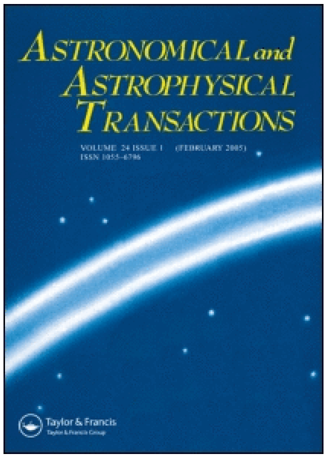

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THE DETERMINATION OF ABUNDANCE OF LITHIUM IN THE SPECTRUM OF THE MAGNETIC Cp STAR β CrB

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The latest results of observations of magnetic star β CrB in the Li region from 1993 to 1995 are presented. β CrB was observed over a number of years. These observations were carried out at the Crimean Observatory with the 2.6-m telescope, using the coude spectrograph equipped with a CCD detector; spectral resolution 0.012 Å, $S/N \geq 200$. The observations cover the period of rotation of the star. To analyse the spectrum of β CrB and derive the abundance of Li the synthetic spectrum method was used. We discuss the possible isotopic shift of Li.

KEY WORDS Lithium in stars, element abandance, magnetic stars

1 INTRODUCTION

The application of modern detectors to astronomical spectroscopy has made it possible to re-examine some old unresolved problems. The real presence of Li in Cp stars is doubtful and doubt has persisted over several years. Moreover, the problem is complicated by some effects, typical of Cp stars, like the presence of a strong magnetic field, inhomogeneity of chemical composition on the stellar surface and binarity of some Cp stars. The most recent observations and investigations of Li in Cp stars (Faraggina *et al.*, 1986; Burkhart and Coupry, 1989; Polosukhina and Lyubimkov, 1996) obtained with modern equipment suggest that a Li resonance doublet is present, but the problem is still unresolved. Unfortunately, there are very few data on Li abundance in Cp stars.

Now, modern equipment offers the opportunity to study this problem more actively. We are conducting a long-term observational programme with the aim of constructing a statistically significant data base for the study of Li in Cp stars.

We have observed β CrB in the Li region over several years. Lithium deserves special attention among the many chemical anomalies of Cp stars, because of the

Table 1. Observational data for β CrB

(1)	(2)	(3)	(4)	(5)	(6)	(7)
		JD 2449000+	S/N	Mean phases	Orbital phases	N
93–06–06	6708	145.392	370	0.4805	0.1939	1
93–06–15	6708	154.365	180	0.9659	0.1962	1
93–06–21	6708	160.347	380	0.2895	0.1977	1
93–06–22	6708	161.335	510	0.3429	0.1980	1
93–06–23	6708	162.341	280	0.3973	0.1982	1
94–02–24	6707	408.469	350	0.7113	0.2618	2
94–02–25	6707	409.486	200	0.7665	0.2621	2
94–03–25	6707	437.490	670	0.2814	0.2693	2
94–07–04	6707	538.379	500	0.7384	0.2953	2
94–07–05	6707	539.380	560	0.7925	0.2956	2
94–09–09	6707	605.326	290	0.3593	0.3126	1
94–09–10	6707	606.305	430	0.4123	0.3129	1
95–03–05	6707	782.533	460	0.9453	0.3584	2
95–06–26	6707	895.287	470	0.0444	0.3875	2
mean spectrum			1590	0.54	0.267	21

Note. Columns: (1) date; (2) spectral region; (3) HJD; (4) S/N ratio; (5) phase of rotation (pos.cross = $2434217^{d}.50 + 18^{d}.487 \times E$); (6) phase of orbital motion (from Oetken and Orweit, 1984: $2425156^{d}.541 + 3873^{d}.0 \times E$); (7) counts of spectra.

changes in the atmospheric abundance of this element during the main-sequence evolutionary phase. A knowledge of the abundance of this element is essential to understand the origin and evolution of the peculiarities observed in Cp stars.

The authors have obtained observations of the Li region during 14 nights for β CrB and have made an analysis of the spectrum in order to: (1) correct the identification of lines in this region; (2) derive the abundance of Li and some other elements, using the synthetic spectrum method; (3) concentrate on the Li isotope problem for magnetic Cp stars, especially for β CrB.

2 THE OBSERVATIONS AND REDUCTION OF THE SPECTRA

The observations of β CrB were carried out during 1993–1995 with the coude spectrograph of the 2.6-m telescope of the Crimean Astrophysical Observatory, equipped with a CCD camera with a red-sensitive GEC detector, 600 × 400 pixel array. The linear dispersion is 2.5 Å$\tilde{\text{m}}$m^{-1} (or 0.056 Å$\tilde{\text{p}}$ix^{-1}) in the region 6708 Å. The spectral resolution is 0.12 Å. The typical S/N ratio is better than 200. The mean exposure time is about 20–30 min. We obtained one to four spectrograms per night. Table 1 gives the list of observations of β CrB.

