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THE CHEMICAL COMPOSITION OF THE ACTIVE STARS

L. V. Glazunova[1,2]

[1] Department of Astronomy, Odessa National University
T.G.Shevchenko Park, Odessa 65014 Ukraine, *astro@paco.odessa.ua*

[2] Odessa National Academy of Telecommunications,
Kuznechnaya street 1, Odessa, 65029, Ukraine

ABSTRACT. The comparison of the results of the studies of the active stars' chemical composition obtained by different authors has been performed. It was concluded that the difference between the abundances of some elements in active and inactive stars becomes significant ($> 3\sigma$) only for the active stars with high chromospheric activity ($lgR^{'}_{HK} > -4$). This is the case primarily for the light elements, namely Li, Na and Al, as well as heavy elements with $Z > 30$.

Key words: Stars: RS CVn end BY Dra binaries, abundances – stars: individual: LX Per, OU Gem, BY Dra.

1. Introduction

Stars with outer convective envelopes and luminosity classes V to III with the observed emission in the CaII $H\&K$ lines, the light curve peculiarities, as well as enhanced X-ray and microwave emission, are termed as active stars (Berdugina, 2005). One of the quantitative measures of chromospheric activity is the activity index $lgR^{'}_{HK} = lg(F_{HK}/\sigma T^4_{eff})$, which was first introduced by Noyes et al. (1984). This index describes the correlation between the emission flux in the CaII H&K lines and luminosity of a star. Several types of active stars of widely differing masses and in different evolutionary stages have been discovered to date; these are young T Tauri (T Tau) stars which have not yet reached the Main Sequence (MS); RS Canum Venaticorum (RS CVn) stars which represent evolved synchronized fast-rotating components of close binary systems; W Ursae Majoris (W UMa) stars; cool low-mass dwarf BY Draconis (BY Dra) stars; and single giants of the FK Comae (FK Com) type. Objects within such a range of evolutionary states have one common feature they all have outer convective envelopes and high rates of spin resulting in the magnetic field enhancement. The highest chromospheric activity is exhibited by the RS CVn binaries and the BY Dra type low-mass dwarfs (Strassmeier, 2005).

The RS CVn stars are close detached binary systems with the orbital periods from several days to several tens of days; in these binaries, one component is usually a G-K subgiant, while another one is a low-mass main-sequence star. The chromospheric activity of the subgiant is deemed to be related with its rather rapid rotation as a close binary component. The activity of these stars was first detected from the sinusoidal variations in their light curve, which did not coincide with the binarys orbital period. The associated brightness variations are considered to be related with the presence of dark spots on the subgiants surface; these are similar to sunspots,but are relatively larger (covering up to 20% of the disc area in some binary systems). The amplitude of the binary brightness variations related to these spots is from several hundredths to several tenths of a magnitude. The difference between the spot and disc temperatures can reach as high as 1500 K. The chromospheric activity index is higher than -4.0 dex.

The BY Dra type stars are main-sequence dwarfs with spectral types G, K and M and masses $0.08 \div 0.5 M_{\odot}$. High magnetic activity is exhibited as strong optical flares and periodical variations in the brightness of the out-of-eclipse portions of the light curve with amplitudes of up to 0.1^m. This peculiarity is due to large spots on the stellar surface (covering up to 10% of the stellar surface).

Such high chromospheric activity on the stellar surface is likely to affect not only resonance, but also subordinate spectral lines, resulting in altered surface chemical composition. The investigated peculiarities of the chemical composition of active stars can be an additional indicator of physical processes on their surfaces.

