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Lithium and Isotopic Ratio ^{6}Li/^{7}Li in Magnetic roAp Stars As an Indicator of Active Processes

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1 The Problem of Lithium

Lithium is one of few elements created in the Big Bang nucleosynthesis. After hydrogen and helium, it is the most abundant element created. However, it is one of the most easily destroyed elements that burns at the temperature of only a few million degrees. Therefore, the lithium content is believed to be an indicator of the stellar age and it plays a unique role in the study of origin and evolution of the stellar chemical composition. Depletion of lithium is sensitive to temperature, rotation, convection, diffusion, and mass loss in the pre–main sequence stars and red giants.

Therefore, to the end of the stellar lifetime, the lithium content is depleted. However, among the evolved stars, an anomaly of high lithium abundance is observed. Lithium–rich giants have a great spread in lithium abundances extending over 6 orders of magnitude. The wide spread of lithium abundances for physically similar stars is one of the enigmas of modern astrophysics.

The presence of the lithium resonance line 6708 Å in a stellar spectrum is an indicator of the breaking in the stellar matter circulation between the inner and outer layers of the stellar atmosphere. There are some physical causes for inhibiting the lithium destruction. In the cases when the lithium abundance is abnormally high, we suspect the existence of some lithium production mechanisms.

Before the beginning of formation of the first stars, the interstellar gas contained the Big Bang products, the isotopes of the two simplest elements — hydrogen and helium with a small proportion of Li, Be, B.

Table 1:

					Distribution	
	Element	Atomic number	Atomic weight	Ionisation potential	Earth, meteorites	Stars, nebular
Hydrogen	H	1	1	13.6	–	12.0
Helium	He	2	4	24.6	–	10.7
Lithium	Li	3	7	5.4	3.65	1.26
Beryllium	Be	4	9	9.3	2.86	2.18
Boron	B	5	11	8.3	2.94	–

With the initiating nuclear reactions in a star the content of some elements starts changing. However, in the external layers it remains unchanged, and nevertheless in the initial stage there can occur the processes leading to an exchange of matter between the stellar surface and its deeper layers. There are indications of the appearance of the CNO cycle elements in the atmospheres of early O and B stars. Mixing processes were realised through convection and diffusion. The abundance of metals during this epoch was almost zero.

The protogalactic cloud had an approximately spherical shape, and the first generations of stars have formed a spherical subsystem of the Galaxy, i. e. the halo. All the old halo stars, observed during our epoch, have low $[Fe/H] < -1$. The enrichment of a young Galaxy with metals was the result of explosions of massive evolved stars (supernovae). From here on, the explosions of massive stars had a more and more important role in the enrichment of the interstellar medium with metals. It has been reflected in the chemical composition of the subsequent generations of stars.

After leaving the main sequence the star moves to the region of giants and supergiants. It passes the phase of the deep convective intermixing, which essentially changes the abundance of light elements, especially the lithium abundance, and the star stays practically without lithium.

Lithium and beryllium are special elements because their abundances change as soon as on the Main Sequence.

The destruction of lithium and beryllium occurs in the nuclear reactions already at temperatures:

$$2.5 \cdot 10^6 \text{ K for Li}$$
$$3.5 \cdot 10^6 \text{ K for Be}$$

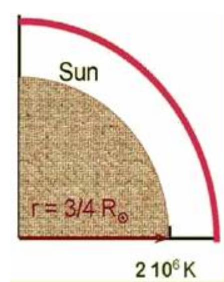
Lithium existed in the initial stage after the Big Bang, and the first, oldest stars practically did not contain any metals.

There is a growing interest to these stars, especially after Spite & Spite (2010) have discovered for the halo stars (metal poor) the so–called "Spite lithium plateau".

Lithium is a very fragile element

decay of Li I isotopes

^{7}Li	$T > 2.5 \cdot 10^6$ K	
	^{7}Li + p $\rightarrow$	^{4}He + ^{4}He
^{6}Li	T>2.0×10^{6}K	
	^{6}Li + D, ^{4}He + ^{4}He,	
	^{6}LiU + p $\rightarrow$	^{4}He + ^{3}He

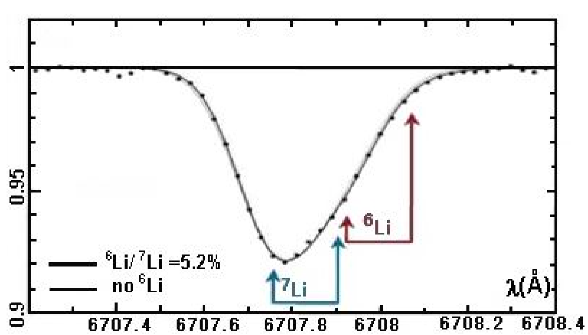


Resolution 100 000, $S/N \sim 100$

Lithium blend

^{7}Li	6707.761
	6707.912
^{6}Li	6707.921
	6708.072

moreover, there is a hyperfine structure



It is not easy to disentangle ^{6}Li and ^{7}Li. The detection of ^{6}Li in 12 metal–poor stars: $^6\text{Li}/^7\text{Li} = 0.04$ (Herbig, 1964, 1965; Asplund et al., 2006).