The reduction of the spectra was performed using the software SPE written by S. Sergeev at the Crimean Observatory. The reduction procedure includes night-sky

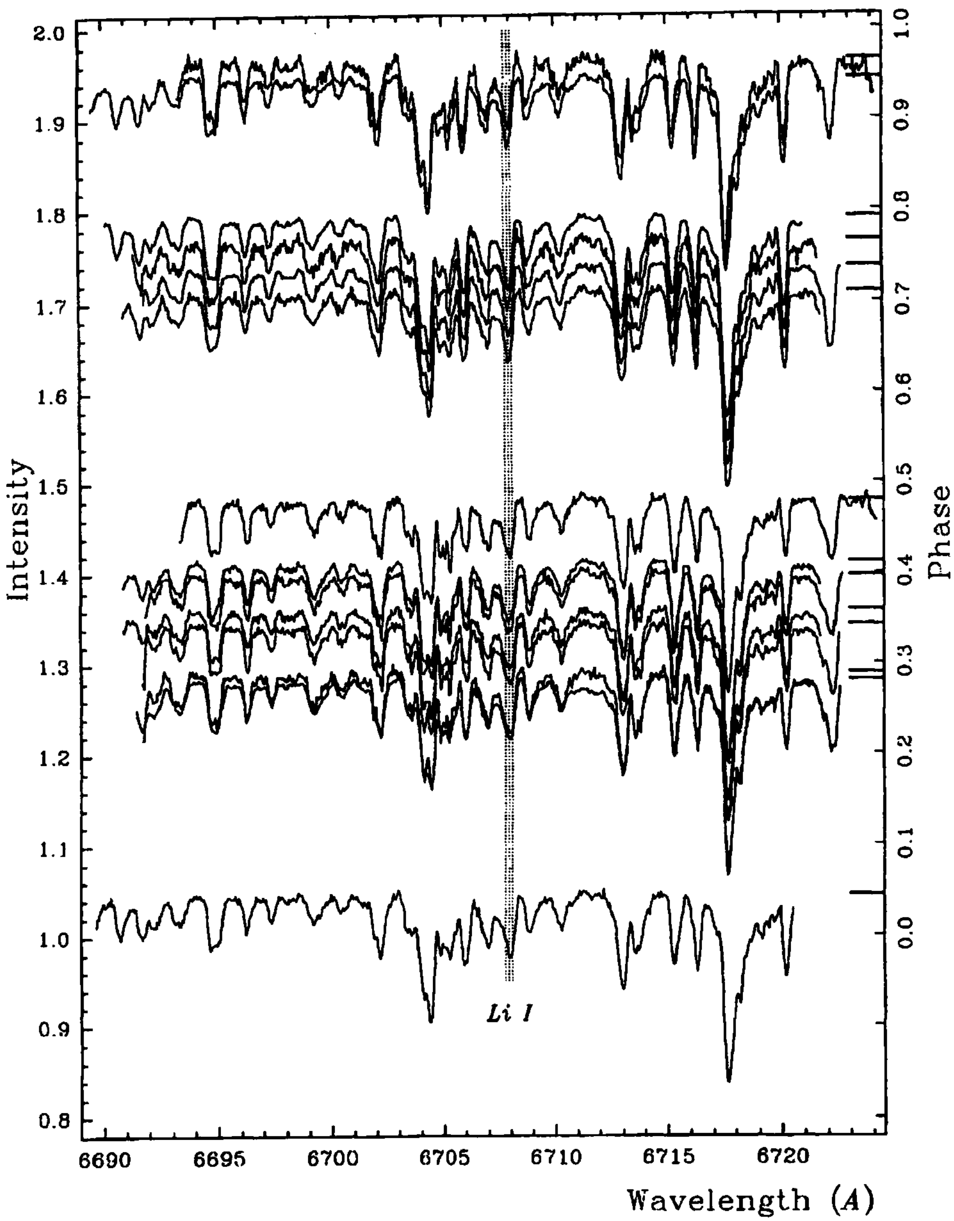

Figure 1a The β CrB spectra normalized to continuum with phase rotation.

subtraction, flat-field correction, normalization of spectra to the continuum, cosmic ray subtraction by visual inspection of the spectra and wavelength calibration.

