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Superflare G and K Stars and the Lithium abundance

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Abstract

We analyzed here the connection of superflares and the lithium abundance in G and K stars based on Li abundance determinations conducted with the echelle spectra of a full set of 280 stars obtained with the ELODIE spectrograph. For high-active stars we show a definite correlation between $\log A(Li)$ and the chromosphere activity. We show that sets of stars with high Li abundance and having superflares possess common properties. It relates, firstly, to stars with activity saturation. We consider the X-ray data for G, K, and M stars separately, and show that transition from a saturation mode to solar-type activity takes place at values of rotation periods 1.1, 3.3, and 7.2 days for G2, K4 and M3 spectral types, respectively. We discuss bimodal distribution of a number of G and K main-sequence stars versus an axial rotation and location of superflare stars with respect to other *Kepler* stars. We conclude that superflare G and K stars are mainly fast rotating young objects, but some of them belong to stars with solar-type activity. At the same time, we found a group of G stars with high Li content ($\log A(Li) = 1.5 - 3$), but being slower rotators with rotation periods > 10 days, which are characterized by low chromospheric activity. This agrees with a large spread in Li abundances in superflare stars. A mechanism leading to this effect is discussed.

Keywords: Stars: activity – Stars: coronae – Stars: rotation – Stars: flares – Stars: abundances

1 Introduction

One of the most important results of study of activity of low-mass stars is a detection with the *Kepler* mission of superflares whose total energy in optics and near IR-range is $10^{33} - 10^{35}$ ergs, that is by 2–4 orders of magnitudes more than the total energy of the largest flares on the Sun. What distinguishes the stars where such cataclisms can occur? This problem is solved in two ways; first is determination of fundamental parameters and flare occurrence frequencies. This was fulfilled by Maehara et al. (2012) and Notsu et al. (2015a, b) where they found that these events are typical for G and partly K stars, which rotate faster than field stars and are more magnetically active. Another way is comparison of general properties of superflare stars with distinctive features of other kinds of active late-type stars. This is comparison of activity at different layers of stellar atmospheres. Messina et al. (2003) were the first who have analyzed rotational modulation of the optical continuum caused by spots and the X-ray fluxes of stars of different spectral types. Lately new X-ray data and observations of optical variability of many late-type stars with the *Kepler* misson have appeared. Recently we considered a possibility of occurrence of very powerful events on late-type stars in the frameworks of current ideas on solar flares (Katsova and Livshits, 2015). Wichmann et al. (2014) Şstarted a programme to study the nature of the stars on which these super flares have been observed.Ť Here we are trying to analyze features of those stars, where such extremal phenomena occur, on the base of new results of multiwavelength observations of late-type stars.

2 Where do Superflares Occur?

As an example, let us consider a restricted set of *Kepler*'s stars where superflare light curves were registered with the higher temporal resolution (1 min). We use data for 83 active late-type dwarfs from *Kepler* short-cadence mode. Superflare stars are taken from the list by Balona (2015) with an exception of binary systems. To study their activity, we appealed to data on activity indicies of these stars. Photospheric activity is manifested in optical and near-IR variability discovered with *Kepler* mission. Therefore, first of all we compare amplitudes of brightness variations with rotation periods of these stars. The amplitudes of rotational modulation (ARM) are sometimes referred to as $\Delta F/F$ or R_{ppm}, and defined by a method by Basri et al. (2011), modified by McQuillan et al. (2014). Physically, they are an estimate of a minimal spot area, in parts per millions. It is a good estimation when the rotation axis of a star is inclined to the line of sight on an angle $i = 90$ degrees. At $i < 20$ degree, this method leads to a large errors in evaluations of spot areas.

These ARM values are presented in Fig.1 versus axial rotation periods for selected 83 G stars with $T_{eff} = 5043 - 5946$ K and K stars with $T_{eff} = 3900 - 5043$ K separately. Comparison of ARM with the maximal spot area on the Sun in the highest cycles (0.3% or ARM up to 3000) shows that most of superflare stars are characterized by high photospheric activity.

Note that this is consistent with detailed results by Maehara et al. (2014) showing that most of superflare stars rotate with periods of 0.5 – 7 days (a maximum around 5 days). Some of these stars rotate with periods of about 15 days.

