CNO and s-Element Abundances in the Atmospheres of the Binaries AY Cet and DR Dra with Active Chromospheres: Testing the Hypothesis on the Formation of Barium Stars

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Abstract – AY Cet and DR Dra are binaries with active chromospheres, in which one of the components is a red giant and the other is a white dwarf. On the basis of high-resolution spectra and using the lines of C\textsubscript{ii}, [O I], CN, Zr I, Ba II, and La II, the abundances of CNO and s-elements in the atmospheres of the main components (giants) in these systems were determined. A comparison with the average abundances of these elements in the atmospheres of normal, barium, and barium-poor giants shows that the giant in the more close binary system AY Cet has a distinct peculiarity that is typical of barium-poor stars — metal deficiency and moderate excesses of the carbon and s-element abundances. In the wider, long-period system DR Dra, the main component exhibits elemental abundances that are normal for a red giant. Various mechanisms for mass transfer in the binaries under study are discussed.

INTRODUCTION

When studying stars with active chromospheres on the basis of ultraviolet spectra, four stars with hot compact companions were detected: AY Cet = 39 Cet = HR 373 [1], DR Dra = 29 Dra = HD 160538 and V1379 Aql = HD 185510 [2], and V832 Ara = HD 165141 [3]. The main components in these systems are red giants. An analysis of the energy distribution in the ultraviolet excess of these stars and estimation of the masses of the secondary components led the authors of [1 - 3] to conclude that the hot components in these systems, with the exception of HD 185510, are white dwarfs. In addition, MacConnell et al. [4] classified the cool star in the system HD 165141 as a barium-moderate star, which suggests the necessity of studying the chemical composition of the main components in this type of system.

McClure et al. [5] showed that all classical barium stars are spectroscopic binaries. Their scenario for the formation of barium stars in binary systems suggests that, presently, the companions of barium stars are white dwarfs. After the discovery of white dwarfs in the systems ζ Cap (barium star) and ζ Cyg (barium-poor star), this hypothesis received considerable support [6]. However, in general, further searches for ultraviolet excess in the spectra of barium stars were not so successful (see, e.g., [7, 8]). Reliable evidence for the presence of a white dwarf was obtained for only four out of the 19 investigated stars, and the dwarf’s parameters were determined. The authors of [7, 8] note that this failure possibly results from limited sensitivity of the equipment employed and low luminosity of the already cooled white dwarfs. Nevertheless, the hypothesis that barium stars are formed as a result of mass transfer in the binary system still provides a unique opportunity for the explanation of the excesses of carbon and s-element abundances observed in the atmospheres of these stars. Thus, this hypothesis necessitates the presence of a white dwarf in the system with a barium star.

I propose in this paper to test the sufficiency of this condition, i.e., to analyze the chemical composition of those binary stars in which one of the components is a red giant and the other is a white dwarf. The detection of excesses of the carbon and s-element abundances in the atmosphere of the giant in such systems would be reliable confirmation of the hypothesis for the formation of barium stars. For this purpose, two chromospherically active binary stars were selected, AY Cet (G5 IIIe+wd) and DR Dra (K0 III+wd), for which there is convincing evidence for the presence of a white dwarf. The abundances of carbon, nitrogen, oxygen, lithium, and iron, as well as the ratios \( ^{12}\text{C}/^{13}\text{C} \), Zr/Fe, Ba/Fe, and La/Fe, were derived for these stars. Both these stars show photometric variability (AV \approx 0.2, the amplitude being variable) caused by the presence of spots on their surfaces, moderate rotational velocity (\( \text{Vsin} i = 4 \) and 8 km s\(^{-1} \), respectively), similar spectral types, and asynchronous rotation for a nearly circular orbit (\( e \approx 0.1 \)). However, their orbital periods are essentially different: DR Dra has a period of about two and a half years (903\(^{d} \)), whereas AY Cet has a period of about two months (57\(^{d} \)). Note also that the period of DR Dra is typical of the class of barium stars. Whether the atmospheres of the giants in these systems were enriched when the envelope was ejected from the secondary component and whether these giants became barium stars are key questions in this study. In addition, since these stars have active chromospheres, it would be interesting to investigate any possible relationship between their activity and chemical composition.