2 Lithium Production

Principal Source: Cosmic Ray Spallation Reactions in the IS gas STANDARD (Secondary behaviour; B proportional O^2):

Acceleration	CR	C	⇒	Li (^{6}Li, ^{7}Li)
	⇒	N	⇒	Be (^{9}Be)
mechanism	p,α	O	⇒	B (^{10}B, ^{11}B)

REVERSE

Acceleration	CR	H	⇒	Li (^{6}Li, ^{7}Li)
	⇒		⇒	Be (^{9}Be)
mechanism	CNO	He	⇒	B (^{10}B, ^{11}B)

^{6}Li, ^{7}Li are the main relics of the initial phase of the Universe, — lithium ^{7}Li is produced in the initial nucleosynthesis, while lithium ^{6}Li — mainly in the "spallation" reactions.

The problem is that the lithium observations of old dwarfs in the halo show the abundance of lithium ^{7}Li which is essentially lower than that predicted by nucleosynthesis, while on the contrary lithium ^{6}Li in old dwarfs is more abundant than it is predicted by the nucleosynthesis calculations (Spite & Spite, 2010).

3 Lithium in Spectra Stars of Different Spectral Types

The main cause of the Li puzzle are the unknown physical processes which are responsible for a great spread in the lithium abundance for stars with identical physical parameters ($T_{\rm eff}$, $\log g$, M). The strongest Li feature in the stellar spectrum is the lithium resonance doublet at 6708 AA ($\chi = 5.0$ eV), it is very sensitive to evolutional changes, temperature regime and the conditions of mixing. Usually lithium is depleted with stellar age. The presence of the Li line 6708 Å in the stellar spectrum is an indication of stellar youth, or a breaking of mixing between the internal (hot) and external (cool) material of a star, or an indication of active processes with an eventual lithium synthesis (Herbig, 1964, 1965).

Magnetic field is one of conditions for the Li synthesis. The effect of surface activity connected with the magnetic field structure on the Li line profiles is a problem under discussion for the late–type chromospherically active Li–rich giants. Attempts to detect spots and rotational modulation with photometric variations have yielded contradictory results (Pallavicini et al., 1993).

Since the discovery of the first Li–rich K giant with a magnetic field, and existence of oxygen giant (Kumar & Reddy, 2010; Palacios et al., 2010), stars with high Li abundance became a challenging question, although different mechanisms were proposed to explain the high Li abundance on the surface of these stars.

Lambert & Sawyer (1984) suggested that Li–rich giants may be the "descendants" of one or more classes of magnetically peculiar CP stars, i. e. there is an evolutional connection between the magnetic CP stars with high Li abundance and Li–rich red giants.

4 Lithium in Ap–CP Stars

The lithium problem in Ap–CP stars has been for a long time a subject of debate. Individual characteristics of CP stars, such as a high abundance of the rare-earth elements, the presence of magnetic fields, a complex structure of the surface distribution of chemical elements, rapid oscillations of some CP stars, make the task to detect the lithium lines and to determine the lithium abundance rather difficult. Peculiarities of roAp stars, oscillating Ap stars possess many features: the amplitude and phases of oscillations in roAp stars change with stellar rotation. These changes are interpreted in the framework of the oblique pulsator model (Shibahashi & Takata,1993).

- The study of radial velocity behaviour in roAP stars leads to understanding that individual lines of different elements reveal different behaviours, and this pulsation picture of radial velocity is individual for roAp stars.

- In some papers it has been shown that the lines of REE Pr III and Nd III have large amplitudes of RV, as compared with lines of the Fe group (very small variations).

- In papers by Kochukhov et al. (2002), Ryabchikova et al. (2000) it is shown that the amplitudes of pulsation change as a function of the atmospheric depth of line formation.