Special care was employed in order to obtain high precision in the determination of the wavelength scale: (1) the wavelenth calibration was performed using the

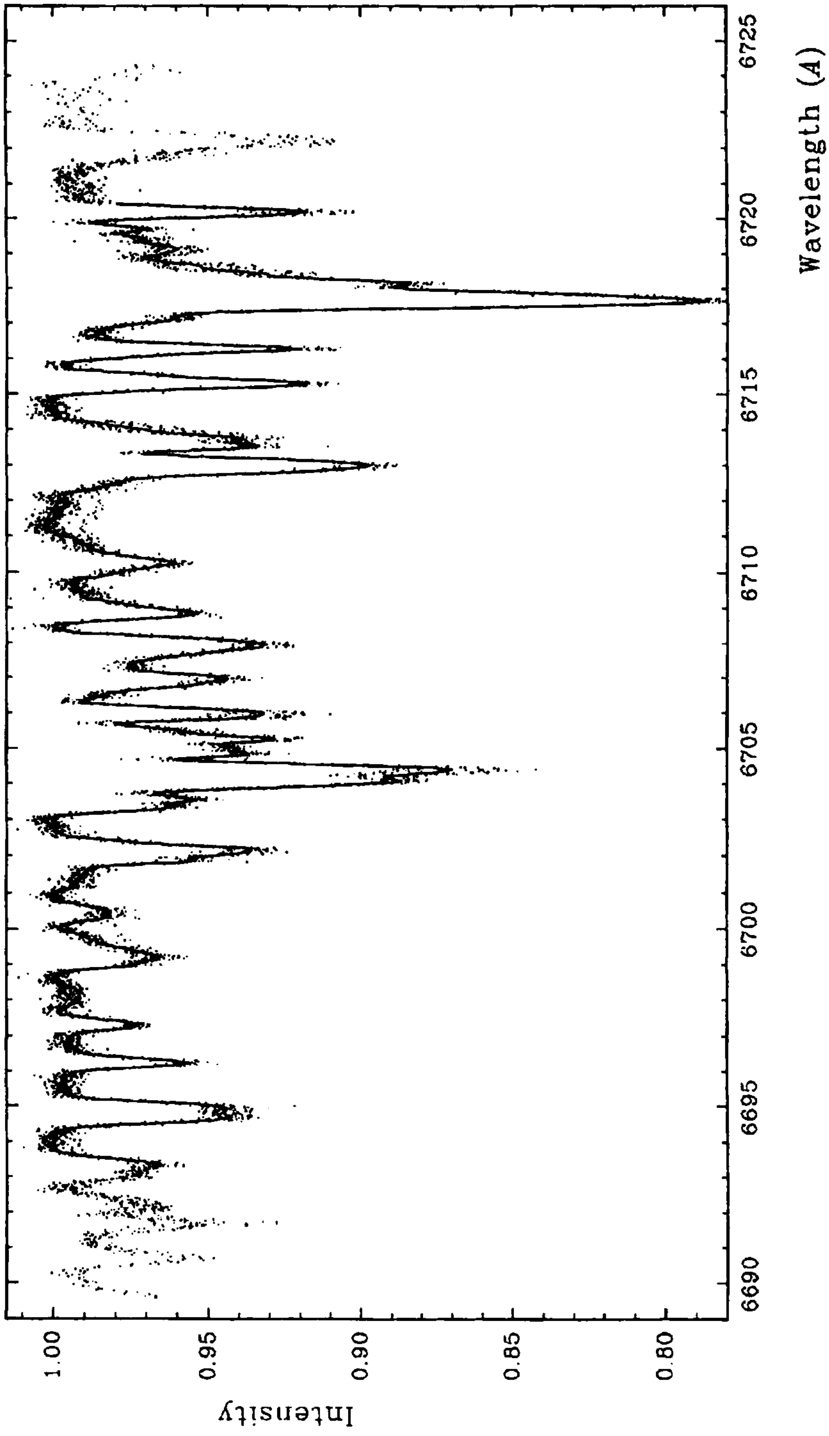

Figure 1b The mean spectrum of β CrB. (The number of spectra $N = 14$).

comparison spectrum of a thorium lamp; (2) the correction of the wavelenth scale was made after critical analysis of the binary radial velocity curve, based on ground data from Neuebauer (1944), Oetken and Orwert (1984) and Kamper *et al.* (1990).

Figure 1a presents the results of the reduction of the individual spectra for every phase. The observations cover the period of rotation of the star (Table 1).

Figure 1b gives the mean spectrum of β CrB ($S/N = 1590$), the result of some iterations, using a cross-correlation function for the individual spectra.