OBSERVATIONS

I obtained all my observational material in 1993 - 1994 with a coude spectrograph mounted on the
2.6-m telescope of the Crimean Astrophysical Observatory. I used an ASTROMED CCD array (Cambridge, England, see [9]) as the detector. A total of five ∼30-Å wide spectra centered at 5135, 6135, 6310, 6707, and 8000 Å were taken for both stars. These spectra contain the lines of MgH, C2, Zr II, Ba II, [O I], Mg I, Li I, CN, and Fe I, which I used to determine the elemental abundances. The spectral resolution was ∼0.18 Å, and the signal-to-noise ratio exceeded 100. The reduction of the spectra obtained included dark-current subtraction, flat-field division, correction for the sky background, wavelength calibration, and normalization to the continuum.

Because the analyzed stars exhibit photometric variability, which appears to be due to their surface temperature being nonuniform, the phases during which the observations were conducted to analyze the chemical composition should be determined. The ephemerides of the minimum light and photometric periods were taken from [3]. For AY Cet, the dates of observations, August 7, 1993, and September 25, 1993, correspond to the phases 0.11 and 0.67, i.e., near minimum and maximum light. For DR Dra, the dates of observations, July 31, 1993, and March 23, 1994, correspond to the phases 0.95 and 0.41, which are also near minimum and maximum light. Following the phase determination, it was found that, for both stars, the portions of the spectra containing C2, CN, and [O I] lines were observed during both minimum and maximum light, while the remaining portions were observed only near the maximum phase. The effect of nonuniform surface temperature on the equivalent widths of the observed lines and on the elemental abundances is assessed below.

MODEL-ATMOSPHERE PARAMETERS

I used the color indices (B-V) averaged over the photometric period to estimate the effective temperatures of both stars. This quantity for AY Cet is 0.90. According to calibration by McWilliam [10], the effective temperature $T_{\text{eff}}$ corresponding to this value is 5030 K. Since the statistical accuracy of McWilliam's calibration is ±200 K, I adopted $T_{\text{eff}} = 5000$ K. This value is possibly slightly underestimated, because it approximately corresponds to the spectral type G8 III, whereas the main component in AY Cet is classified as a G5 III star. The temperature difference between these two spectral types may reach 200 K, which is consistent with the accuracy of the adopted value. Similarly, the effective temperature of the main component in DR Dra with the average color index (B-V) = 1.05 is 4680 K. However, as noted by Fekel et al. [11], a comparison of the spectra for DR Dra and β Gem shows reasonably good agreement. For β Gem, $T_{\text{eff}} = 4820$ K, according to calibration by Bell and Gustafsson [12], or $T_{\text{eff}} = 4865$ K, according to a new study of this star by Drake and Smith [13]. Thus, $T_{\text{eff}}$ for DR Dra determined from the color index (B-V) appears to be underestimated as well. Consequently, I adopted a value of 4800 ± 100 K.

The surface gravities were calculated by means of two independent methods: from the dependence of log g upon temperature $T_{\text{eff}}$, mass $M/M_\odot$, and luminosity $L/L_\odot$ and from MgH-line profiles using the techniques described in [14]. The absolute magnitudes for both stars were estimated from their distances. For AY Cet and DR Dra, I adopted $M_V = 1.3$ and 1.6, respectively, which correspond to distances of 67 and 96 pc and to an approximately identical luminosity of log $L/L_\odot = 1.4$. The mass of the main component in AY Cet was estimated by Simon et al. [1] from the analysis of its orbital elements to be 2.1 $M_\odot$. A comparison of the temperature and luminosity of this star with evolutionary calculations performed by Maeder and Meynet [15] for single stars is not at variance with this value – the star is found near the minimum luminosity of the track for a star with a mass of 2.0 $M_\odot$, i.e., at the beginning of the ascent along the giant branch. The mass of the main component in DR Dra is also likely to be close to 2.0 $M_\odot$, because AY Cet and DR Dra have equal luminosities, whereas their effective temperatures differ only slightly. A comparison with evolutionary tracks by Maeder and Meynet gives 1.8 $M_\odot$. Thus, the surface gravities log g derived from the above values of effective temperature, luminosity, and mass of the stars under investigation were found to be 3.0 for AY Cet and 2.9 for DR Dra.

