

*Letter to the Editor***Li I enhancement during a long-duration stellar flare**David Montes^{1,2,*} and Lawrence W. Ramsey^{2,*}¹ Departamento de Astrofísica, Facultad de Físicas, Universidad Complutense de Madrid, E-28040 Madrid, Spain
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Abstract. We report the possible detection of a Li I $\lambda 6708$ Å line enhancement during an unusual long-duration optical flare in the recently discovered, X-ray/EUV selected, chromospherically active binary 2RE J0743+224. The Li I equivalent width (EW) variations follow the temporal evolution of the flare and large changes are observed in the intensity of the line. The maximum Li I enhancement (40% in EW) occurs just after the maximum chromospheric emission observed in the flare. A significant increase of the ${}^6\text{Li}/{}^7\text{Li}$ isotopic ratio is also detected. No significant simultaneous variations are detected in other photospheric lines. Neither line blends nor starspots seem to be the primary cause of the observed Li I line variation. From all this we suggest that this Li I enhancement is produced by spallation reactions during the flare.

Key words: stars: activity – stars: chromospheres – stars: binaries: spectroscopic – stars: flare – stars: abundances – stars: individual (2RE J0743+224)

1. Introduction

The resonance doublet of Li I at $\lambda 6708$ Å is an important diagnostic of age in late-type stars since it is easily destroyed by thermonuclear reactions in the stellar interiors. However, Li I observations of several types of chromospherically active stars, such as pre-main sequence stars, late-type dwarfs in open clusters, as well as post-main sequence objects, show a significant range of abundances. It is well-known that a large number of chromospherically active binaries (CAB hereafter) show Li I abundances higher than the normal values characteristic of stars of the same mass and evolutionary stage (Pallavicini et al. 1992, Liu et al. 1993; Fernández-Figueroa et al. 1993; Randich et al. 1994; Barrado et al. 1997, 1998; Montes et al. 1998). This line is very temperature sensitive because of its low ionization potential of 5.37 eV. Thus the equivalent width (EW) should be enhanced in dark spots but reduced in the bright facular regions as demonstrated by solar observations (Giampapa 1984).

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A number of researchers (Fekel 1996; Barrado 1996; Hussain et al. 1997; Fernández & Miranda 1998; Neuhäuser et al. 1998) have investigated starspots as the possible cause of the observed Li I abundances spreads. However, Li can also be produced by low energy spallation reactions in stellar flares (Fowler et al. 1955; Canal 1974; Canal et al. 1975). Some evidence of Li production by spallation have been found in the Sun (Livshits 1997; Livingston et al. 1997), but no detection has been reported in other stars. Spallation has only been discussed as a possibility to explain the high Li abundances observed in some stars (Pallavicini et al. 1992; Mathioudakis et al. 1995; Favata et al. 1996).

In this letter we describe the Li I $\lambda 6708$ Å line enhancement detected during the observations of an unusual long-duration optical flare in the recently discovered, X-ray/EUV selected CAB 2RE J0743+224, and discuss the possible causes.

2. Observations and analysis

High resolution (0.16 Å) observations of this star were obtained during a 10 night run 1998 January 12-21 using the 2.1m telescope at McDonald Observatory and the Sandiford Cassegrain Echelle Spectrograph (McCarthy et al. 1993). The spectra in the Li I line region are plotted in Fig. 1. These observations are analyzed in detail in a separate paper (Montes & Ramsey 1998b) where stellar properties, orbital parameters, and chromospheric behavior are discussed. We found that this star, previously classified as single-lined spectroscopic binary (Jeffries et al. 1995), is a double-lined spectroscopic binary (SB2) with a K1 III primary and an orbital period of 10 days.