3 ANALYSIS OF OBSERVATIONS AND RESULTS

Owing to the chemical peculiarity of the atmosphere and the complexity of the spectrum of β CrB, the identification of spectral lines is not a straight forward procedure. Our approach relies on calculation of the synthetic spectrum for the observed Li region.

The fundamental parameters of the atmosphere were chosen on the basis of critical analysis of observed and theoretical flux distributions in the visual and UV regions (Breger, 1976; Jamar *et al.*, 1976; Adelman, 1985) (Figure 2).

We adopted values of $T_{\rm eff} = 8000K$, $logg = 4.0$ and metallicity $[M/H] = 1$. The model atmosphere with appropriate parameters (microturbulence velocity $V_{\rm turb} = 2$ km s^{-1}, solar Li isotopic ratio $R = 0.087$), was drawn from the grid of models calculated by Kurucz (1993).

Table 2. List of all elements in the Li region

Element	*Wavelength*	*Element*	*Wavelength*	*Element*	*Wavelength*
Fe II	6693.169	Fe II	6705.748	Fe I	6713.196
Fe II	6693.210	Ce II	6706.051	Cr II	6713.409
Sm II	6693.555	N I	6706.107	C I	6713.586
Gd II	6694.867	Cr II	6706.222	Fe I	6713.745
Si I	6696.044	Fe II	6706.880	Fe I	6715.383
Fe I	6696.304	Fe II	6707.232	Cr I	6715.407
Fe I	6699.142	Fe I	6707.433	Fe I	6716.233
Fe II	6699.164	Li I	6707.761	Cr II	6716.962
Fe II	6699.615	Li I	6707.912	Fe I	6717.298
Fe II	6699.725	Li I	6707.921	Fe I	6717.527
Fe II	6701.248	Li I	6708.072	Ca I	6717.681
Cr I	6701.641	N I	6708.759	Ti II	6717.794
Gd II	6702.093	Fe II	6708.885	Fe II	6717.964
N I	6702.862	Cr II	6710.219	Gd II	6718.130
Fe I	6703.568	Fe I	6710.319	Fe II	6718.883
Gd II	6704.147	Cr II	6710.561	Fe II	6719.639
Fe I	6704.481	Cr II	6710.769	Ce II	6720.280
Ce II	6704.524	C I	6711.323	Cr II	6720.522
N I	6704.839	Fe I	6712.438	Si I	6720.908
Fe I	6705.102	Fe I	6712.676		
Fe I	6705.131	Fe I	6713.046		