The spectral features with effective wavelengths of 5134.6, 5138.7, and 5140.2 Å were used to determine the surface gravities from MgH-line profiles. For both stars, I solved a self-consistent problem for log g and magnesium abundance loge(Mg), which was derived from equivalent widths of the lines Mg I 6318 and 6319 Å. Furthermore, in the wavelength region 5133 - 5142 Å, allowance was made for the contribution of C2 lines, whose intensity was checked using the 5135.6 Å feature and atomic lines taken from [16]. The values of log g thus derived were 2.7 for AY Cet, with loge(Mg) = 7.2, and 2.6 for DR Dra, with loge(Mg) = 7.6. Averaging these values with those obtained by the first method yields log g = 2.8 and 2.7 for AY Cet and DR Dra, respectively, the uncertainty being no more than ±0.2 dex.

My model atmospheres with the calculated parameters $T_{\text{eff}}$ and log g were interpolated using a grid from Bell et al. [17]. I then derived the iron abundance from Fe I lines near 6707 Å. The microturbulence was assumed to be 1.7 km s$^{-1}$, the most likely value for red giants. The studied stars significantly differ in their metal abundances. DR Dra has a nearly solar iron abundance ([Fe/H] = -0.05) and, as noted above, solar magnesium abundance. The iron and magnesium abundances in the atmosphere of AY Cet are much lower than the solar values ([Fe/H] = -0.58, [Mg/H] = -0.4).

Since I employed the method of synthetic spectra to calculate the elemental abundances, I had to use the parameter V sin i, the projection of the rotational velocity of a star onto the line-of-sight, to reconcile the observed and theoretical line profiles. This parameter for AY Cet and DR Dra is, respectively, 4 and 8 km s$^{-1}$. These values are consistent with 6 and 8 km s$^{-1}$, the
Table 1

<table>
<thead>
<tr>
<th></th>
<th>AY Cet</th>
<th>DR Dra</th>
<th>Normal giants</th>
<th>Barium-poor giants</th>
<th>Barium giants</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Fe/H]</td>
<td>−0.58</td>
<td>−0.05</td>
<td>+0.04</td>
<td>−0.10</td>
<td>−0.10</td>
</tr>
<tr>
<td>[C/Fe]</td>
<td>+0.06</td>
<td>−0.32</td>
<td>−0.22</td>
<td>−0.23</td>
<td>+0.08</td>
</tr>
<tr>
<td>[N/Fe]</td>
<td>+0.19</td>
<td>+0.01</td>
<td>+0.24</td>
<td>+0.35</td>
<td>+0.36</td>
</tr>
<tr>
<td>[O/Fe]</td>
<td>+0.21</td>
<td>−0.08</td>
<td>−0.04</td>
<td>+0.04</td>
<td>−0.05</td>
</tr>
<tr>
<td>C/12C</td>
<td>30 ± 10</td>
<td>24 ± 5</td>
<td>22</td>
<td>20</td>
<td>25</td>
</tr>
<tr>
<td>C/N</td>
<td>3.55</td>
<td>2.24</td>
<td>1.56</td>
<td>1.26</td>
<td>2.51</td>
</tr>
<tr>
<td>log ε(Li)</td>
<td>0.4</td>
<td>0.6</td>
<td>0.33</td>
<td>−0.26</td>
<td>0.45</td>
</tr>
<tr>
<td>[Zr/Fe]3</td>
<td>+0.37</td>
<td>−0.03</td>
<td>−</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>[Ba/Fe]6</td>
<td>+0.18</td>
<td>−0.22</td>
<td>−</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>[La/Fe]5</td>
<td>+0.28</td>
<td>+0.05</td>
<td>−</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>[s/Fe]</td>
<td>+0.28</td>
<td>−0.07</td>
<td>0.00</td>
<td>+0.21</td>
<td>+0.73</td>
</tr>
</tbody>
</table>