2. The chemical composition of inactive stars with outer convective envelopes and luminosity classes V to III

Before proceeding to a discussion of the chemical composition of chromospherically active stars, the peculiarities and errors in determinations of the chemical composition of late-type inactive stars in our Galaxy should be considered. This can be done by exemplifying the study of the chemical composition of the HR 1614 moving group dwarfs by De Silva et al. (2007), in which the abundances of 13 elements were determined from high-dispersion spectra of 14 cluster stars and four field stars. The reported mean standard deviation deviation) of the derived iron abundances in the cluster stars was σ=±0.033 dex, while the intrinsic accuracy of the model atmospheric parameters was as follows: $T_{eff} = \pm 50$ K, lgg = ±0.1, $\xi = \pm 0.1$ $km\ s^{-1}$. A noticeable difference (exceeding 3 σ) between the mean abundance estimates and the solar values was observed for the light elements, such as Na (–0.09±0.08 dex) and Al (–0.13±0.06 dex), and for heavier elements with $Z > 39$, namely Zr (–0.15±0.07 dex) and Nd (–0.21±0.02 dex); the overabundance of barium (+0.15±0.05 dex) was also observed. The field stars exhibited the same tendency in the estimated elemental abundance dynamics as that observed in the cluster stars, with the only exception being a much narrower scatter of the elemental abundance determinations: Na (–0.18±0.04 dex), Al(–0.2±0.05 dex), Zr (–0.15±0.04 dex) and Ba (+0.25±0.03 dex). These four stars have almost equal gravitational acceleration; and it is this parameter which has the most direct effect on the level of errors in the determination of the atmospheric abundances of these elements.

The abundances of 23 elements in 276 dwarfs of the population of the thin and thick components of the Galactic disc were determined in the studies by Mishenina et al. (2004, 2008, 2013). The intrinsic accuracy in the determinations of the model atmospheric parameters were expected to be as follows: $T_{eff} = \pm 100\ K$; $\lg g = \pm 0.2$; $\xi = \pm 0.2 km\ s^{-1}$. Standard deviation of the estimated abundances of the light elements ($Z < 13$) was $\sigma = \pm 0.15$ dex, which was twice as high as that for the iron-group elements ($\sigma = \pm 0.08\ dex$). The dispersion of the estimated abundances of the heavy elements ($Z > 38$) was $0.12 \div 0.14$ dex for cooler stars ($T_{eff} = 5000$ K) and $0.08 \div 0.10$ dex for hotter stars ($T_{eff} = 6000$ K). The authors deduced the following conclusions:

• A decrease in the abundances of α-elements, in particular for O, Mg, Si and Ti, was observed with increasing metallicity though the dispersion of the estimated Ca abundances was higher.

• High dispersion observed for Al is likely to be caused by the NLTE-effects, and it may be reduced when these effects are taken into account.

• High dispersion observed for Na remains at the same level even when the NLTE effects are factored in. This can be due to the fact that many sources contribute to the Na production, which results in its highly inhomogeneous distribution in the interstellar medium.

• High dispersion in the Ba and La abundance estimates is likely due to high uncertainties in the stellar age determinations, which resulted in the uncertainties in the determined contributions of the slow $s-$ and rapid $r-$ neutron-capture processes, which are the main donors of these elements.

As can be seen, the dispersion of the estimated elemental abundances in the studies by Mishenina et al. are consistent with that reported by De Silva et al. (2007), given the error in the model parameter determinations in the latter study is half that in the former ones. For several elements the differences between the stellar abundance determinations and solar values are so small (within 2σ) that can not be reckoned as significant However, we can unambiguously assert that the error in the determinations of the atmospheric abundances of certain chemical elements (such as Na, Al, Ba and possibly some others) in dwarfs is by a factor of two or even three greater than that for other elements.

The analysis of the chemical composition of cool giants in our Galaxy can be exemplified by the study of Reddy et al. (2012) concerned with the determination of mean abundances of 22 chemical elements in the giants belonging to clusters of different ages. The intrinsic accuracy in the determinations of the model atmospheric parameters were expected to be as follows: $\delta T_{eff} = \pm 100$ K; $\delta \lg g = \pm 0.25$; $\delta\xi = \pm 0.2\ km\ s^{-1}$. The mean dispersion of the estimated abundances for all investigated elements was $0.03-0.05$ dex. The distribution of elements by their atomic numbers is typical for giants as such: the excess in the abundance estimates when compared to the solar values, which was 0.1 dex for the light elements (α-elements) and 0.2 dex for the heavy elements ($s-$ and $r-$elements), is accounted for by the evolutionary change in the elemental abundances of the giant atmosphere.

