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NINE NEARBY K-GIANTS WITH PLANETS: A DETAILED ANALYSIS OF THEIR CHEMICAL COMPOSITION

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The chemical composition of 9 K-giants with planets located within 100 pc of the sun is studied. Here fundamental parameters of the stars which we have found previously are used; for the giant μ Leo the metallicity index [Fe/H] = +0.26 is redetermined along with the microturbulence parameter V_t=1.3 km/s from the lines of FeI. The abundances of 17 chemical elements from lithium (Z = 3) to hafnium (Z = 72) are found. Some elements are analyzed without assuming LTE (local thermodynamic equilibrium). Infrared CN molecular lines are used to determine the nitrogen abundance and the carbon isotope ratio $^{12}C/^{13}C$. Low values of $^{12}C/^{13}C$=8-18 show that the program giants have passed through deep convective mixing in the FDU (First Dredge-Up) phase. When analyzing the abundances obtained we added our recent data for the magnetic giants EK Eri and OU And found by the same technique. Lithium was not found for 7 of the 11 giants in question. An absence of lithium in atmospheres of stars that have passed through deep mixing in the FDU phase agrees with theoretical predictions. However for 4 of the giants, we found lithium; earlier for 3 of these 4 stars a magnetic field has been detected. These two phenomena, i.e., the presence of lithium in its atmosphere and the existence of a magnetic field, are unexpected for post-FDU giants in terms of the standard theory, can be be explained in the framework of a single hypothesis: an engulfment by a star of the planet with a mass several times that of Jupiter. For the 11 giants examined here we found a distinct correlation between the [N/C] and [N/O] values. A comparison of the observed relation with the theoretical model computed with rotation included showed that the theory cannot explain the high values of [N/C]=1.0 – 1.4 obtained for the most of the giants. Apparently, the known hypothesis of extra mixing is needed here. The combined abundance of C+N+O, which, according to the theory, should remain constant from the star's formation, showed a

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correlation with the metallicity index [Fe/H]. In this regard, for the stars with the normal metallicity [Fe/H] = ±0.1 a value of $\log\varepsilon(\mathrm{C+N+O}) = 8.97$ *was found that agrees perfectly with the solar value* $\log\varepsilon(\mathrm{C+N+O}) = 8.94$. *For the giant m Leo with a high metallicity [Fe/H]=+0.26 the highest value of* $\log\varepsilon(\mathrm{C+N+O}) = 9.31$ *was obtained. An anticorrelation was found between [RE/Fe], the mean abundance of rare earth (RE) elements (relative to Fe) and the index [Fe/H]. It is in good agreement with data for F- and G-dwarfs in the sun's neighborhood and reflects the initial chemical composition of the giants studied here.*

Keywords: *red giants: chemical composition: exoplanets*

1. Introduction

The discovery of thousands of exoplanets near young stars has raised several important questions for researchers. One of these concerns the chemical composition of these stars. Does it not indicate some kind of differences (as a whole or in details) from the chemical composition of "normal" stars that have no planets? Couldn't distinctive features of the chemical composition (if they exist) not have a certain influence on the formation of planetary systems near these stars or, hypothetically, on the appearance of life on one of the planets?

A statistical approach is used to solve problems of the chemical composition of stars with planets that simultaneously examines up to thousands of such stars and then makes use of automatic methods for selecting and analyzing spectrum lines. In this paper we use another, traditional method in which for the chosen stars a detailed analysis is made of the content of many elements over all accessible lines, both in the visible and the infrared, taking deviations from local thermal equilibrium (LTE) into account where possible.

Here we analyze in detail the chemical composition of 9 nearby and bright K-giants with planets, which we began studying before (Lyubimkov, et al., [1]). Table 1 is a list of these giants together with some data on them from

TABLE 1. Some Data on the 9 Program Giants

Star	HR	HD	*V*, mag	Sp	*V*sin*i*, km/s	π, mas	*d*, pc
α Ari	617	12929	2.01	K1 III	4.2	49.56	20
α Tau	1457	29139	0.86	K5 III	4.3	48.94	20
β Gem	2990	62509	1.14	K0 III	2.8	96.54	10
	3145	66141	4.38	K2 III	4.7	12.84	78
β Cnc	3249	69267	3.52	K4 III	6.9	10.75	93
μ Leo	3905	85503	3.88	K2 III	4.5	26.28	38
γ^1 Leo	4057	89484	1.98	K1 III	4.3	25.96	39
β UMi	5563	131873	2.08	K4 III	5.0	24.91	40
ε CrB	5947	143107	4.13	K2 III	2.4	14.73	68

[1], including the observed rotation speed $V\sin i$ and distance d, found from the parallax π. It is clear that the distance d varies from 10 to 93 pc, i.e., these are really fairly close stars. The rotation speeds are low ($V\sin i$ = 2.4-6.9km/s), so the lines in the spectra of these stars are fairly narrow and sharp, which is important for analyzing the chemical composition.

Information on the planets found near these giants is given in [1]. We note that the masses m of the planets (more precisely, $m\sin i$) vary from 1.8 to 8.8 M_{Jup}, where M_{Jup} is the mass of Jupiter.

The fundamental parameters of the 9 giants were determined in [1], including their effective temperature T_{eff} acceleration of gravity in the atmosphere $\log g$, metallicity index [Fe/H], and others. Also determined there are the abundances of 3 light elements, lithium, carbon, and oxygen (including the deviations from LTE). Now we can substantially extend our data on the chemical composition of these stars. In particular, in order to have full data regarding the group of CNO-elements, it is necessary to determine the amount of nitrogen. Since the lines of NI in the spectra of K-giants are too faint, we shall use infrared lines of the CN molecule. Analysis of these lines also makes it possible to determine the ratio $^{12}C/^{13}C$ of the carbon lines, which is an important indicator of the evolutionary state of the red giants.