A dramatic increase in the chromospheric emissions ($H\alpha$ and Ca II IRT lines) is detected during the observations (see the temporal evolution of the $H\alpha$ EW in the upper left panel of Fig. 2). The increase of the emission starts the 3th night (1998 January 15) reach a maximum on the 5th night and at the end of the observations (1998 January 22) the chromospheric lines had not yet recovered the quiescent value. The total duration of the event was evidently larger than 8 days. We interpret this behaviour as an unusual long-duration flare based on a) the temporal evolution of the event, b) the broad component observed

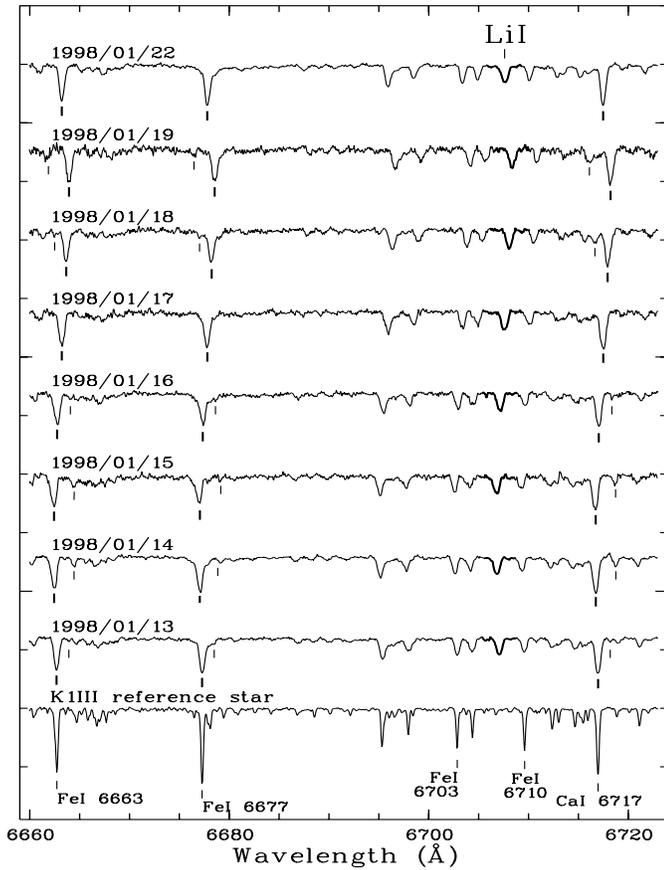


Fig. 1. Spectra of 2RE J0743+224 in the Li I λ 6708 Å line region from 1998 January 13 to 22. A K I III reference star (HR 5340) is also plotted for comparison, with the more intense photospheric lines identified. The wavelength position of the lines of both components are marked.

in the $H\alpha$ line profile, c) the detection of the He I D_3 line in emission and d) a filled-in of the He I λ 6678 Å line. A detailed description of the flare is given in Montes & Ramsey (1998a, b).

Here we analyze the spectra in the Li I λ 6708 Å line region. The Li I absorption feature is clearly observed (Fig. 1) and appears centered at the wavelength corresponding to the primary component with no evidence for a contribution from the secondary. The mean EW is 130 m Å which is a little bit above the normal value for this kind of star, typically < 100 m Å, (Randich et al. 1994; Barrado et al. 1997, 1998). In addition, a small absorption feature corresponding to the Li I λ 6104 Å is marginally detected in the spectrum taken the 4th night. A careful analysis of the Li I λ 6708 Å line indicates that the line profile, EW, and intensity, I , are changing during the observations. The measured EW and I are given in Table 1 and the EW is plotted in Fig 2, where we can see that the increase of Li I line follows the temporal evolution of the flare. The maximum Li I enhancement (50% in EW) occurs just after the maximum chromospheric emission observed in the flare (5th night). However, any real variations of the Li I EW (in excess of the uncertainties) are clearly indicated on nights 1 and 7 only.