3. The study of the chemical composition of active stars

A comparison between the elemental abundances in active (30) and inactive (101) dwarf stars was conducted in the study by Mishenina et al. (2008), and the following conclusions were inferred from the results obtained:

• both active and inactive dwarfs have shown almost the same correlations between the elemental abundances and metallicities;

• the lithium abundance determinations appeared not to be dependent on the stellar indices of chromospheric activity.

It is noteworthy that among the stars which had been assigned as active stars by various criteria, this study was focused on the stars with low chromospheric activity indices (lower than -4.32 dex). The most comprehensive study of the chemical composition of active stars with high chromospheric activity indices was performed by Morel et al. (2006), who investigated the

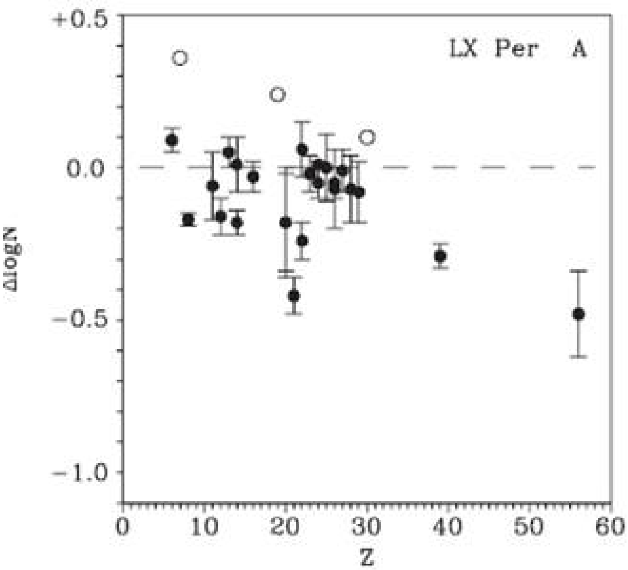

Figure 1: The distribution of the chemical elements in the atmospheres of the LX Per binary components (A component).

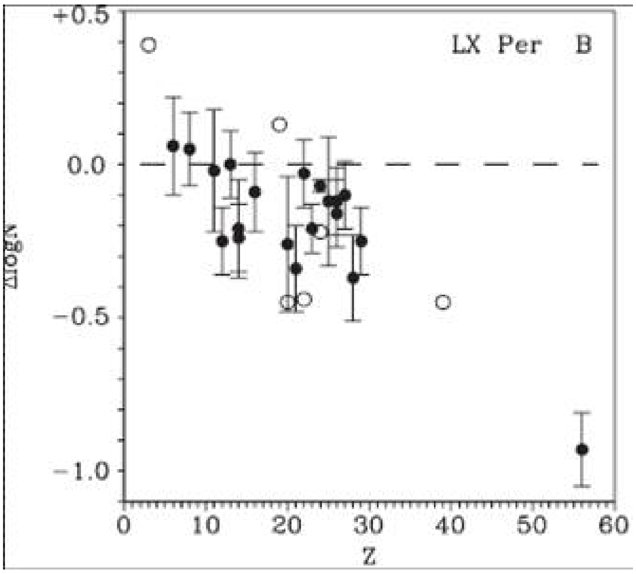

Figure 2: The distribution of the chemical elements in the atmospheres of the LX Per binary components (B component).

abundances of 10 elements with atomic numbers in the range 11 to 28, and 56 (Ba) in eight RS CVn stars with the index $\lg R'_{HK}$ ranged from −3.83 to −3.69. The largest difference between the abundance estimates and solar values was reported for Na ($+0.4 \pm 0.1$ dex) and Al ($+0.3 \pm 0.1$ dex); this difference was less significant for other α-elements, while the scatter of barium abundances was rather wide ($+0.2 \pm 0.2$ dex) in both active and inactive stars. These elements are noticeably sensitive to the NLTE-effects.