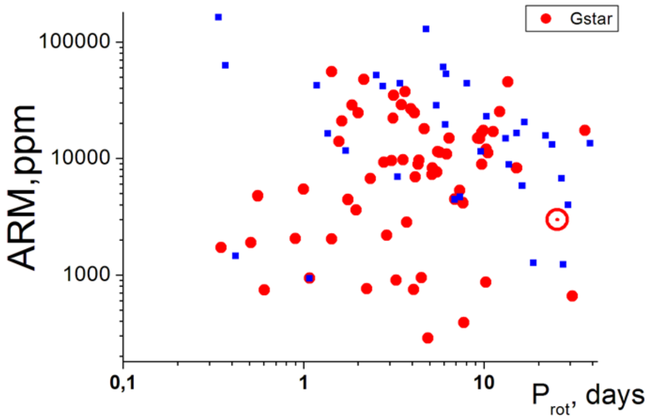

Figure 1: Amplitudes of the rotation modulation (ARM) for G (red) and K (blue) superflare stars

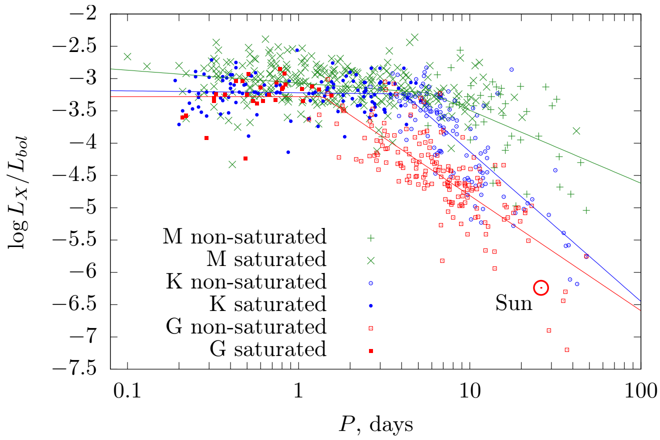

Figure 2: The coronal activity index versus the rotation period

Here we try to answer a question "Is activity in superflare stars saturated?" Activity saturation manifests itself the best in the soft X-ray range. Research of activity of many of stellar coronae became possible owing to the creation of catalog of active F – M stars based on the X-ray observations with space missions *XMM-Newton*, *ROSAT*, *Einstein* (Wright et al. 2011). We plotted again the coronal activity index $R_X = \log(L_X/L_{bol})$ versus the rotation period. It is reliably shown that there are two groups of stars: the first one is a large number of stars with activity saturation where R_X is close to 10^{-3} and does not depend practically on the rotation period. These stars are fast rotators. The second group of stars are less active and demonstrate clear dependence of R_X on P_{rot}. We call activity of stars of this group the solar-type activity. For these stars, Skumanich's law, $v \propto t^{-1/2}$, where v is axial rotation rate and t is an age of a star, is valid. Thus, decline of the coronal activity when a star is braking became a basis for a method of gyrochronology (age estimate from the activity level).

Reiners et al. (2014) proposed an original method for an analysis of data from the Catalog by Wright et al. (2011) and established correctly the rotation period, that corresponds to transition from saturation to solar-type activity. On the average, this period is $P_{sat} = 1.6$ days.

However all these authors considered all late-type stars together without separation onto spectral types. We carried out research, similar to that done by Reiners et al., but separately for G, K, and M stars. We used the original Catalog by Wright et al. (2011) including 824 stars. After Reiners et al. (2014), we adopted this relationship as $L_X/L_{bol} = kR^{\alpha}P^{\beta}$, where R is a radius of a star and P is its rotation period. Details of our approach see in Nizamov et al. (2016). Result is given in Fig. 2. The transition from a saturation mode to solar-type activity takes place at values of rotation periods 1.1, 3.3, and 7.2 days for G2, K4 and M3 spectral types respectively. Strictly speaking, these values are obtained for a case of $L_X \propto P_{rot}^{-2}$.

In lack of X-ray data for the most of superflare stars, let us consider data on the amplitude of rotational modulation, ARM, for them against the background of the entire array of *Kepler* stars. Fig.3 shows location of G and K superflare stars (the same as those in Fig.1) among the background active *Kepler* stars, selected from McQuillan et al. (2014) within the effective temperature interval $T_{eff} = 5000 - 5500$ K. It is clearly seen that even the minimal level of the photospheric activity of these superflare stars exceeds significantly the maximal solar ARM value, which is about of 3000. The *Kepler* data for 34030 stars demonstrate distinctly bimodality in distribution of a number of stars over the rotation periods (McQuillan et al., 2014). This effect of bimodality is the most pronounced for K stars. Separation stars on two subgroups is traced both in values ARM and P_{rot}. This reflects simultaneous existence of stars with activity saturation and with solar-type activity both in one range of rotation periods (for instance, 5 – 15 days) and in restricted interval of T_{eff}. Bimodality is manifested also both in the X-rays and in the H_{α} data, where there is clearly two flux radiation levels for K stars (see Fig.7 in Martinez-Arnaiz et al., 2011).