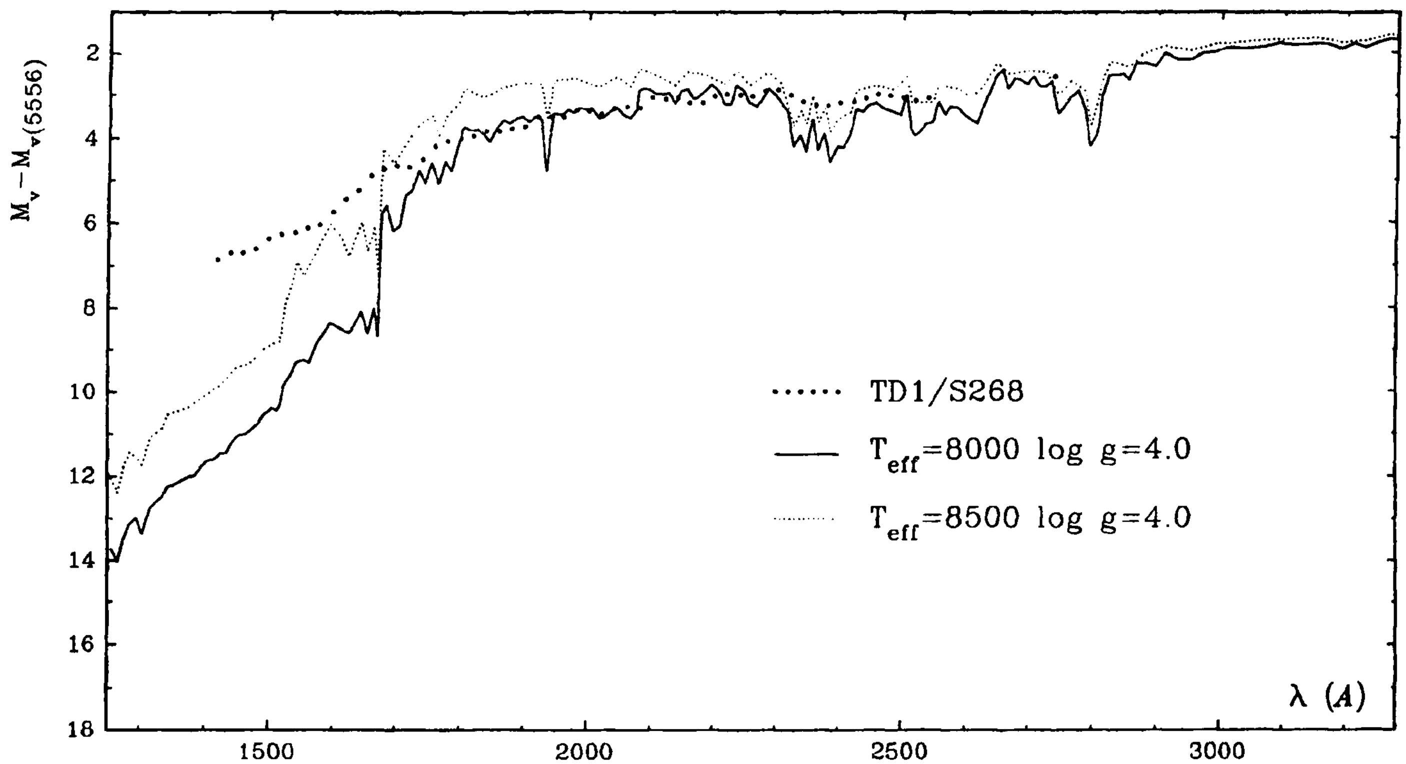

Figure 2 The energy distribution flux in the visual region – Adelman's observation (1985); in the UV region – the space observation $TD/S268$.

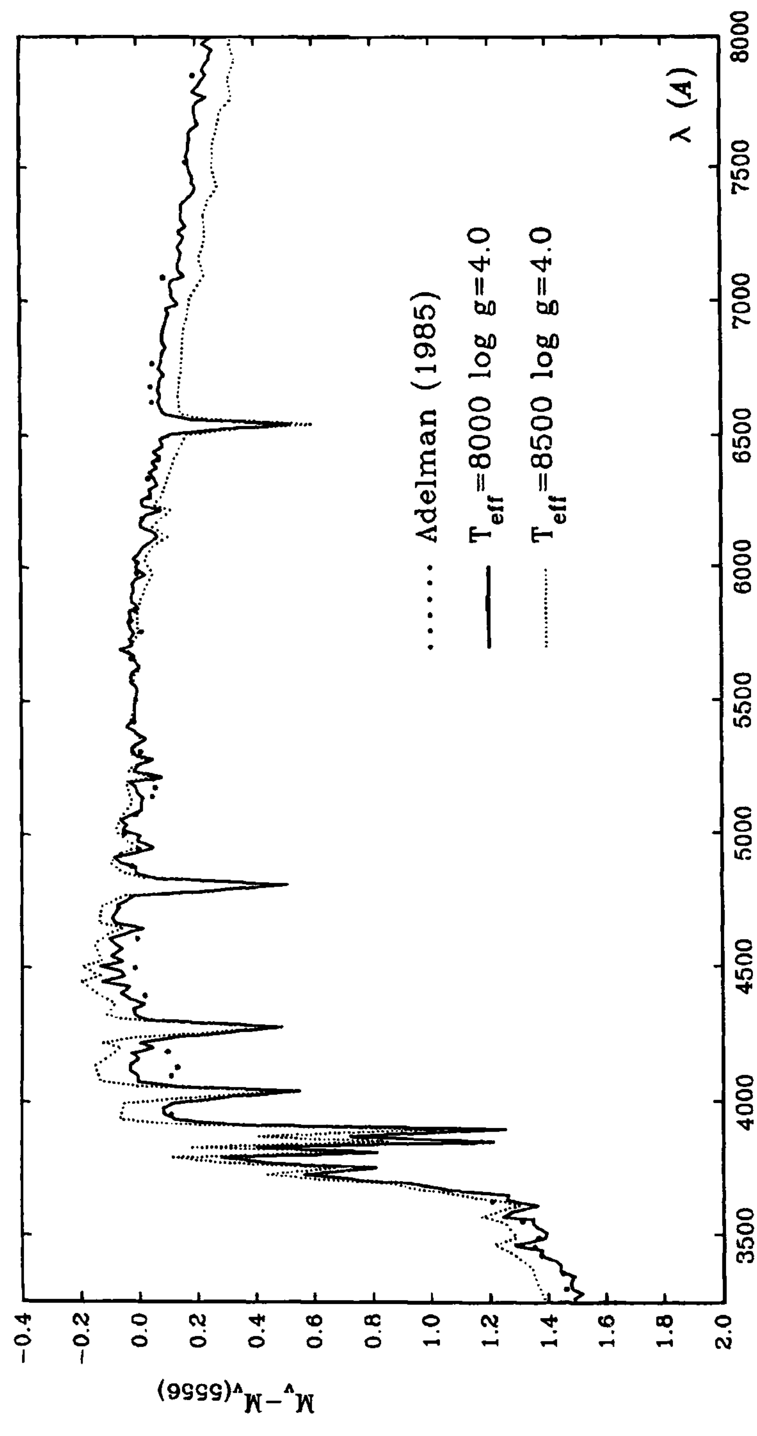

Figure 2 Continued.