As shown by theoretical calculations performed in Lind et al. (2011), the error in the abundance determinations for these elements is expected to be not lower than 0.1÷0.15 dex, which is rather consistent with the dispersion of the abundance estimates for these elements in inactive late-type dwarfs. Hence, such a large difference between the abundances of certain elements and the solar values (especially for Na and Al) is due to their sensitivity to the NLTE-effects, which are considerably enhanced in active stars. The increased abundances of the elements sensitive to the NLTE effects in chromospherically active stars (with $\lg R'_{HK} > -4$) are well illustrated in the study by Morel & Micela (2004) concerned with the investigation of the oxygen atmospheric abundances in active and inactive stars from the OI 6300 Å line, which is not sensitive to the NLTE-effects, and from the OI 7774 Å triplet, which is sensitive to the NLTE-effects. As reported in this study, the oxygen abundances derived from the OI 7774 Å triplet were on average 1.0 ± 0.2 dex higher than those determined from the OI 6300 Å line.

4. The in-depth analysis of the chemical composition in the atmospheres of active stars by exemplifying certain binary systems

Let us consider in more detail the results and problems related to the abundance determinations in active stars exemplifying the most prominent representatives of the RS CVn stars, which have been the subject of numerous studies. There are very few investigations of the chemical composition of active stars in binaries with well-known parameters of the binary system and its components; and this can be an essential factor in drawing conclusions on the pattern of the abundance variations. Just several rather bright RS CVn and BY Dra stars have been thoroughly investigated to date.

Lambda Andromedae (λ And) is a RS CVn-type binary system (Tautvaisiene et al., 2010) with the rotation period of the active star subgiant $P_{rot} = 54$ days and orbital period $P_{orb} = 21$ days; the secondary component of the binary is a white dwarf. The effective temperature of the subgiant $T_{eff} = 4830$ K; its projected rotational velocity $vsini = 6.5$ km/s; its activity index $\lg R'_{HK} = -3.68$, and metallicity $[Fe/H] = -0.53$ dex. As shown by the results of photometric observations (Frasca et al., 2008), in this binary system the spots on the subgiants surface cover up to 12% of the surface area while their temperature is 800 K lower than the photospheric one. The investigation of the atmospheric abundances of the λ And binary subgiant, which is a bright star, have been numerously reported. The scatter of the elemental abundances es-

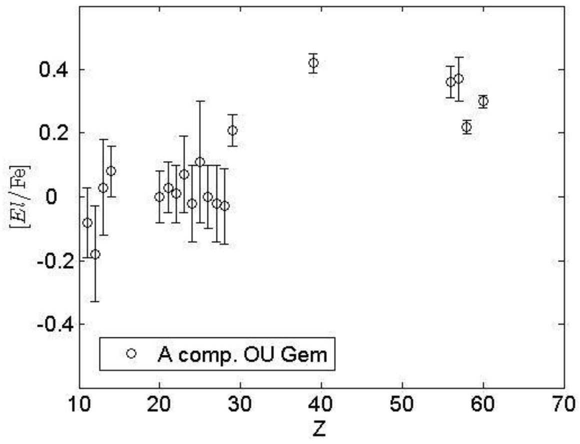

Figure 3: The distribution of the chemical elements in the atmospheres of the OU Gem binary components (A component).

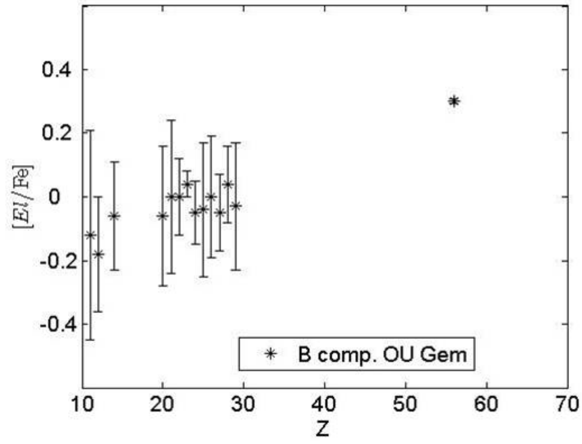

Figure 4: The distribution of the chemical elements in the atmospheres of the OU Gem binary components (B component).

timated in different studies of the subgiant is very wide (± 0.25 dex on average), though the error in the abundance determinations averages to ± 0.05 dex. Such a wide scatter resulted from the employment of different model parameters of the subgiants atmosphere due to the spotted stellar surface associated with the mean effective temperature variations with the rotation phase, rather than from the errors in simulations. The mean abundance of the chemical elements generated in different nuclear processes is on average higher than the solar values; these differences amount to $[\alpha/Fe] = 0.4$ dex, $[s/Fe] = 0.2$ dex and $[r/Fe] = 0.4$ dex. We suggest that such differences can be related to two processes:

1) the enrichment in the heavy elements resulted from the exchange of matter between a massive star (which is a white dwarf in this case) and less massive star (which is a subgiant in this case);

2) substantial NLTE-effects. A noticeable atmospheric lithium deficit in the active star (-0.5 dex) should also be noted.