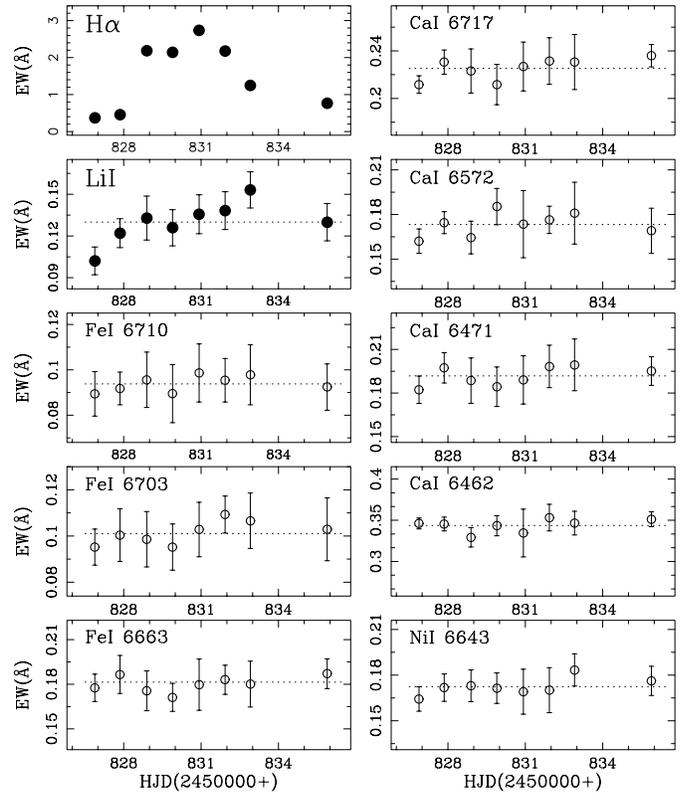


Fig. 2. Measured EW for $H\alpha$, Li I 6708 Å and other photospheric lines during the flare. The dotted line is the mean EW for each line.

In order to test if these variations are real we have also measured the EW of other photospheric lines. We have selected several isolated lines in the same spectral order as the Li I line; Fe I λ 6710.3 Å and Fe I λ 6703.6 Å which are close and similar in strength to the Li I line. In addition we study the more intense lines Fe I λ 6663.4 Å and Ca I λ 6717.7 Å. Other intense lines included in different spectral orders were also measured. All are neutral lines and, as the Li I line, the EW should be enhanced in a different way depending of their excitational potential when the the temperature decrease. These lines are listed in Table 2 together with their excitational potential (χ) and the mean EW (\overline{EW}), the standard deviation (σ), and the peak to peak variation ($EW_{\max} - EW_{\min}$). The measured EW for each night is plotted in Fig 2, the errors bars have been calculated taking into account the error in placing of the continuum and the σ obtained from repeated measures in each line. As can be seen the variations in these lines are very small and, contrary to the Li I line no correlation with the temporal evolution of the flare is evident. The peak to peak variation in the Li I line is a factor 3 larger than in the other lines and the σ of similar strength lines is 3 times smaller. Furthermore, no clear systematic behavior is observed with different excitation potentials.

3. Discussion and conclusions

One source of variability of the Li I λ 6708 Å line could be due to blending with TiO bands at 6707.29, 6707.92, and 6708.16 Å

Table 1. Measured Li I $\lambda 6708 \text{ \AA}$ line parameters

HJD (2450000+)	EW (\AA)	I	Δ Ca - Li (\AA)	λ_0 (\AA)	${}^6\text{Li}/{}^7\text{Li}$
826.8794	0.102	0.146	9.892	6707.789	0.
827.8537	0.122	0.149	9.899	6707.782	0.
828.8925	0.133	0.161	9.898	6707.783	0.
829.8929	0.126	0.165	9.886	6707.795	0.
830.9239	0.136	0.164	9.889	6707.792	0.
831.9308	0.138	0.177	9.880	6707.801	0.
832.9098	0.153	0.178	9.861	6707.820	0.06
835.8891	0.130	0.144	9.853	6707.828	0.11

and CN bands at 6707.64 \AA as these molecular bands also become stronger at the lower temperatures of the starspots. However, the calculations of the Li I abundance in sunspots that take into account these bands (Engvold et al. 1970; Ritzenhoff et al. 1997) concluded that the molecular blend is of lower importance. Thus it seems reasonable to assume that this effect in the stellar spectra is also negligible. At this spectral resolution the Li I line is blended with the nearby Fe I $\lambda 6707.41 \text{ \AA}$ line, which is clearly seen in the spectra of the inactive and Li free star HR 5340 (K1 III). The mean EW measured in these spectra is 20 m\AA , which is much smaller than the observed Li I EW. Furthermore, as the other photospheric lines we measured did not show significant variations, we conclude that this line does not produce the variation in the measured Li I EW. Due to the SB2 nature of this binary in some orbital phases the lines of the primary component could be blended with the lines from the secondary (see Fig. 1). This is clearly seen in the spectrum from the 5th night (which is very close to the conjunction). The EW of the strongest lines measured during this night are noticeably larger than in the rest of the nights due to the contribution ($\approx 15\%$) to the EW from the secondary. We have corrected the EW for this effect by subtracting the EW of the lines in the secondary measured at other orbital phases where the lines are not blended. These corrected values are what we have plotted in Fig. 2. However, for weak lines with EW similar to the Li I line the contribution of the secondary seems to be negligible and this effect is not observed. In conclusion the observed Li I line variations do not seem to be due to any kind of line blends.