Here is important the above defined period corresponding to transition from the stars with activity saturation to stars with solar-type activity. This period grows from G to M stars. An interval of rotation periods of K stars with saturated activity is greater than that of active G stars, and these K stars contribute more to the total activity of objects of this spectral type. It relates both to quasi-stationary activity and to flares including superflares. As for M dwarfs, the character of their activity depends on other factors which eliminates this effect.

Fig.3 shows that superflare stars are situated in the interval of rotation periods 1 – 10 days and values ARM=10000, that is directly in the space of activity saturation of G stars. At the same time a part of K stars falls into regions of location of slower rotating stars.

Thus, we conclude that superflare G and K stars are mainly fast rotating young objects, but some of them belong to stars with solar-type activity.

3 The Lithium Abundance in Superflare G and K stars

It becomes clear that the superflare stars are mainly stars with activity saturation. Many of these stars have high lithium abundances. We decide to compare superflare stars with those with registered Li 6708 line. Fig.4 shows the Li abundances versus T_{eff} for more than 1300 late-type dwarfs and subgiants taken from Ramirez et al. (2012). 25 superflare stars (blue circles) with the lithium data presented by Honda et al. (2015) are plotted against these lithium stars.

Here it is seen that superflare stars demonstrate a spread in the lithium abundance, and only part of them fall in the same region where most of Li-stars of the same spectral type are situated. This relates mostly to K stars, and the high Li abundance can be inherent both for K stars with activity saturation and for the case of low-active ones (Honda et al. 2015). Note also that both the lithium content and occurrence of superflares are sensitive to the stellar radius. Increase of the radius by 5 – 10% leads to changes in the A(Li) and the frequency of occurence and the total energy of superflares.

Earlier we found a weak Li abundance-activity correlation for FGK stars which were more active than the Sun (Mishenina et al., 2012). These results are based on the 130 spectra collected with the ELODIE spectrograph using the 1.93-m telescope at the Observatoire de Haute Provence. The Li abundances in new set of 150 stars were obtained with the same method as Mishenina et al . (2012), by fitting the observational profiles to the synthetic spectra computed with the STARSP LTE spectral synthesis code, developed by Tsymbal (1996). A sample of a stellar spectrum in the Li 6708 line region is given in Fig.5. Such a correlation was confirmed on a wider set of more active stars, while some inactive stars demonstrated also the high lithium content (Fig. 6 in accordance with Katsova et al., 2013). We present here re-analyse of a full set of stars with the registered Li line.

Comparison of both sets presented in Fig. 7 shows that added (new) stars are mainly G dwarfs with low chromospheric activity. Note that stars of old and new sets have similar metallicity. Results of a new analysis are given in Fig.8a, b and c as a dependence of log A(Li) on the effective temperature, rotation velocity $v \sin i$, and the index of the

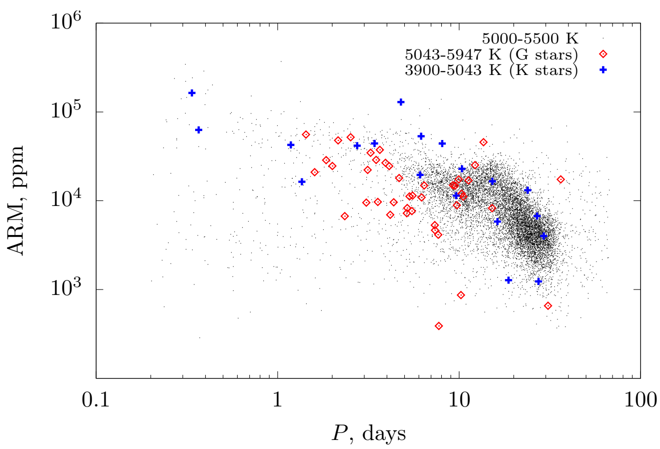

Figure 3: Amplitudes of rotation modulation (or relative spot area) versus P_{rot} for superflare G and K stars against the background other several thousands *Kepler* main-sequence stars with $T_{eff} = 5000 - 5500$ K by McQuillan et al. (2014). Note that ARM values < 1000 relate to stars observed under an angle between the rotation axis and the line of sight $i < 20°$.