29 Dra is a RS CVn-type star (Barisevicius et al. 2010), its one component is a subgiant whose rotation period $V_{rot} = 32$ days while the secondary component is a white dwarf. The effective temperature of the subgiant $T_{eff} = 4720$ K; its projected rotational velocity $vsini = 6.7\ km/s$; the activity index $\lg R'_{HK} = -4.65$, and the atmospheric metallicity $[Fe/H] = -0.20 \pm 0.05$ dex. This binary system has also been widely investigated. In contrast to the λ And binary system, whose chromospheric activity is higher, the scatter of the elemental abundances in 29 Dra is far narrower (<0.1 dex). This indicates that the model atmospheric parameters are less dependent on the rotation phase of the subgiant. The relative abundances of the iron-group elements, as well as $s-$ and $r-$process elements, equal to solar ones. The abundance of $\alpha-$process elements is 0.1 dex higher than the solar value. Such a difference between the abundance estimates for $\alpha-$process elements and the solar values is likely to be mainly due to the exchange of matter in the binary with a more massive star evolving to become a white dwarf; and to a lesser extent, it may be accounted for by the NLTE-effects related to the chromospheric activity of the subgiant. A noticeable atmospheric lithium deficit in the active star (-0.45 dex) should also be noted.

Thus, it was not a right selection of the two RS CVn-type binary systems, namely 29 Dra and λ And, as target ones to investigate the chemical composition of chromospherically active stars, because the elemental abundances in the primary components atmosphere may significantly vary at the stage of exchange of matter in the course of the binary evolution, though the contribution from the secondary component, which is a white dwarf, to the combined spectrum is near-zero in these binaries. The studies of the λ And binary system have also shown the dependence of the subgiants model atmospheric parameters on the phases of its rotation. Hence, the active stars in the 29 Dra and λ And binary systems cannot be used as target ones to study the impact of the chromospheric activity on the formation of the spectral lines.

The studies of another bright star of the RS CVn type, namely 33 Piscium (33 Psc) (Barisevicius et al., 2011), have been performed many times. This binary system contains a subgiant along with a late-type main-sequence star whose contribution to the combined spectrum of the binary is insignificant. The subgiant exhibits low chromospheric activity ($\lg R'_{HK} < -4.7$). The orbital period of the binary

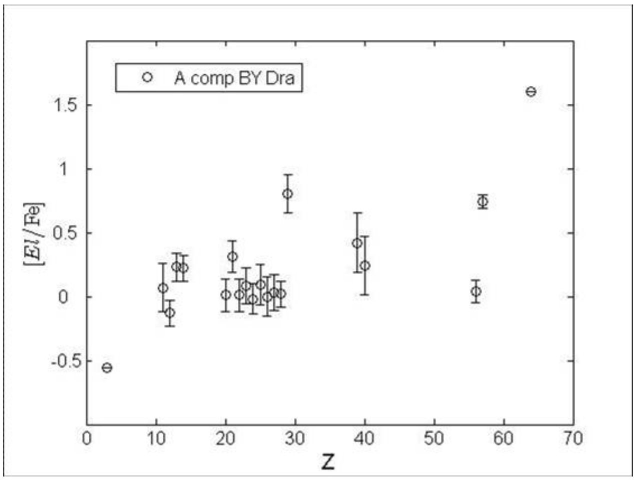

Figure 5: The distribution of the chemical elements in the atmospheres of the BY Dra binary components (A component).

