Li, C, N, and O abundances and the $^{12}$C/$^{13}$C isotope ratio in the atmospheres of the K giants 39 Cyg and $\alpha$ Ari

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The lithium, carbon, nitrogen, and oxygen abundances and the isotope ratio $^{12}$C/$^{13}$C in the atmospheres of two K giants [39 Cyg (K3 III), a star with an intense Li I 6708 Å line, and $\alpha$ Ari (K2 III), with a weak Li I line typical of K giants] have been determined by the synthetic spectrum method based on model atmospheres. Selected sections of the spectrum have been observed with a CCD array mounted at the first coudé focus of the 2.6-m telescope at the Crimean Astrophysical Observatory ($\sim$0.2 Å resolution). Possible reasons for the enhanced lithium abundance $\epsilon$(Li) = +1.15 dex and the reduced isotope ratio $^{12}$C/$^{13}$C = 12 in the atmosphere of 39 Cyg are discussed.

A high lithium abundance in the atmospheres of K stars is a fairly rare phenomenon, so the accumulation of observational data on such stars is important. An anomalously intense Li I 6708 Å doublet for a K giant is observed in the spectrum of the star 39 Cyg. This was the reason for a detailed study of the atmosphere of that star. We were interested in determining the chemical composition, the lithium abundance, the abundances of the light elements C, N, and O, and the isotope ratio $^{12}$C/$^{13}$C. Such determinations will help in deciding about the evolutionary stage of 39 Cyg.

We have already determined the metal abundances from the equivalent widths of atomic lines in the atmosphere of 39 Cyg, using model atmospheres, on the basis of high-dispersion (4 and 6 Å/mm) photographic spectra. As a result, we established that the atmosphere of the giant 39 Cyg is characterized by a nearly normal chemical composition, although the sodium abundance turned out to be somewhat higher than the solar value, [Na] = +0.3 dex. The enhanced lithium line was of course also unusual.

A more accurate analysis by the synthetic spectrum method is required to determine the abundances of lithium and other light elements, carbon, nitrogen, and oxygen, and the ratio $^{12}$C/$^{13}$C. We carried out observations using a CCD array mounted at the first coudé focus of the 2.6-m telescope at the Crimean Astrophysical Observatory. The spectral resolution was $\sim$0.2 Å. To determine the nitrogen abundance, we were able to use an infrared spectral range ($\lambda$ = 8000 Å, bands of the red system of CN), and were also able to considerably improve the signal-to-noise ratio. We recorded individual sections of the spectra of the stars 39 Cyg and $\alpha$ Ari: $\lambda\lambda$ 8220–7990, 6720–6690, 6380–6350, 6315–6285, and 5650–5620 Å. The spectra were obtained in July 1988 for $\alpha$ Ari and 39 Cyg and additional spectra were obtained in August 1989 for $\alpha$ Ari. The model atmospheres were calculated with the SAM-1 program, modified for late-type stars. The abundances of atoms and molecules were determined in the approximation of local thermodynamic equilibrium by solving a system of equations of ionization—dissociation

### TABLE I. Main C, N, and O Indicator Lines

<table>
<thead>
<tr>
<th>Molecule (element)</th>
<th>Wavelength, Å</th>
<th>$\epsilon$</th>
<th>$E(\epsilon)$</th>
<th>Identification</th>
<th>$D_0$</th>
<th>$I_0$</th>
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<td>C$_2$ [Swann system (0–1)]</td>
<td>5635.499</td>
<td>0.1702</td>
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<td>P$_r$(11)</td>
<td>6.118</td>
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<td>35,499</td>
<td>0.1658</td>
<td>0.42</td>
<td>P$_r$(12)</td>
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<tr>
<td>35,490</td>
<td>0.1552</td>
<td>0.41</td>
<td>P$_r$(10)</td>
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<tr>
<td>35,333</td>
<td>0.1832</td>
<td>0.42</td>
<td>P$_r$(12)</td>
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<tr>
<td>35,333</td>
<td>0.2009</td>
<td>0.43</td>
<td>P$_r$(13)</td>
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<td>0.1675</td>
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<td>P$_r$(13)</td>
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<tr>
<td>35,324</td>
<td>0.1403</td>
<td>0.41</td>
<td>P$_r$(9)</td>
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<td>P$_r$(14)</td>
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<td>35,195</td>
<td>0.1517</td>
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<td>35,195</td>
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<td>35,079</td>
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<td>O I</td>
<td>6300.309</td>
<td>0.1780–9</td>
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<td>6300.689</td>
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<td>Fe I</td>
<td>8002.544</td>
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<td>$^{12}$CN (2–0) red system</td>
<td>8002.412</td>
<td>0.2858–01</td>
<td>0.311</td>
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<td>7,60</td>
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<td>8010.084</td>
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<td>0.3133–01</td>
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<td>Q$_r$(20)</td>
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<td>$^{12}$CN (2–0) red system</td>
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<td>0.2311–01</td>
<td>0.244</td>
<td>Q$_r$(23)</td>
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<td>8004.728</td>
<td>0.2158–01</td>
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<td>Q$_r$(21)</td>
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<td>8004.728</td>
<td>0.7464–02</td>
<td>0.189</td>
<td>Q$_r$(21)</td>
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<td>10,458</td>
<td>0.2270–01</td>
<td>0.239</td>
<td>Q$_r$(22)</td>
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<td>18,419</td>
<td>0.2382–01</td>
<td>0.250</td>
<td>Q$_r$(23)</td>
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equilibrium with allowance for the most abundant molecules.