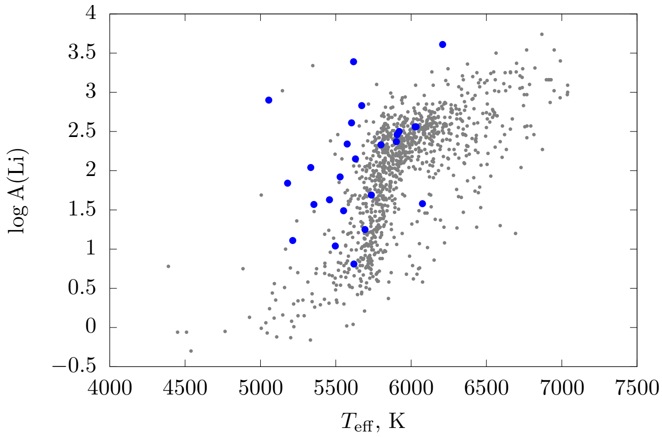

Figure 4: 25 Superflare stars (blue circles) from data by Honda et al. (2015) with registered lithium abundances against nearby FGK dwarfs and subgiants (black circles) by Ramirez et al. (2012). Upper limits in the Li abundances of both sets of data are excluded.

chromospheric activity R'_{HK}.

This Fig. 8 shows that in fact, we found a group of G stars with high Li content ($\log A(Li) = 1.53$), most of which rotate as slow as the Sun. These new stars are slower rotators with rotation periods > 10 days. Of course, some of new stars are fast rotators with activity saturation. The best separation of the slow (blue) and fast (red) rotators is seen in Fig.8c. It came as a surprise that high Li-stars can be characterized by the lower chromospheric activity, $\log R'_{HK} = 10^{-5}$, than the Sun in the minimum of a cycle.

As it was mentioned above, the part of superflare stars are fast rotators with activity saturation. It relates to a wide family of stars with rotation periods from a few hours to 8 days, and maximal number of objects rotates with period of about 5 days. Many of these stars demonstrate high Li abundances while their activity does not depend practically on the rotation period. Our finding a group of inactive G stars with high lithium content requires a separate study.

Indeed, the existence of stars with low activity (and hence considered as old) but with high lithium abundance is an apparent problem. Why can an old star be lithium-rich?

In answer to this question, we suppose that already on the pre-main sequence stage (pMS), solar-like stars may be formed with different lithium abundance. After the pMS-stage ends and during MS stage, lithium abundance only slightly diminishes in stars more massive than the Sun.

This picture of lithium evolution is supported by the study of the present Sun. Analysis of new helioseismic data show that the rate of lithium depletion is small in the convective zone of the present Sun. Therefore the lithium abundance is near the same during the Main Sequence stage, and it has decreased from the primordial abundance already at early stage. In assumption of its constant value during the MS-stage, the present low solar lithium abundance cannot be explained. So, a conclusion is made about crucial role of pMS-stage in the lithium evolution. Observations of solar twins also support this hypothesis: there is large dispersion of lithium abundance even in young stars and the mean value does not depend on stellar age (Oreshina et al. 2015,