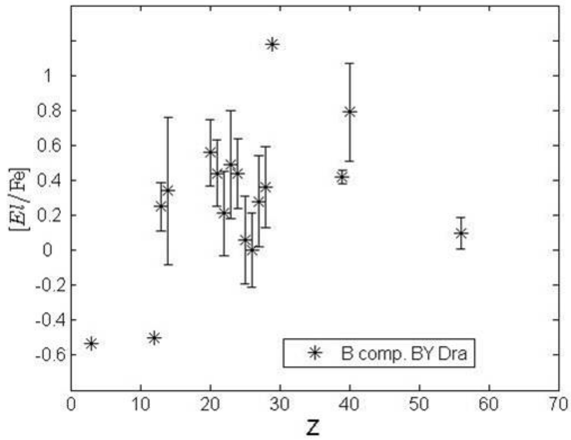

Figure 6: The distribution of the chemical elements in the atmospheres of the BY Dra binary components (B component).

system $P_{orb} = 73$ days; the effective temperature of the subgiant $T_{eff} = 4750$ K; its projected rotational velocity $vsini = 2\ km/s$ and atmospheric metallicity $[Fe/H] = -0.09 \pm 0.06$ dex. The scatter of the abundance estimates for different elements reported in different studies is within the error in the model determinations, except for certain lines. On average, the relative abundances of all elements are typical for the main-sequence stars and subgiants and almost equal to the solar ones.

5. The investigation of the chemical composition of chromospherically active stars from the composite spectra of binary systems

The results of in-depth studies of a number of RS CVn and BY Dra binary systems with combined spectra, i.e. the spectra exhibiting the lines from both binary components, are also available at present. LX Persei (LX Per) is an eclipsing spectroscopic binary of the RS CVn type (Kang et al., 2013), which contains a main-sequence star and an active subgiant. The orbital period of the binary $P_{orb} = 8$ days; the effective temperatures of the primary (A) and secondary (B) components are $T_A = 6200$ K and $T_B = 4790 \pm 230$ K, respectively; the ratio of the components luminosities $L_A/L_B = 0.90$; the projected rotational velocities of the A and B components $vsini_A = 9.1$ and $vsini_B = 21\ km/s$, respectively; the activity index of the subgiant $\lg R'_{HK} = -4.55$; the metallicities of the A and B components $[Fe/H]_A = -0.05 \pm 0.05$ dex and $[Fe/H]_B = -0.12 \pm 0.11$ dex, respectively. The out-of-eclipse portion of the light curve shows peculiar variations with amplitudes ranging from 0.03 to 0.08^m, though these variations showed no periodicity typical for the RS CVn stars. Fig. 1 presents the distribution of the chemical elements in both binary components (Kang et al. 2013). As is seen in Fig. 1,2 the elemental abundances in both components show significant peculiar variations, which exceed several-fold the error in the abundance determinations. Though there are not many lines of the heavy elements ($Z > 40$), their abundance estimates show the most pronounced difference, such as a considerable deficit, when compared to the solar values; however, the barium lines can be reliably observed. Evolutionary changes in the abundances of the heavy elements imply their increase, rather than decrease; overlooking the NLTE-effects can also result in the increased.

Such a peculiar pattern of the distribution of the heavy elements has been obtained for the first time, and the authors suggested it can be due to the accretion of material from the gas-dust shell, in which the separation of the gas and dust components had occurred. This explanation cannot be deemed as credible, especially with regard to the stars with outer convective envelope. Accretion of material from the gas-dust shells is not a rare case in binary systems; however, such a peculiar pattern of the distribution of the chemical elements in the atmospheres of the binary components has not yet been observed. However, it must be admitted that there are just few studies of the atmospheric elemental abundances in the binary components, especially from the combined spectra, available as of today. The cause of such a pattern of the elemental distribution may be sought in the peculiarities of the binary system itself. The most pronounced feature of this binary is the rotational velocities of its components (9 and 21 km/sec), which are higher than those typical for the stars with the outer convection envelopes, as well as a noticeable peculiar variations in the CaII H&K emission lines (from 3 to 10Å) while the H_α emission remains practically unaltered (Wieler, 1978).