For some roAp stars (Sachkov et al., 2008) it is shown that the lines Fe are formed in layers (the optical depth in the interval of $-1 \leq \log \tau_{5000} \leq 0$), while Pr and Nd concentrate above $\log \tau_{5000} \leq -8$, higher than Hα. These investigations also explain the anomalies of REE. Some distinctions in the abundances of Nd II, Nd III, Pr II, Pr III are characteristic for many roAp stars.

For roAp stars the anomaly in the Hα line is typical. The very narrow core of Hα line in the spectrum of HD 101065 is formed at the optical depth of $-5 \leq \log \tau_{5000} \leq -2$.

4.1 Lithium in the Spectrum of a roAp Star 10 Aql in July 2006

The UVES spectra of a roAp star 10 Aql were obtained in July 2006 with high–resolution spectrographs at the 8–m ESO VLT (see Sachkov et al., 2008). The red arm of the UVES spectrometer was configured to observe the spectral region of 4960 − 6990 Å (central wavelength 6000 Å). The wavelength coverage is complete, except for a 100 Å gap centred at 6000 Å. The observations were obtained with the high–resolution UVES image slicer (slicer No. 3), providing an improved radial velocity stability and giving the maximum resolving power for $\lambda/\Delta\lambda \approx 90000$ in the red spectral region.

The spectra for four nights (3.07, 9.07, 15.07 and 17.07 of 2006) were reduced and normalised to the continuum level by D. Lyashko with a purpose–built routine for a fast reduction of spectroscopic time–series observations (Tsymbal et al., 2003). An internal accuracy of 30 − 40 m/s was achieved using several hundred ThAr lines in all echelle orders. The continuum normalisation and merging of echelle orders was carried out via the transformation of the blaze function to the response function in each order.

We calculated a set of synthetic spectra for the regions 6130-6155 Å and 6700-6720 ÅṪhe first step was the choice of a model atmosphere from the Kurucz grid (CD–ROM 1994).

We used the Fe I and Fe II lines in the range of 6130 − 6155 Å to determine $v \sin i$, surface magnetic field B_s and the best model atmosphere. We obtained $v \sin i = 4$ km/s, $B_s = 1500$ G, $\log N(\mathrm{Fe})/N(\mathrm{H}) = -4.68$ with the 7550/4.0 model. Then we calculated the model spectra to fit them to each night's mean observed spectra. The results are presented in Table 2.

Table 2: Abundancies $\log N(\mathrm{el})/N(\mathrm{H})$ for modeled spectra of 10 Aql (Kurucz 7550/4.0, $V_r = 4$ km/s, $B_s = 1500$ G)

	Date			
Element	3.07.2006	09.09.2006	15.07.2006	17.07.2006
Li	−9.11	−9.04	−9.04	−9.12
^{6}Li/^{7}Li	0.0	0.2	0.0	0.16
Ce	−9.15	−8.95	−9.15	−9.05
Pr	−9.35	−9.25	−9.35	−9.35
Nd	−9.80	−9.40	−9.80	−9.15!!!
Sm	−9.10	−8.95	−9.10	−9.10

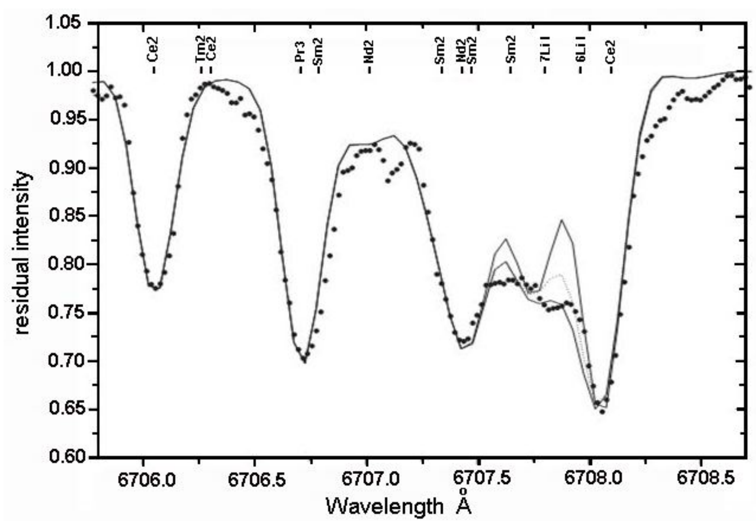


Figure 1: The fitting of observed and calculated spectra of HD 101065 near 6708 Å. The dots: observed spectrum; dashed line: calculated spectrum taking into account lines of the main isotope ^{7}Li only; the thick line: spectrum with the ratio ^{6}Li/^{7}Li = 0.3. The thin line corresponds to a spectrum computed without Li but with the Sm II line 6707.799 Å. The positions of lines which are the main contributors in the absorption are marked at the top of the figure.