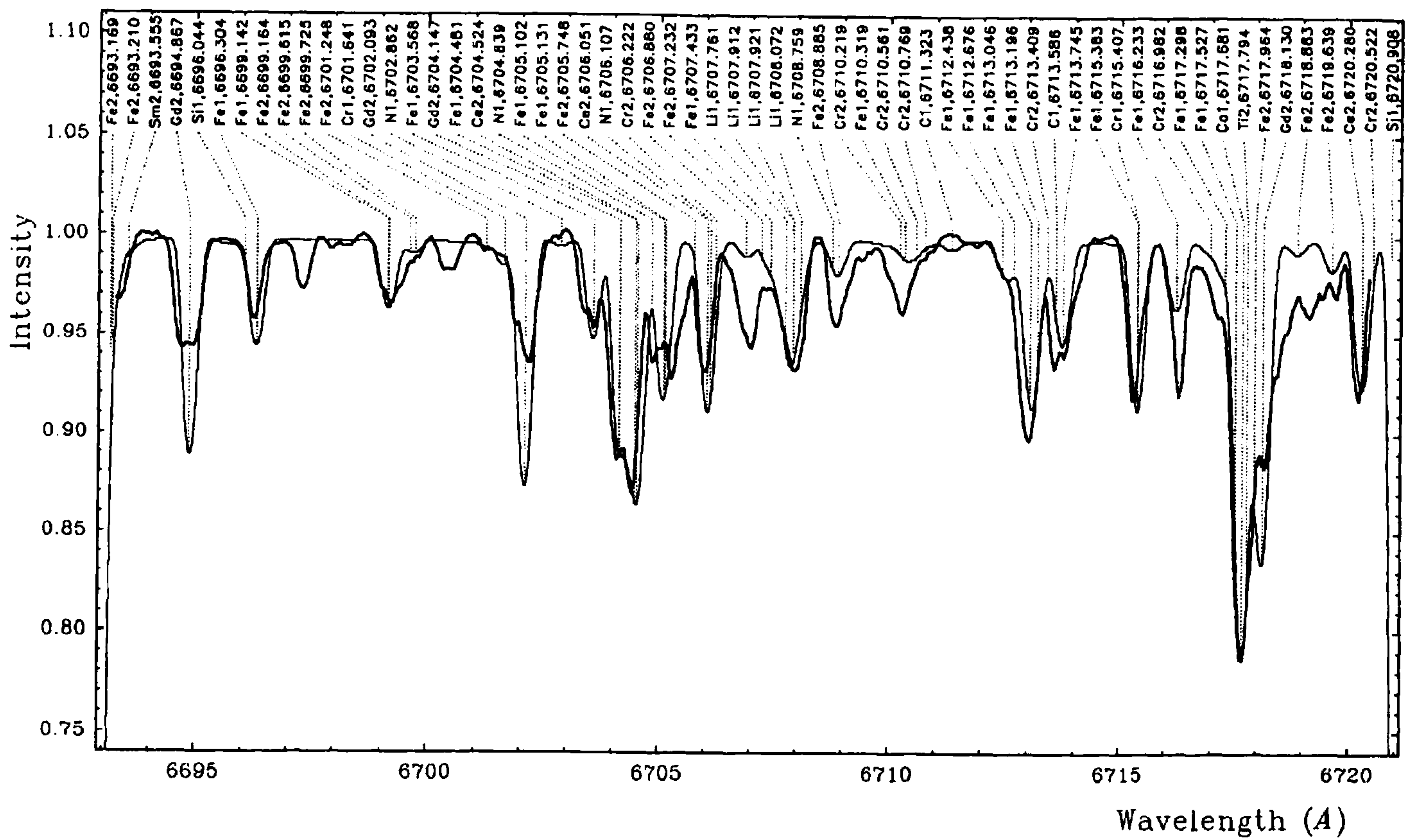

Figure 3 A comparison of mean spectrum of β CrB and synthetic spectra for the model: $T_{\rm eff} = 8000$, $logg = 4.0$, $V_{\rm turb} = 2$ km s^{-1}, the metallicity $[M/H] = 1$, $R_{\rm Li} = 0.70$.