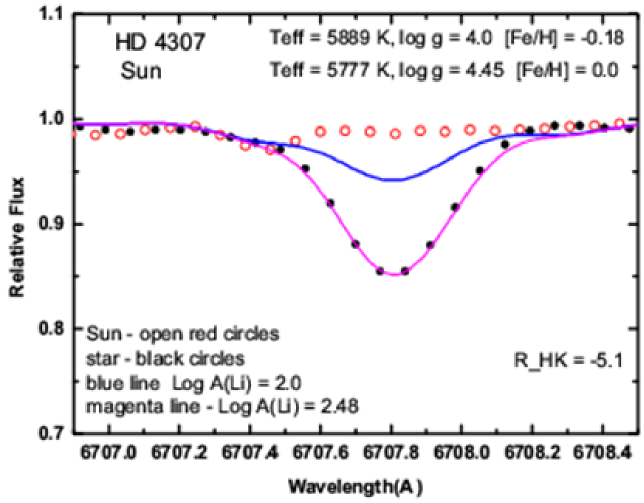

Figure 5: A sample of the spectrum of HD 4307 with well observed Li 6708 Å line

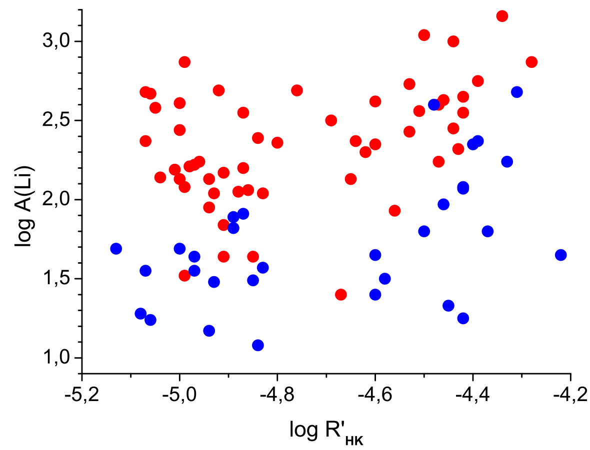

Figure 6: The lithium abundances versus the chromospheric activity index for previous set of stars. Red points are stars hotter than the Sun, blue points present stars cooler than the Sun

Thevenin et al. 2016).

In principle, this mechanism can explain a large spread in Li abundances in superflare stars reported by Honda et al. (2015). However, such a scenario can be realized rather in pMS stars of ages of dozens Myr when initial Li abundance does not exceed 1.5 – 2. In Li-rich stars, rotating much faster, processes can occur that lead to decline lithium abundance during life time on MS. This problem requires additional consideration.

4 Conclusions

The starting point of all our considerations is quite obvious statement that superflare stars are characterized by high activity at all the layers of the stellar atmosphere. In order to find objective evidence for this assertion, we compared firstly activity levels of late-type dwarfs and superflare stars. First of all, we came back to problem of coronal activity in stars of different spectral types. Here we have continued study of relation between the coronal activity index and the rotation period. Earlier Wright et al. (2011) and Reiners et al. (2014) conducted an appropriate analysis for all late-type stars. We modified an approach proposed by Reiners et al. and obtained results for G, K, and M stars, separately. We received that that transition from a saturation mode to solar-type activity takes place at values of rotation periods 1.1, 3.3, and 7.2 days for G2, K4, and M3 spectral types, respectively. Insofar as most superflare stars rotate with periods of 0.5 – 7 days with a maximum around 5 days, as it follows from Maehara et al. (2014), this means that activity of G and K superflare stars is saturated or close to saturation mode. This conclusion is valid for chromospheres also, as it is seen in IR $Ca\,II$ observations and H_α data (Notsu et al. 2015b, Martinez-Arnaiz et al 2011).

Secondly, we compare activity in G and K star photospheres with those in superflare stars. *Kepler* data demonstrate bimodality in distribution of a number of active late-type stars. This bimodality presents both in rotation periods and in amplitudes of rotation modulation (this means apparently bimodality in spot area). On the example of a limited set of uperflare stars, we have demonstrated similar bimodal distribution in a number of stars.

Third, involvement of our resuls of study of Li abundances of late-type stars supports above mentioned conclusions. Indeed, both superflare stars and stars with high Li abundances are characterized by fast rotation and are quite young, therefore their activity level and the lithium content demonstrate a definite correlation. Besides, we reveal some number of G stars with low activity and the high Li abundance. In these stars, processes, responsible for the lithium content, are apparently associated with specific initial physical conditions with which they come to the main sequence.

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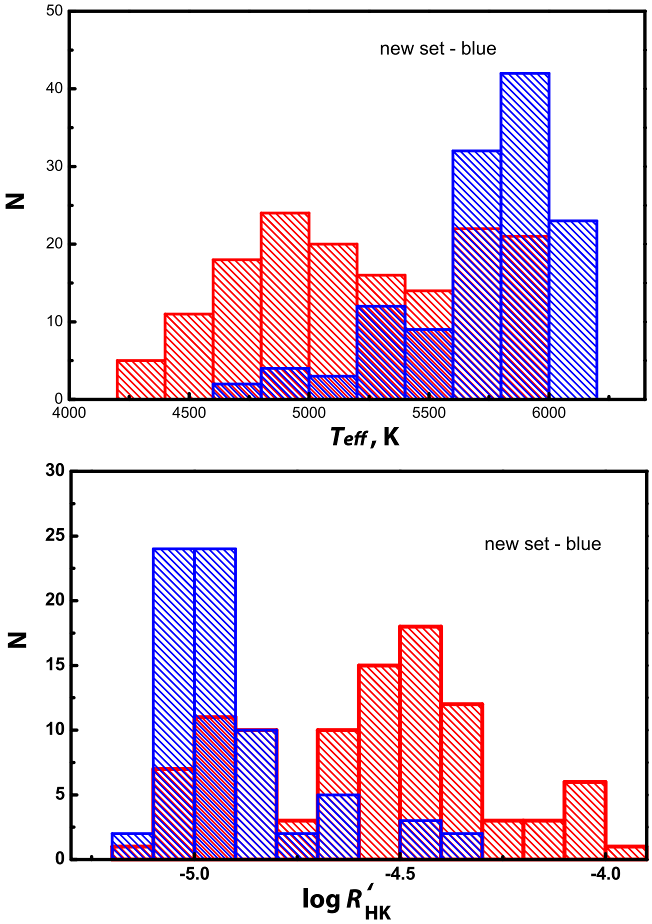