The lithium abundance in the atmospheres of \( \alpha \) Ari and
39 Cyg was determined by the synthetic spectrum method in the
vicinity of the 6708 Å doublet. We allowed for atomic
lines from the list of Kurucz and Peytremann\(^7\) with improved
oscillator strengths from more recent papers, as well as CN
and TiO molecular lines with our calculated oscillator
strengths. For the atmosphere of 39 Cyg we determined a
lithium abundance \( \varepsilon(\text{Li}) = 0.70 \) dex; for \( \alpha \) Ari we were able to estimate only the upper limit on the abundance, \( \varepsilon(\text{Li}) < -0.5 \) dex.

We then estimated the correction to the lithium abun-
dance due to departures from LTE. The combined system of
steady-state and radiative transfer equations was solved by the
method of partial linearization.\(^5\) We used a six-level model of
the lithium atom, in which the Li II ground state represented
the sixth level. In solving the non-LTE problem, we allowed
for absorption in atomic and molecular lines at the frequen-
cies of bound–free lithium transitions, which affect the ion-
ized state of metals in the atmospheres of cool stars.\(^3\) It
turned out that the correction for non-LTE effects depends on
the lithium abundance in the stellar atmosphere. In our case,
it was significant only for 39 Cyg, for which it was +0.45
dex. With allowance for it, the lithium abundance in the
atmosphere of 39 Cyg is \( \varepsilon(\text{Li}) = 1.15 \) dex. In Fig. 1 we give
the observed and calculated profiles of the 6708 Å lithium
line. We were unable to identify the blending line in the left-
hand wing of the lithium line.

Determining the C, N, and O abundances requires a
joint solution of the system of ionization–dissociation equi-
librium equations for each change in the abundance of one of
these elements. The procedure for determining the C, N, and
O abundances involved simultaneously fitting theoretical
profiles of sections of the spectrum containing molecular lines
of C\(_2\) (1–0 band of the 5630-5640 Å Swan system) and CN
(2–0 and 5–1 bands of the 8000-8020 Å red system) and
profiles of the forbidden [O I] 6300.23 and 6363.88 Å ox-
gen lines and the respective observed profiles. In the calcula-
tions of the synthetic spectrum we included lines from the list
of Kurucz and Peytremann\(^7\) with improved oscillator
strengths. In the 5630-5640 Å range we also allowed for lines
of the (5–0) band of the red system of CN.

The best agreement of the O I, C\(_2\), and CN line profiles
(with allowance for blended lines), and hence the respective
abundances, were found using a program that automatically
minimized a functional constructed from the difference be-
tween the observed and calculated intensities of the chosen
absorption lines. Data on the lines that we used as the main
indicators of C, N, and O abundance are given in Table I, in
which \( E(\text{eV}) \) is the excitation potential of the lower level, \( D_0 \)
is the dissociation potential, and \( f_e \) is the electron oscillator
strength. The wavelengths of C\(_2\) molecular lines of the Swan
system were taken from Ref. 9, those of the red system of
\(^{12}\)CN from Ref. 10, and of \(^{13}\)CN from Ref. 11. For \( \alpha \) Ari we obtained good convergence in the solution of the afore-
mentioned functional using the central intensities of two [O I]
lines, 6300.23 and 6363.88 Å. We note that having described
the observed 6300.23 Å [O I] line for \( \alpha \) Ari for \( \varepsilon(\text{O}) = +0.02 \) dex. For the cooler star 39 Cyg, the forbidden
6363.88 Å oxygen line turned out to be highly distorted by
molecular absorption, so we did not include it in the analysis.