The Li I line variations could be caused by possible cold spots and faculae on the stellar surface (see review by Fekel 1996). Since this line is very temperature sensitive, the EW should be enhanced in dark spots but reduced in the bright facular regions as shown by solar observations (Grevesse 1968; Traub & Roesler 1971; Giampapa 1984). While Giampapa (1984) suggests this can substantially alter the EW in stellar spectra, other authors find this is not the case. No detection of Li I EW variations in six active dwarfs have been reported by Boesgaard (1991). The calculations of Soderblom et al. (1993) indicate that the effect is only significant when the fraction of the surface covered by spots is very high (see also Stuijk et al. 1997). Pallavicini et al. (1993) show by means of spectral synthesis simulations that the effects may be less pronounced

Table 2. Photospheric line parameters

Line Id.(M)	λ (\AA)	χ (eV)	$\overline{\text{EW}}$ (\AA)	σ	$\text{EW}_{\text{max-min}}$ (\AA)
Li I (1)	6707.8	0.000	0.130	0.014	0.051
Ca I (18)	6462.566	2.523	0.344	0.008	0.024
Ca I (18)	6471.660	2.526	0.192	0.006	0.017
Ca I (1)	6572.781	0.000	0.173	0.007	0.023
Ca I (32)	6717.685	2.709	0.225	0.009	0.024
Fe I (268)	6546.245	2.758	0.174	0.006	0.021
Fe I (111)	6663.446	2.424	0.180	0.005	0.016
Fe I (268)	6703.573	2.758	0.101	0.005	0.017
Fe I (34)	6710.310	1.485	0.094	0.003	0.009
Ni I (43)	6643.641	1.676	0.172	0.005	0.019

than suggested by Giampapa (1984) and found no evidence that changes in the EW is correlated with the photometric variability due to starspots in four active stars. The simulations done by Barrado (1996) also indicated smaller changes in the EW and even, in certain cases, the presence of faculae can cancel these changes, leaving the EW unaltered. By application of the Doppler imaging technique, Hussain et al. (1997) show that the Li I behaves in much the same way that conventional Doppler imaging Ca I and Fe I lines do. Until now significant variations in the Li I EW have been found only in some stars with very high Li I abundances such as pre-main sequence stars (Patterer et al. 1993; Fernández & Miranda 1998; Neuhäuser et al. 1998) and other young and very active stars (Robinson et al. 1986; Jeffries et al. 1994; Soderblom et al. 1996). Large Li I EW variation has been observed at larger V band amplitude in V410 Tau. Here a peak to peak variability the Li I EW of 0.12 \AA has been found by Fernández & Miranda (1998) when the amplitude in V was 0.6 mag, while little or no variation have been reported by previous work on this star at lower V amplitudes (Basri et al. 1991; Patterer et al. 1993; Martín 1993; Welty & Ramsey 1995). This result is confirmed on the young star Par 1724 by Neuhäuser et al. (1998). However, in CAB little or no variations have been previously reported (Pallavicini et al. 1993). Recent observations (Berdyugina et al. 1998) of the extremely CAB II Peg, which exhibits high V band variations and spot filling factors, show very small Li I EW variations (10 m\AA), poorly correlated with quasi-simultaneous photometric observations. The Li I EW variations that we observe are clearly larger than those reported in other CAB with similar activity levels and Li I abundance. Indeed, in other stars that exhibit large Li I EW variations other photospheric lines exhibit similar EW variations (Fernández & Miranda 1998), contrary to the behavior we report here. Taking into account all these facts, the starspots that we infer on the surface of 2RE J0743+224 from the analysis of the TiO 7055 \AA band (Montes & Ramsey 1998b), do not seem to be the primary cause of the observed Li I line variation.