Figure 7: Histograms comparing the previous (red) and new (blue) sets of stars studied

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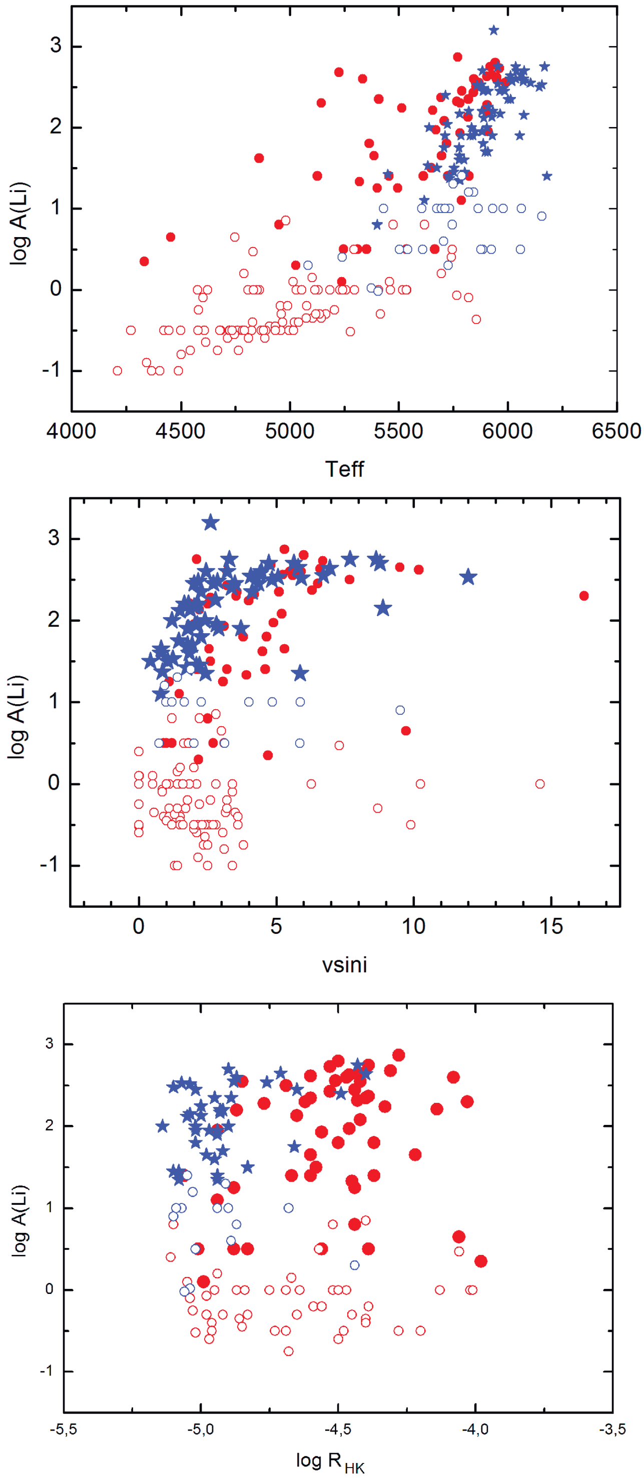

Figure 8: Dependences of log A(Li) on T_{eff} (a), log $A(Li)$ on $v \sin i$ (b), and log $A(Li)$ on R'_{HK} (c). Red colour relates to stars of the pervious set, blue color represents stars of new set. Blue and red open circles are upper limits for log A(Li) in corresponding sets