4.2 HD 101065 (Example of the Most Peculiar roAp Star)

The presence of lithium in the spectrum of this unique star was first mentioned by Przybylski (1961), and this remark was noticed by Warner (1966), who made additional observations of this star at the Radcliffe Observatory, using the 74” reflector in the spectral range of 3770 – 6880 Å (dispersion 6 Å/mm). He found very strong lines of singly ionised REE in the region of 5500 – 6880 Å, the relative intensities of which are similar to laboratory intensities from the tables of Meggers et al. (1961). However, as mentioned by Przybylski (1966), the line Sm II 6707.45 Å can be considered only as a part of the lithium blend, and the main contribution to this blend remains with the resonant lithium doublet Li I 6708 Å. The first estimation of the lithium abundance relative to the solar value was made by Warner (1966): [Li] = 2.4 dex. This author also mentioned the probable presence of ^{6}Li.

We have carried out detailed calculations of the blend 6708 Å (6705.75 – 6708.75 Å) using the REE list of atomic data from the DREAM and VALD databases (Shavrina et al., 2003).

The evidence for the presence of lithium in the spectrum of HD 101065 is most probable, as shown by the excellent fit of synthetic spectra which include the Li lines, while the synthetic spectra

Table 3: The main absorption contributors in the range 6707.60 – 6708.16 Å

El.	λ, Å	.60	.62	.64	.66	.68	.70	.72	.74	.76	.78	.80	.82	.84	.86	.88	.90	.92	.94	.96	.98	.00	.02	.04	.06	.08	.10	.12	.14	.16
Sm II	6707.648	6	21	20	20	12	6	2	1																					
Nd II	6707.755						1	1	2	2	1	1																		
^{7}Li I	6707.756	1	2	3	3	4	5	6	7	7	6	6	5	4	2	1	1	1												
^{7}Li I	6707.768	1	3	4	4	5	7	9	11	11	11	10	9	7	4	3	2	2	1											
^{7}Li I	6707.907											1	1	1	1	2	2	2	2	2	1	1	1							
^{7}Li I	6707.908											1	1	1	1	1	1	1	1	1	1	1								
^{6}Li I	6707.919										1	1	1	2	2	3	3	3	3	3	2	1	1	1						
^{7}Li I	6707.920											1	1	1	1	1	2	2	2	2	2	1	1							
^{6}Li I	6707.920											1	1	1	1	1	2	2	2	2	2	1	1							
^{6}Li I	6707.923											1	2	2	2	3	3	3	4	3	3	3	1	1	1					
Nd II	6707.029																		2	8	26	62	75	71	55	31	12	3		
^{6}Li I	6707.073																		1	1	2	2	2	3	3	4	4	3	2	1
Ce II	6708.077																								1	1	1			
Ce II	6708.099																					1	3	8	21	37	46	28	13	5

without lithium (only REE lines, Sm II 6707.799) clearly fail to achieve a good match. All possible transitions between the REE energy levels of the NIST were included in the line list for synthetic spectra calculations. The presence of other REE lines near 6708 Å that would not be included in our list remains improbable. All the transitions near 6708 Å are due to low energy levels, and low energy REE levels that would not belong to the NIST are unlikely. The only line which might mimic the Li lines is Sm II 6707.799 Å. But we showed that the absorption in this line is not large enough to account for the observed spectral feature, while a perfect fit is obtained when accounting for the Li line components, which are distributed over a rather wide range (see Tab. 3).

We carried out the calculations with the Zeeman and Paschen–Back splitting of the Li line. For $H = 2300$ G, the Paschen–Back effect is negligible (this is common for magnetic fields lower than 4000 G and cannot induce any additional asymmetry. The Zeeman broadening is also unimportant due to the significant separation (0.15 Å) of the components of the Li doublet. Based on our spectra the calculations in two wider spectral ranges, 6120 – 6180 Å and 6675–6735 Å, we adopted the value $V_t = 2$ km/s, which must compensate for the magnetic broadening of other lines.

In Table 3 we show the ratios of the main contributors in the total absorption (in percentage) in each wavelength with a 0.02 Å step, as they are calculated by the STARSP code, for the lithium doublet range of 6707.60 – 6708.16 Å without the instrumental smoothing, for the model atmosphere 6600/4.2 with $V_t = 2$ km/s, and ^{6}Li/^{7}Li = 0.3.