1) Lambert and Ries [27], Kjærgaard et al. [28]
2) Sneden [29]
3) Berdyugina [18]
4) Brown et al. [30]
5) Pinsonneault et al. [31]
6) The abundances of s-elements (Zr, Ba, and La) were derived relative to the standard star β Gem:

\[
[X/Fe]_{\beta \text{ Gem}} = [X/Fe] - [X/Fe(\beta \text{ Gem}) / Fe(\beta \text{ Gem})] \]

\[
[X/Fe] = [X/H] - [Fe/H] \quad \text{and} \quad [X/H] = \log \varepsilon(X) - \log \varepsilon(X)_{\odot}.
\]

The accuracy of the lithium abundance thus found is ±0.2 (see Table 1).

Zirconium, barium, and lanthanum are the elements that are formed in the process of slow neutron capture (s-process) at late stages of stellar evolution. The s-element abundances in the atmospheres of normal giants, as a rule, do not differ from the solar values. I used the lines Zr I 6127, 6134, 6140, and 6143 Å along with the lines Ba II 6141.7 Å and La II 6320.4 Å to derive the abundances of these s-elements. The oscillator strengths and excitation potentials of the lower levels for these lines were taken from [16]. In the vicinity of the Zr I and Ba II lines, I also took into account the blending caused by weak rotational lines of bands (9, 4) and (8, 3) of the CN red system when calculating the synthetic spectra. The calculations of the parameters of these lines were performed in the same way as for the CN bands, which are taken into consideration in other spectral regions [18]. Furthermore, the CNO abundances derived earlier make it possible to allow fairly accurately for the CN-line contribution.

Brown et al. [20] showed that the zirconium abundance in the atmospheres of G and K giants, as determined from Zr I lines, is lower than the solar value, whereas this is not the case for the zirconium abundance derived from Zr II lines. This effect may be the result of a deviation from local thermodynamic equilibrium (LTE) in the region of Zr I-line formation. In order to obtain the most accurate zirconium abundances in the atmospheres of the stars under investigation, I applied the well-known differential method. I used β Gem as a standard star, because its effective temperature \(T_{\text{eff}} = 4865 \text{ K}\) and surface gravity \(\log g = 2.75\) proved to be the closest to the parameters of the stars under study [13]. Thus, I eliminate not only the effect of deviation from LTE, but also uncertainties in the oscillator strengths of the selected lines. Furthermore, to avoid the dependence of elemental abundances on model-atmosphere parameters, I considered the abundances relative to iron. Thus, the error in the determination of [Zr/Fe], [Ba/Fe], and [La/Fe], given in Table 1, is uniquely specified by the quality of the observed spectrum, and, according to my estimates, this error does not exceed ±0.05 dex. Portions of the observed and synthetic spectra with the Zr I and Ba II lines are shown in the figure.

LITHIUM, CNO, AND S-ELEMENT ABUNDANCES

The carbon, nitrogen, and oxygen abundances were derived along with the \(^{12}\text{C}/^{13}\text{C}\) ratio from the lines of C\(^{12}\), C\(^{13}\),CN, and [O I] using the techniques described in [18]. This paper also gives all parameters of the main and blending lines adopted in my calculations. Table 1 summarizes the results for both stars. Since the stars have distinctly different metallicities, the CNO abundances relative to the iron abundance are given. In addition, the relative abundances prove to be more accurate, because they are independent of the chosen model-atmosphere parameters. The uncertainty in the determination of these parameters is approximately 0.1 dex.