OU Geminorum (OU Gem) is a spectroscopic binary system consisting of two main-sequence BY Dra-type stars (Glazunova et al., 2014); its orbital period P_{orb} = 7 days; the rotation period of the primary component (determined from the light curve plotted from photometric observations) P_{rot} = 7.4 days; the effective temperatures of the primary (A) and secondary (B) components T_A = 5025 K and T_B = 4500 K, respectively; the ratio of the components luminosities L_A/L_B = 3.0; the projected rotational velocities of the A and B components $vsini_A = 6.0$ and $vsini_B = 6.5$ km/sec, respectively; the activity indices of the A and B components $\lg R'_{HKA} = -4.39$ and $\lg R'_{HKB} = -4.5$, respectively; the atmospheric metallicities of the A and B components $[Fe/H]_A = -0.2 \pm 0.1$ dex and $[Fe/H]_B = -0.15 \pm 0.19$ dex, respectively. Fig. 3,4 shows the distribution of the chemical elements in the atmospheres of the binary components adopted from the study Glazunova et al. (2014). As is seen in Fig. 3,4 the distribution of the light elements in the atmospheres of both binary components is typical for the main-sequence cool stars as described above. The heavy elements ($Z > 40$) are noticeably overabundant in the atmospheres of both components. The lithium lines cannot be observed in the binary spectrum, which may be indicative of the low atmospheric abundance of this element in both components (less −0.5 dex).

BY Draconis (By Dra) is a spectroscopic binary system consisting of two main-sequence stars which exhibit very high CaII H&K emission, i.e. both binary components are chromospherically active stars. Moreover, this binary system has a visual component, which is also a main-sequence star. The orbital period of the binary system P_{orb} = 6 days; the rotation period of the primary component (determined from the light curve) P_{rot} = 3.8 days; the effective temperatures of the primary (A) and secondary (B) components $T_A = 4560 \pm 150$ K and T_B = 4430 K, respectively; the ratio of the components luminosities L_A/L_B = 2.3; the projected rotational velocities of the A and B components $vsini_A = 8.0$ and $vsini_B = 7.5$ km/sec, respectively; the activity index of the primary component $\lg R'_{HK} = -3.45$; the atmospheric metallicities of the A and B components $[Fe/H]_A = 0.04 \pm 0.15$ dex and $[Fe/H]_B = -0.04 \pm 0.21$ dex, respectively. According to research, the spot on the primary components surface resulting in a photometric wave with an amplitude of 0.2 m covers up to 20% of its disc area; the spot temperature is 300 K lower than the photospheric one (Chugainov, 1976). Fig. 5,6 shows the distribution of the chemical elements in the atmospheres of both binary components according to the results of the examination of two spectra performed by Glazunova & Kovtyukh (2014). As is seen from Fig. 3, with the 0.1 dex mean error in the determinations of the atmospheric abundances in the primary component, the abundance estimates of the elements with $Z < 29$ are almost similar to the solar values, with the only exception being lithium, which is significantly underabundant in the atmospheres of both components. The scatter of the estimated abundances of the elements with $Z > 29$ considerably exceeds the error in their determinations. However, the derived abundance of barium ($Z = 56$) is practically similar to the solar value.

6. Conclusions and discussion

Based on the reported results of very few studies concerned with the investigation of the chemical composition of active stars and on our studies of two active binary systems of the BY Dra type, it is impossible to infer an unambiguous conclusion about the values and reasons for the variations in the atmospheric elemental abundances in active stars. We may only discuss the following tendencies in the elemental abundance dynamics in these stars:

- There is a noticeable increase in the abundances of the light elements ($Z < 20$), which are sensitive to the NLTE-effects, in active stars with the chromospheric activity indices $\lg R'_{HK} > -4.0$;
- An excess of the heavy elements ($Z > 39$) has been observed in three active stars with rather high activity indices (> −4.5), namely in the λ And, OU Gem and BY Dra binaries;
- The dispersion of the barium abundance estimates in different active binaries, as well as in inactive dwarfs, is rather wide ranging within 0.15÷0.2 dex;
- A significant underabundance of the heavy elements, including barium, may be observed in certain active binary systems (e.g. LX Per);
- Lithium is noticeably underabundant in active stars compared to inactive stars with the similar temperature range.

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