The analysis using the synthetic spectrum method critically depends on the incompleteness of the lines list used. We started the calculations with the original list of Kurucz (1993) and the elements abundances of β CrB determined by Adelman (1973) and Savanov and Malanushenko (1990).

By increasing or decreasing the abundance of different elements in the calculations of the synthetic spectrum it was possible to identity most of the prominent absorption teatures in the spectrum of β CrB, for example, the lines Gd and Ce. The coincidence of the wavelengths of the observed and calculated spectral lines is an additional confirmation of the adopted wavelength scale.

Our final lines list for the spectrum synthesis of the region 6690–6720Å is presented in Table 2. In the Figure 3 the calculated spectrum for β CrB is compared with the observed spectrum.

Only a few lines show shifts toward the red or blue side. We also have discussed the possible causes of this shift. One of these causes may be uncorrected wavelengths for some lines in the list of Kurucz (1993) (for example, Fe I lines 6715.383Å, 6716.233Å). In the calculations of the synthetic spectrum Nave *et al.* (1994) data for Fe I were used. Nave's data are laboratory data and are the best available today.

4 THE LITHIUM DOUBLET

We propose that the principal contribution to the 6708 Å blend comes from the resonance doublet Li I with the two components split by 0.152 Å belonging to the two isotopes Li^7 and Li^6:

Li^7	λ6707.76 Å
	λ6707.91 Å
Li^7	λ6707.92 Å
	λ6708.07 Å

The present determinations (Andersen *et al.*, 1984; Lambert and Sawer, 1984; Nissen *et al.*, 1994) of isotopic composition of Li for different types of stars give $R = Li^6/Li^7 \leq 0.05$ (against the old determinations by Herbig (1964, 1965) and feast who found $R \leq 0.5$). However, the strong surface magnetic fields (especially in cold Cp stars) can make the Li problem very complicated, because they hamper the mixing of surface matter with the internal hotter matter. We have computed two synthetic spectra of β CrB for two different isotopic ratios: $R_1 = 0.08$ and $R_2 = 0.70$. Comparison with the observed spectrum shows that the observed blend agrees better with R_2, and probably a still higher value of R is possible (Figure 4). If spallation reactions occur at the surface, the magnetic field may retain the products of these reactions on the surface and lead to a different isotopic composition. However, a more acceptable explanation could be that the blend of Li is blended with an unidentified feature due to some rare eartl element. The possible sources of blending with the Li doublet are Sm II λ6707.473 Å and V I $\lambda\lambda$6707.518, 6708.094 Å which appear on the theoretical spectrum, only if we use very high overabundance of V

