence stars with $T_{\text{eff}} > 6600$ K, and Li also appears to be over-deficient in these stars (see also Lambert *et al.*, 1980). In her sample, about one in three of the Main-Sequence stars with $T_{\text{eff}} > 6600$ K showed a Be deficiency (Li deficiency) and these stars would evolve to the red giant phase with an Li deficiency of a factor of 10 more than normal. Thus, in this sample HD 94956 and HD 207774 may be examples of such Li over-deficiency. If we correct for that factor of 10 in the abundance of Li, those two stars fall on the mean line defined by seven stars in Figure 1. From this figure it is clear that two stars (HD 21018 and HD 120170) which show a high Li abundance ($\log \epsilon(\text{Li}) \sim 3.0$) have a smaller deficiency in the

CH band, whereas HR 6766, which has a low Li abundance ($\log \epsilon(\text{Li}) = 0.75$), has a maximum CH band deficiency.

The presence and over-abundance of Li in weak G-band stars and the linear variation of Li abundance with carbon deficiency (Figure 1) poses a problem. In these stars the primordial Li would be completely destroyed at the temperatures required for the CNO cycle. Production of Li in weak G-band stars seems to be necessary to account for the abundance of $\log \epsilon(\text{Li}) \sim 3.0$. The Li abundance in the giants is reduced through dilution. Iben (1965) predicts for a $3\,M_\odot$ star a reduction by a factor of 60. However, Li is not depleted in the atmospheres of stars that are more massive than $2\,M_\odot$; these stars, when they evolve to the red giant phase, are expected to have $\log \epsilon(\text{Li}) = 1.2$, which is an upper limit. The observed Li abundance in weak G-band stars range from $\log \epsilon(\text{Li}) = 0.75$ to $\log \epsilon(\text{Li}) = 3.0$ (Figure 1), and poses a problem as to how and when this production occurs in relation to the mixing of the CN-processed material. To account for the simultaneous depletion of C and Li in weak G-band stars, they should have a high Li abundance ($\log \epsilon(\text{Li}) \sim 4.8$) during their Main-Sequence phase or Li is produced before the meridional circulation becomes operative in the red giant phase. In the absence of stars with a high Li abundance ($\log \epsilon(\text{Li}) \geqslant 3.0$) on the Main-Sequence, the production of Li seems to be necessary.

Dean *et al.* (1977) suggested a thermonuclear production of Li in weak G-band stars by the mechanism proposed by Cameron and Fowler (1971), $^3\text{He}(\alpha, \gamma)\ ^7\text{Be}(e^-, \nu)^7\text{Li}$, and the observed CNO abundances come from the same mixing mechanism. This mechanism has been studied by Scalo *et al.* (1975) and Sackman *et al.* (1974). The main objections to this model are: great luminosities are required for high temperatures ($T \sim 3 \times 10^6$ K) to appear in the convective envelopes; the lower mass limit for the hot-bottom envelopes is also a problem (Scalo *et al.*, 1975, give $M \geqslant 1.5\,M_\odot$); and the surface Li abundance is sensitive to mixing time-scales. The maximum amount of ^7Li that can be made in the envelope is porportional to the amount of ^3He in the envelopes. Further, there are objections to the diffusion model on which the above-mentioned calculations are made (Iben, 1975). Sweigart and Mengel (1979) proposed that meridional circulation in the red giant phase is responsible for stars showing low $^{12}\text{C}/^{13}\text{C}$ ratios, including the weak G-band stars. In Population I weak G-band stars the circulation currents would not be expected to reach the ON-processed material, and thus they would show normal oxygen abundance and a correlation between carbon depletion and nitrogen enhancement. Observational evidence (Rao, 1978; Cottrell and Norris, 1978; and Sneden *et al.*, 1978) seems to support the above-mentioned process. Sweigart and Mengel's (1979) model of meridional circulation during the red giant phase does not explain the high Li abundance in weak G-band stars. Lambert *et al.* (1980) raised an objection against Sweigart and Mengel's mechanism on the grounds that it cannot account for the large Li abundance and small $\text{C}^{12}/\text{C}^{13}$ ratios. In the $1.4\,M_\odot$ star model of Sweigart and Mengel, they show that if the Li is produced by the Cameron and Fowler (1971) process, then the ^{7}Li produced is destroyed at the production site before it is carried out to the surface. Much higher velocities associated with convection currents are needed for the production of ^{7}Li. Lambert *et al.* (1980) suggested two alternative scenarios. First, CN-processed material is continuously added to the surface during the events. The Li abundance initially decreases and only increases after the surface has reached the $^{12}C/^{13}C \sim 4$ condition. The isotope ratio $^{12}C/^{13}C$ is known only for three weak G-band stars. In this context, observations of a $^{12}C/^{13}C$ ratio for high Li abundance ($\log \epsilon(\text{Li}) = 3.0$) in weak G-band stars is important. The linear relationship between Li abundance and ΔI_{CH} values (Figure 1) does not support the scenario proposed by Lambert *et al.* (1980). Their second scenario is that, in the progenitors of weak G-band stars, the conditions are such that C is depleted and Li is produced. The core He flash in low-mass stars is supposed to create such a situation; however, it is not known whether the He core flash leads to mixing. According to this hypothesis, weak G-band stars with a very low abundance of C should have a very high abundance of Li – which is contrary to what is observed (Figure 1). Recently, Canal *et al.* (1980) have discussed the production of Li in weak G-band stars – in particular,HR 6766 – by spallation reactions on the surface. They have shown that Li can be produced in very short time-scales by the spallation process. However, to account for the Li abundance in HR 1023, the time-scales are 180 times more than those given in their Table 3 (Canal *et al.*, 1980) for the same parameters. To explain the observed relationship between Li abundance and C depletion, Li production seems to be necessary and appears to occur between the time the star leaves the Main-Sequence and becomes a giant. The time-scales during this transition are 6.6×10^7 yr and 1×10^8 yr for stars of 2.25 $M_\odot$ and 1.5 $M_\odot$, respectively (Iben, 1967). An order of magnitude estimate for the fresh production of Li by spallation reactions seem to require (for solar composition and with the parameters given by Canal, 1975) 7.8×10^7 yr for a red giant of 2.0 $M_\odot$ to have an abundance of $\log \epsilon(\text{Li}) = 4.8$. However, the rate of production has to be more than the dilution such that the star has $\log \epsilon(\text{Li}) \sim 3.0$, when meridional circulation starts and the abundance of Li and C get depleted together.

In conclusion, the available data on Li abundance and CH band weakness (Figure 1) in weak G-band stars clearly indicates the existence of a linear relationship between Li and carbon abundance. Weak G-band stars with a high Li abundance are least depleted in C, and weak G-band stars with a relatively low Li abundance have a very low abundance of C. Li production seems to be a necessity after the star leaves the Main-Sequence and reaches the giant branch, probably by spallation reactions on the surface. Then mixing due to meridional circulation on the giant branch (Sweigart and Mengel, 1979) might bring out the CN-processed material to the surface, at the same time destroying the surface Li. Thus, both carbon and lithium abundances get depleted together.

The determination of isotope abundance ratio $^{12}C/^{13}C$ and $^6Li/^7Li$ and C, N and O abundance is important for a significant sample of weak G-band stars.

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