The head of the 5635.2 Å (0–1) Swan band served as the
indicator of carbon abundance in the method described above.
As indicators of nitrogen abundance, we took four fairly clean lines of the (2–0) band of the red system of CN:
8002.41 Å, Q\(_2\)(27), 8010.08 Å, Q\(_2\)(28), 8017.01 Å, Q\(_2\)(30),
and 8018.05 Å, Q\(_2\)(29). The first line is blended with the Fe I
8002.59 Å line, which has a well-known value of \( g_f \) and
which we allowed for in the calculations. All the indicated
CN lines are described well by one set of C, N, and O abun-
dances.

A blend of three \(^{13}\)CN lines, 8004.554 Å, Q\(_2\)(23),
8004.728 Å, Q\(_2\)(21), and 8004.781 Å, P\(_2\)(17), and two single
\(^{13}\)CN lines, 8010.458 Å, Q\(_2\)(22), and 8016.419 Å, Q\(_2\)(23),
served as indicators of \(^{13}\)CN abundance. But in the spectrum
of \( \alpha \) Ari, all these lines except for 8010.458 Å are blended
with H\(_2\)O lines, and the \(^{13}\)CN abundance was determined
only from that line. In determining the \(^{13}\)CN abundance for
39 Cyg, we used all the indicated lines, although the right-
hand wing of the 8010.08 Å line is distorted by unknown
absorption.

The matching of the calculated and observed profiles for
the selected sections of the spectrum is given in Figs. 2-6 for
39 Cyg.

The abundances obtained for C, N, and O, which simulta-
nously describe the intensities of C\(_2\), [O I], and CN lines,
are given in Table II. There we also give values of the ratio

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interior of both stars and can be explained by the first convective mixing in the red giant stage.12,14

3. A ratio $^{12}\text{C}/^{13}\text{C} = 16$ was obtained for the atmosphere of $\alpha$ Ari. Although it is low, it is still close to the value for a red giant that has passed through the first convective mixing, for which $^{12}\text{C}/^{13}\text{C} \geq 20$ (Ref. 13). An even lower value, $^{12}\text{C}/^{13}\text{C} = 12$, was obtained for the atmosphere of 39 Cyg. Additional mixing can evidently be assumed in this case.

The results for 39 Cyg are of particular interest. The lithium abundance in that atmosphere is enhanced, $\varepsilon$(Li) = 1.15 dex, the ratios $^{12}\text{C}/^{13}\text{C}$ and C/N are reduced, and the sodium abundance is somewhat enhanced, [Na] = +0.3, while other elements have the solar abundance.

It is interesting to compare this set of results with the analogous results for the K giant 9 Boo (Refs. 2, 3, 15, and 16). The K3-4 III star 9 Boo has a high lithium abundance, $\varepsilon$(Li) = 2.5 dex; it cannot be explained by the destruction and dilution of the original lithium through mixing of the stellar interior on the ascending red giant branch, since the maximum $\varepsilon$(Li) after the first convective mixing is $\sim 1.2$ dex (Ref. 13). In addition, the ratios C/N $\approx 0.5$ and $^{12}\text{C}/^{13}\text{C} = 10$ for 9 Boo are low even for the first convective mixing.12,14 This can probably be explained by additional mixing in the atmosphere of 9 Boo. But the star’s low luminosity rules out a second convective mixing on the asymptotic giant branch, in which lithium synthesis is possible in the helium burning layer. Lithium is probably synthesized in the interior of this star in the helium flash stage in the core with subsequent rapid transport to the surface. A helium flash in the core is possible in 9 Boo with a mass 1.15-1.30 $M_\odot$ (Ref. 16).

We encountered similar problems in studying 39 Cyg, as noted above. Let us consider the positions of 39 Cyg and $\alpha$ Ari on the Hertzsprung–Russell diagram. If we take the absolute magnitudes of these stars from Ref. 17, then with allowance for the bolometric corrections we obtain $\log L/L_\odot = 1.90$ and 1.16 for 39 Cyg and $\alpha$ Ari, respectively. Using these magnitudes and the tracks from Ref. 18, we obtain the masses 1.5 $M_\odot$ for 39 Cyg and 2.0 $M_\odot$ for $\alpha$ Ari (see Table III). The upper limit on stellar mass for a possible helium flash in the core is about 1.85 $M_\odot$ (Ref. 18), i.e., such a flash could have occurred in 39 Cyg, and this could explain the low ratio $^{12}\text{C}/^{13}\text{C} = 12$ in its atmosphere. Such a mechanism for explaining the low ratios $^{12}\text{C}/^{13}\text{C}$ in red giants has been suggested by Scalo and Miller.19 The possibility of mixing of matter in the interior of a star with a hydrogen

$^{12}\text{C}/^{13}\text{C}$ determined from $^{12}\text{CN}$ and $^{13}\text{CN}$ lines.