The possibility of detecting Li I abundance inhomogeneities resulting from spallation reactions in the solar photosphere have been discussed by Hultqvist (1974, 1977). Evidence for such

Li formation have been found through the deexcitation line Li (478 keV) that results from α - α reactions. This line has been detected by γ -ray spectral observations of solar flares with OSO-7 (Chupp et al. 1973), SMM (Murphy et al. 1990) and Yohkoh (Yoshimori et al. 1994; Kotov et al. 1996). Recent calculation of Li production in solar flares by Livshits (1997) agree with γ line observations and suggest that enhancement of Li, especially in the intensity of the Li I λ 6708 Å line, should be observed in the Sun and other active stars. Evidence for a Li enhancement at one umbral position, during a solar flare is reported by Livingston et al. (1997). In other stars (including the UV Ceti flares stars) no evidences of production of Li by nuclear reactions have been previously reported. The possibility of Li production have been discussed only in terms of the energy required (Ryter et al. 1970; Karpen & Worden 1979), as a possibility to explain the high Li abundances observed in CAB (Pallavicini et al. 1992) and stars with high flare activity (Mathioudakis et al. 1995), to explain the widespread presence of Li in very cool dwarfs (Favata et al. 1996), or the ^6Li detection in Population II stars (Deliyanis & Malaney 1995).

Another signature of Li production from spallation reactions is that the $^6\text{Li}/^7\text{Li}$ isotopic ratio should increase. The predicted $^6\text{Li}/^7\text{Li}$ ratio for the Li produced by spallation is ≈ 0.4 (Audouze 1970) or ≈ 0.5 (Walker et al. 1985). The ratio measured in the Sun is between 0.01 and 0.04 (Traub & Roesler 1971; Müller et al. 1975). In Population I stars it is ≤ 0.04 (Andersen et al. 1984; Maurice et al. 1984; Rebolo et al. 1986; Pallavicini et al. 1987), and in Population II stars it is ≈ 0.05 in the two halo stars in which ^6Li has been positively detected, but still lower upper limits are found for a larger number of other stars. (Smith et al. 1993; Hobbs & Thorburn 1994, 1997). In order to estimate the $^6\text{Li}/^7\text{Li}$ in our high resolution spectra we adopt a method used by Herbig (1964) based on the shift of the center of gravity (cog) of the Li I blend toward longer wavelengths as the ^6Li fraction increases. If each Li I component is weighted by its gf -value, pure ^7Li would produce a cog wavelength of 6707.8117 Å while pure ^6Li would be 6707.9713 Å. For weak lines, intermediate mixtures would yield a wavelength, λ_0 , between the two isotopes that would be weighted by the $^6\text{Li}/^7\text{Li}$ ratio as $^6\text{Li}/^7\text{Li} = (\lambda_0 - 6707.8117) / (6707.9713 - \lambda_0)$. To determine the value of λ_0 we have measured the difference between the Li I and Ca I features ($\Delta = \text{Ca I} - \text{Li I}$) where we adopt a wavelength of 6717.681 Å for the Ca I line. We give these values and the corresponding $^6\text{Li}/^7\text{Li}$ ratio obtained in Table 1. The largest difference in the inferred Li I wavelengths amounts to only 0.046 Å, or 30% of one resolution element, and the effects of the blended Fe I, CN, and TiO lines on these inferred, apparent wavelengths of the Li I line are uncertain. In order to estimate the possible errors we have also measured this difference, Δ , for other photospheric lines included in the same spectral order than the Li I feature. The other line Δ 's do not show any trend during the observations and the σ with respect to the mean value is ≈ 0.008 . The Li I line Δ 's shows a tendency to decrease toward the end of the flare, attaining a maximum difference 0.05. This significant change in Δ and thus in the

$^6\text{Li}/^7\text{Li}$ ratio is consistent with increasing ^6Li during the flare as is predicted for the production of Li I by spallation reactions.

The Li I EW variations that we observe are clearly correlated with the temporal evolution of the flare, and large changes are observed in the core of the Li I line, as predict the models of Li production in flares (Livshits 1997). Thus taking into account that the other possible causes of variability have been minimized above we suggest that this Li I is produced by spallation reactions in the flare. The observed $^6\text{Li}/^7\text{Li}$ ratio also support this hypothesis. Neither the EW variation or the $^6\text{Li}/^7\text{Li}$ variation are entirely convincing by themselves but together they are strongly suggestive. This is the first time that such Li I enhancement associate with a stellar flare is reported, and probably the long-duration of this flare is a key factor for this detection.

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