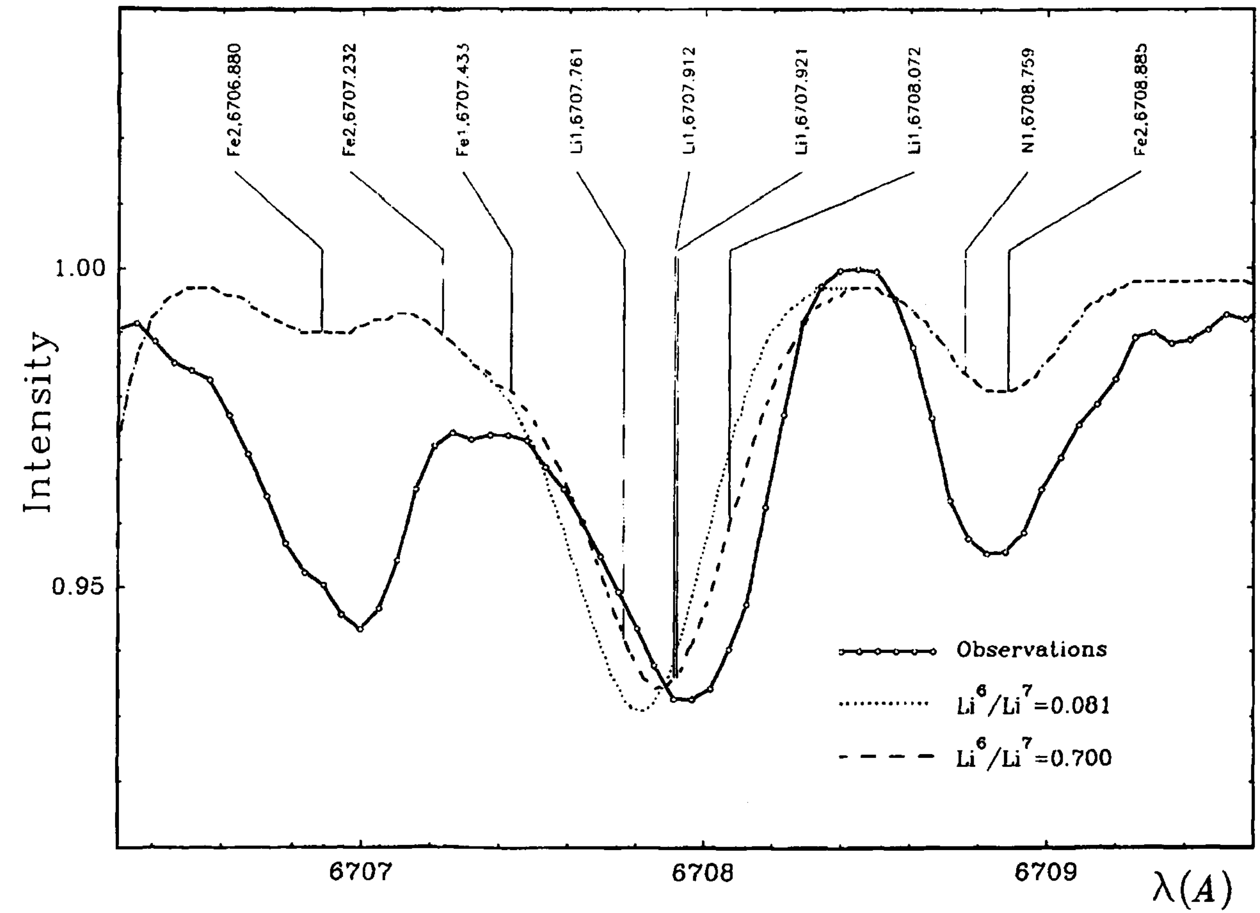

Figure 4 A comparison of the observing profile blend λ6708 Å with the computing profile with different isotopic ratios $R_1 = 0.08$ and $R_2 = 0.70$.

Table 3. Differences in abundance from solar chemical composition

Element		β CrB	$\odot$	$\Delta\beta CrB - \odot$
Li	3	−9.30	−10.88	+1.58
C	6	−4.98	−3.48	−1.50
N	7	−4.30	−3.99	−0.31
Al	13	−8.00	−5.57	−2.43
Si	14	−5.49	−4.49	−1.00
Ca	20	−5.90	−5.68	−0.22
Sc	21	−8.38	−8.94	+0.56
Ti	22	−8.05	−7.05	−1.00
Cr	24	−5.37	−6.37	+1.00
Mn	25	−6.16	−6.65	+0.50
Fe	26	−4.35	−4.37	+0.02
Co	27	−6.69	−7.12	+0.43
Ni	28	−6.79	−5.79	−1.00
Sr	38	−7.71	−9.14	+1.43
Zr	40	−8.54	−9.54	+1.00
Ba	56	−9.51	−9.91	+0.40
Ce	58	−8.05	−10.49	+2.44
Pr	59	−9.81	−11.33	+1.52
Sm	62	−10.03	−11.04	+1.01
Eu	63	−8.53	−11.53	+3.00
Gd	64	−7.90	−8.92	+1.02
Th	90	−9.70	−11.92	+2.22

and Sm. This possibility has been considered in other papers several times. Thus, according to our calculations the influence of these blending lines on the Li doublet should be minimal. Certainly, the possibility remains, that the Li doublet is blended with some unknown element, especially heavy elements and rare earths which are overabundant by factors ranging from 10 to 1000 (see Eu, Table 3).

Table 3 shows the results of determination abundance of Li and other elements present in this region.

Accurate determination of the Li abundance in magnetic stars requires broadening by the magnetic field to be taken into account. To compensate for this effect we have introduced a broadening corresponding to a rotational velocity $V_{\rm rad}$ = 10 km sec^{-1} (this method has already been by other authors used, e. g. Mathys, 1992).

The high abundance of Li (see Table 3) is very interesting. However, we note that there is a very clear shift between the observed blend at λ6708 Å relative to the computed spectrum. We have attempted to explain this shift by a high Li isotopic ratio $R = {\rm Li}^6/{\rm Li}^7 = 0.7$ (Figure 4) (see above).

The overabundance of Li relative to the solar abundance, and the high isotopic ratio is an important peculiarity of β CrB. However, the possibility of blends with the lines of some unknown elements cannot be ignored. On the grounds of theoretical considerations the surface layers of magnetic stars seem to be a plausible site for the production of light elements by spallation reactions induced by accelerated particles in strong surface magnetic fields. However, the observational evidence supporting this idea is not very strong.

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