5 Conclusions

There are two basic explanations of the chemical peculiarity of Ap stars — nucleosynthesis and gravitation (and ambipolar diffusion, Babel & Michaud, 1991).

- The vertical magnetic field provokes diffusion processes, and it is strengthened on the poles. It also explains the enhanced abundances of some elements (ions) in the polar regions. The ambipolar diffusion will give the greatest effect on the light elements, and especially on lithium.

Table 4: Lithium abundance in sharp–lined roAp–CP stars

	HD 101065	HD 134214	HD 137949	HD 137949	HD 166473	HD 201601
$T_{\rm eff}/\log g/[m]$	6600/4.2/0	7500/4.0/0	7750/4.5/0	7250/4.5/0	7750/4.0/0	7750/4.0/0
N(Li) 6780 Å	3.1	3.9	4.1	3.6	3.6	3.8
N(Li) 6103 Å	3.5	4.1	4.4	4.4	4.0	4.0
^{6}Li/^{7}Li 6708 Å	0.4	0.3	0.2	0.3	0.4	0.5

- The most important result of the International collaboration was the discovery of the profile variability of the Li I 6708 Å line with the rotation phase in the spectra of two southern roAp stars HD 83368 and HD 60435 (North et al., 1998).

- The Doppler shift of the Li I line in the spectrum of HD 83368 is about 0.7 Å ($v \sin i = \pm 27.6$ km/s) as a result of rotational modulation of the lithium spotted stellar surface. It was shown also that Li spots are situated near the magnetic poles of the dipole magnetic field (Polosukhina et al., 1999)

- A high lithium abundance can be explained by the physical processes which prevent mixing in the stellar atmosphere and maintain its high initial abundance, the suppression of the convective motions by strong magnetic fields, and the effect of ambipolar diffusion.

- The place where nucleosynthesis could occur is the surface of a star near the polar regions of the magnetic field. High lithium abundance may be produced in CP stars with strong magnetic fields by the spallation reactions in the regions of magnetic poles, where the accelerated protons and alpha–particles destroy the CNO nucleus and produce lithium. (Goriely S., 2007).

References

Asplund M., Lambert D., Nissen P., Primas F., Smith V., 2006, ApJ, 644, 229

Babel J., Michaud G., 1991, A&A, 1991, 248, 155

Goriely S., A&A, 2007, 466, 619

Hauck B., Mermilliod M., 1998, A&AS, 129, 431

Herbig G. H., 1964, ApJ, 140, 702

Herbig G. H., 1965, ApJ, 141, 588

Kochukhov O., Landstreet J. D., Ryabchikova T., Weiss W. W., Kupka F., 2002, MNRAS, 337, L1

Kumar Y. B., Reddy B. E., 2010, IAUS, 268, 327

Lambert D. L., Sawyer S. R., 1984, AJ, 283, 192

Meggers W. F., Corliss C. H., Scribner B. F., 1961, "Tables of spectral–line intensities", Washington, U. S. Dept. of Commerce, National Bureau of Standards

Moon T. T., Dworetsky M. M., 1985, MNRAS, 217, 305

North P., Polosukhina N., Malanushenko V., Hack M., 1998, A&A, 333, 644

Palacios A., Lèbre A., do Nascimento J. D., Konstantinova–Antova R., Kolev D., Aurière M., de Laverny P., de Medeiros J. R., 2010, IAUS, 268, 347

Pallavicini R., Cutispoto G., Randich S., Gratton R., 1993, A&A, 267, 145

Polosukhina N., Kurtz D., Hack M., North P., Ilyin I., Zverko J., Shakhovskoy D., 1999, A&A, 351, 283

Przybylski A., 1961, Acta Astronomica, 11, 59

Przybylski A., 1966, Nature, 210, iss. 5031, 20

Ryabchikova T. A., Savanov I. S., Hatzes A. P., Weiss W. W., Handler G., 2000, A&A, 357, 981

Sachkov M., Kochukhov O., Ryabchikova T., Huber D., Leone F., Bagnulo S., Weiss W. W., 2008, MNRAS, 389, 903

Shavrina A. V., Polosukhina N. S., Pavlenko Ya. V., Yushchenko A. V., Quinet P., Hack M., North P., Gopka V. F., Zverko J., Žižnovský J., Veles A., 2003, 409, 707
Shibahashi H., Takata M., 1993, Publ. of the Astron. Society of Japan, 45, 617
Spite M., Spite F., 2010, IAUS, 268, 201
Tsymbal V., Lyashko D., Weiss W. W., 2003, IAUS, 210, E49
Warner B., 1966, Nature, 211, iss. 5044, 55