The lithium abundance log\(\varepsilon(\text{Li})\) was determined from the 6707.8 Å resonance line, with the multiplet splitting of the levels taken into account. A list of blending lines was compiled in accordance with [19]. The contribution of weak CN lines of vibrational bands (5, 1) and (7, 3) to the observed profile of the spectral feature under study was checked using the line \(Q_{t}(22)\) 6706.7 Å of band (7, 3). By superposing the observed and synthetic profiles of the lines Fe I 6707.5 Å, V I 6708.1 Å, and CN 6706.7 Å, the absorption excess near 6707.8 Å was revealed and attributed to the Li I line.

THE EFFECT OF NONUNIFORM TEMPERATURE ON THE ACCURACY OF ABUNDANCE DETERMINATIONS

As was already noted, the analyzed stars with active chromospheres exhibit periodic photometric variability, which is interpreted as being the result of the presence of spots on their surface. Clearly, the intensity of absorption lines observed at different phases of the photometric period may vary, because the temperatures of the spots and nonperturbed photosphere are different. In order to assess the effect of nonuniform temperature on the accuracy of abundance determinations for various elements, at least two parameters should be

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known: the total area of the spots A relative to the full surface of a star and the temperature difference between the perturbed and nonperturbed photosphere \( \Delta T \). These two parameters can be estimated, for example, from the amplitude of variations in brightness \( V \) and in color index \((B-V)\). As follows from the observations of various authors, the amplitudes of variations in these quantities are also variable, which is likely to be due to a change in the structure and total area of the spots on the stellar surfaces [21, 22]. Typical values of \( \Delta V \) and \( \Delta(B-V) \) for both stars are, respectively, 0.017 and 0.005. Using these values and assuming the temperature of the nonperturbed photosphere to be 5000 K, one can estimate the parameters \( A \) and \( \Delta T \) for a single round spot on a star’s surface by applying the techniques described in [23]. In this case, the effect of the spot position (astero-centric longitude and latitude) on the shape of the light curves and the curves of color-index variations can be ignored, since only the maximum magnitude of this effect, rather than its phase dependence, is of interest. For a spot located at the center of the star’s apparent disk (minimum light), the sought parameters \( A \) and \( \Delta T \) that correspond to typical values of \( \Delta V \) and \( \Delta(B-V) \) are, respectively, 0.10 ± 0.03 and 500 ± 200 K.

As seen from Table 2, a considerable strengthening of these lines should be observed during minimum light. Consequently, for a more reliable estimation of elemental abundances, observation should be conducted during the maximum phase, when the total area of the photosphere covered by the spots is at a minimum. In this work, my observations of the region with Zr I lines were performed at phases that are close to maximum: 0.67 and 0.41 for A\(\) Cet and DR Dra, respectively (phase 0.0 corresponds to minimum light). Therefore, one can hope that the Zr I-line strengthening due to the presence of a spot at these phases was not significant. Furthermore, when considering the relative abundances, this effect should be reduced.

**DISCUSSION OF THE RESULTS**

As seen from Table 1, the abundances of CNO elements relative to the iron abundance in the atmospheres of the studied stars differ from the average values for normal giants by ~0.2 dex for a mean error of 0.1 dex. These differences are not the same for different elements: an enhanced abundance of carbon and oxygen is observed in A\(\) Cet, whereas there is a deficiency of nitrogen in DR Dra in comparison with normal giants. In such a situation, the C/N ratios are found to be higher than a normal value of 1.5 in both cases; however, this may be caused by different mechanisms. The reduced isotope ratios \(^{12}\text{C}/^{13}\text{C} \) strongly suggest that convective mixing in the atmospheres of the stars under study has begun; during this phase, a decrease in carbon abundance and an increase in nitrogen abundance in the