The C, N, and O abundances and the ratio $^{12}\text{C}/^{13}\text{C}$ for $\alpha$ Ari from the literature12,13 are also given in Table II for comparison. We give only one determination of $^{12}\text{C}/^{13}\text{C}$ (the most reliable by our estimate). The range of values in the literature is 15-22. For 39 Cyg the Li, C, N, and O abundances and $^{12}\text{C}/^{13}\text{C}$ have been determined for the first time.

An analysis of the results obtained enables us to draw the following conclusions.

1. The lithium abundance in the atmosphere of 39 Cyg, $\varepsilon$(Li) = 1.15 dex, is high compared with that of many K giants of the same mass. Conversely, the lithium abundance in the atmosphere of $\alpha$ Ari is low, $\varepsilon$(Li) $< -0.5$ dex. We can attempt to explain the lithium abundances in both stars, however, by dilution of the original lithium, $\varepsilon$(Li) $\approx 3.0$, as a result of the first convective mixing. In this mechanism, the upper limit of $\varepsilon$(Li) should be $\sim 1.2$ dex (Ref. 13).

2. Both stars, 39 Cyg and $\alpha$ Ari, show a low C/N ratio, 1.8 and 2.3, respectively, compared with the solar ratio (C/N = 4.9). These values indicate an advanced CN cycle in the

![FIG. 5. Same as in Fig. 4: 1) observed profile for 39 Cyg; 2) calculated profile for $^{12}\text{C}/^{13}\text{C} = 10$; 3) $7$; 4) $15$. We did not identify the blend in the right-hand wing of the 8010.08 Å line.](image)

![FIG. 6. Same as in Fig. 4: 1) observed profile for 39 Cyg; calculated profiles for $^{12}\text{C}/^{13}\text{C} = 5$ (2) and 10 (3).](image)
TABLE II. Determinations of C, N, and O Abundances and $^{12}$C/$^{13}$C in the Atmospheres of 39 Cyg and $\alpha$ Ari

<table>
<thead>
<tr>
<th>Star</th>
<th>Model</th>
<th>$s_0$</th>
<th>$v_I$</th>
<th>$[LI]$</th>
<th>$[Fe]$</th>
<th>$[C]$</th>
<th>$[NI]$</th>
<th>$[O]$</th>
<th>$^{12}$C/$^{13}$C</th>
<th>C/N</th>
<th>O/C</th>
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</thead>
<tbody>
<tr>
<td>39 Cyg</td>
<td>4400/1.7</td>
<td>K3 III</td>
<td>1.7</td>
<td>1.15</td>
<td>0.0</td>
<td>0.36</td>
<td>0.08</td>
<td>0.15</td>
<td>12±3</td>
<td>1.82</td>
<td>2.88</td>
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<tr>
<td>$\alpha$ Ari</td>
<td>4850/2.5</td>
<td>K2 III</td>
<td>2.0</td>
<td>-0.5</td>
<td>-0.30</td>
<td>-0.29</td>
<td>0.03</td>
<td>0.02</td>
<td>16±4</td>
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<td>+0.19</td>
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<td>19±4</td>
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<td>Sun</td>
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<td>-</td>
<td>-</td>
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<td>-0.03</td>
<td>+0.17</td>
<td>-</td>
<td>4.79</td>
<td>1.78</td>
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</table>

Note. We estimate the error in determining the O, C, N, and Li abundances to be 0.2 dex.

TABLE III. Parameters of the Investigated Stars

<table>
<thead>
<tr>
<th>Star</th>
<th>$M_V$</th>
<th>$M_{bol}$</th>
<th>$\log L/L_\odot$</th>
<th>$M/M_\odot$</th>
<th>Star</th>
<th>$M_V$</th>
<th>$M_{bol}$</th>
<th>$\log L/L_\odot$</th>
<th>$M/M_\odot$</th>
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<tbody>
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<td>39 Cyg</td>
<td>+0.4</td>
<td>-0.2</td>
<td>1.9</td>
<td>4.5</td>
<td>$\alpha$ Ari</td>
<td>+1.1</td>
<td>+0.6</td>
<td>1.6</td>
<td>2.0</td>
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</table>

burning layer during a helium flash in the core was demonstrated in Ref. 20. The original lithium abundance at the surface must have been even lower in this case. But 39 Cyg has a high lithium abundance in our case. Might lithium synthesis by possible during a helium flash in the core, with subsequent rapid transport to the surface?

We thank S. V. Milyutin for assistance in the observations.