<table>
<thead>
<tr>
<th>Spectral line</th>
<th>( \lambda, \text{Å} )</th>
<th>( \Delta W_{\lambda}, \text{mÅ} )</th>
<th>( \Delta \log \epsilon(X) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>C()</td>
<td>5135.6</td>
<td>0.6</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>O I</td>
<td>6300.3</td>
<td>0.1</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>(^{12}\text{CN} )</td>
<td>8003.2</td>
<td>0.4</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>(^{13}\text{CN} )</td>
<td>8004.7</td>
<td>0.2</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Li I</td>
<td>6707.8</td>
<td>2.2</td>
<td>0.20</td>
</tr>
<tr>
<td>Fe I</td>
<td>6705.1</td>
<td>1.8</td>
<td>0.10</td>
</tr>
<tr>
<td>Zr I</td>
<td>6127.9</td>
<td>10.3</td>
<td>0.28</td>
</tr>
<tr>
<td>Ba II</td>
<td>6141.7</td>
<td>3.1</td>
<td>0.13</td>
</tr>
<tr>
<td>La II</td>
<td>6320.4</td>
<td>1.5</td>
<td>0.07</td>
</tr>
</tbody>
</table>

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atmosphere of a normal star with a mass of \( \sim 2 M_\odot \) occur. For a star with a lower mass, the nitrogen enrichment is not significant, since the CN cycle was not complete on the main sequence. Thus, there are signs that DR Dra is a normal low-mass giant or a subgiant. Furthermore, the relative abundances of s-elements in the atmosphere of this star suggests that this star cannot be a barium-star candidate. Judging by carbon abundances, AY Cet is close to the class of barium stars, and, moreover, it has a moderate \((\sim 0.3\) dex\) excess of s-elements. However, the excess value is more typical of the class of barium-poor stars. Therefore, one may conclude that the main component in the system AY Cet is at least a barium-poor star.

As pointed out in the Introduction, the main distinction between the studied stars lies in the duration of their orbital period and in the separation between the components. The semimajor axes of the orbits asin \( a \) for AY Cet and DR Dra are about 0.4 AU and 2.4 AU, respectively. The chemical composition of the main component in AY Cet proved to be close to the class of barium stars, whereas this parameter for the system DR Dra virtually coincides with that for a normal giant or a subgiant. In terms of the hypothesis for the formation of barium stars in binaries, the degree of peculiarity of a barium star is determined by a variety of factors, including the separation between components, the initial mass of the secondary component, and the evolutionary stage at which the mass transfer occurred in the system (see the review by Lambert [24]). It is likely that the chemical composition of the material in the envelope transferred from the more massive secondary component to the forming barium star plays a crucial role — its degree of peculiarity depends upon the spectral type of the donor star (M, S, or C giant). In my case, only the closer system AY Cet proved to be chemically peculiar, i.e., strong evidence was found that supports the hypothesis under discussion. Nevertheless, it may well be that the system DR Dra evolves according to the same scenario, because the source of material could be a less massive M giant. In that case, assuming that the studied stars are of equal age, the white dwarf in the system DR Dra should be younger and, consequently, hotter than in the system AY Cet, which is confirmed by data from the catalog of Strassmeier et al. [3]: the temperatures of the white dwarfs in AY Cet and DR Dra with an identical mass of \( 0.55 M_\odot \) are, respectively, 18,000 and 30,000 K. Thus, the principal question posed in this study — are giants paired with white dwarf barium stars? — is answered affirmatively only for the case of the closer system AY Cet; however, the absence of peculiar excesses in the atmosphere of the giant in DR Dra can also be explained in terms of the scenario for the formation of barium stars.

The question as to whether enhanced chromospheric activity affects the evolution of the chemical composition of a star at the red-giant stage still remains unsolved. As noted above, both stars under investigation show an enhanced C/N ratio. In addition, the previously studied giants \( \lambda \) And [25] and HD 9746 [26] with active chromospheres exhibit the same peculiar feature: C/N = 2.57 and 3.89, respectively. To answer the question as to whether the high ratios C/N are typical of all giants with active chromospheres, further investigations of this type of star are required.

REFERENCES