The method for determining the N abundance and the ratio $^{12}C/^{13}C$ from the CN lines, as well as analysis of the abundances of the elements heavier than iron from Cu to Hf have been described in detail in a recent paper by Lyubimkov, et al. [2]. In it, two red giants with magnetic fields, EK Eri (K0 III) and OU And (G1 III), which are presumably successors of magnetic Ap-stars, were examined. The giant β Gem (Pollux), which is also included in the present paper, was also examined there as a comparison star. We use the method of [2] and the results obtained there in the present study.

2. Fundamental parameters of the giants and the method for the calculations

The fundamental (or basis) parameters of the studied giants are shown in Table 2; they were obtained in [1], except for the parameters [Fe/H] and V_t for μ Leo (see below). Here, first of all, we show the effective temperatures T_{eff} of the star and the acceleration of the force of gravity g in the stellar atmosphere ($\log g$ is shown). Two other quantities obtained from the analysis of the lines of FeI are shown: the metallicity index [Fe/H] and the microturbulence parameter V_t. Recall that $[\mathrm{Fe/H}] = \log\varepsilon(\mathrm{Fe}) - \log\varepsilon_{\odot}(\mathrm{Fe})$, where $\log\varepsilon(\mathrm{Fe})$ and $\log\varepsilon_{\odot}(\mathrm{Fe})$ are the abundance of iron in the atmospheres of the star and of the sun, respectively. In [1] an abundances of $\log\varepsilon_{\odot}(\mathrm{Fe}) = 7.50$ [3] was assumed for the sun. In this paper for calculating [Fe/H] we used a refined value of $\log\varepsilon_{\odot}(\mathrm{Fe}) = 7.48$ [4].

For the giant μ Leo, the chemical composition of which is of heightened interest (see below) and therefore requires special accuracy among the employed quantities [Fe/H] and V_t, we have again determined these parameters using the PEPSI spectra [5]. On analyzing 21 FeI lines from the list of [1], for μ Leo we obtained an iron abundance of $\log\varepsilon(\mathrm{Fe}) = 7.74 \pm 0.06$ and a microturbulence parameter of $V_t = 1.29 \pm 0.09$ km/s. The values of [Fe/H] = 0.26 and $V_t = 1.3$km/s were assumed in the subsequent calculations.

TABLE 2. Basis Parameters for the 9 Program Giants, as well as the Giants EK Eri and OU And with the Magnetic Fields Studied in [2]

Star	T_{eff}	log$g$	[Fe/H]	V_t, km/s	$M / M_{\odot}$	log$t$
β Gem	4830	2.85	0.03	1.4	2.3	8.89
α Ari	4510	2.40	-0.11	1.2	2.0	9.10
μ Leo	4475	2.50	0.26	1.3	1.5	9.56
γ^1 Leo	4465	1.90	-0.35	1.7	2.8	8.62
ε CrB	4360	2.12	-0.10	1.4	2.0	9.10
HR 3145	4265	1.87	-0.35	1.8	1.2	9.73
β UMi	4020	1.31	-0.33	1.3	1.6	9.29
β Cnc	4010	1.37	-0.18	1.5	2.5	8.89
α Tau	3920	1.20	-0.37	1.4	1.2	9.74
EK Eri	5025	3.26	0.10	1.2	1.8	9.16
OU And	5330	2.83	-0.11	1.6	2.9	8.60

Table 2 also lists two quantities, the mass M and age t, which were found in [1] with the aid of evolution tracks. Here the evolution tracks of Claret [6,7] were used. As we showed in [2] for the example of β Gem, in the case of our giants the transition of the more modern tracks of MIST [8] does not lead to noticeable changes in the evolution parameters.

For our problem it is important to have exact knowledge of T_{eff} and log$g$, since they are the basis of the model of the stellar atmosphere used for analyzing the chemical composition. It is known that the determined elemental abundances in the case of cold stars are especially sensitive to errors in the effective temperature T_{eff}. The exactness of the values of T_{eff} given in Table 1 is fairly high: according to [1], the error in determining T_{eff} for 3 stars (αTau, γ^1Leo, and εCrB) is ± 40K; for the other 6 giants it equals ± 30K.

We note that in [1], the parameters $T_{eff,}$ log$g$, [Fe/H], V_t, and M that we determined for β Gem, μ Leo, and α TAu were compared with the values given in Refs. 9 and 10 for 34 “benchmark” stars in classes F, G, and K, including for these three objects. Given the new determinations of [Fe/H] and V_t for μ Leo (see above), we conclude that there is outstanding agreement with the data of Refs. 9 and 10; nevertheless, we again confirm the high accuracy of the values given in Table 1.

It is interesting to note that for 2 stars of the 9 giants listed in Table 1, weak magnetic fields were observed; according to [1] 1 the maximum field is B_{max} = 0.7G for β Gem and 0.3 G for α TAu. For the giants EK Eri and OU And, studied in [2], the field is substantially stronger B_{max} = 98.6 G and 41.4 G, respectively (they are the highest values of B_{max} found in [1] 1).

Our calculations are based on models of the atmospheres calculated with Kurucz’s code ATLAS9 using the new values of ODF [12]. The analysis of the elemental abundances is based on calculations of synthetic spectra and their comparison with the observed spectra. The atomic data required for calculating the lines of the elements being studied, as well as the lines of other elements involved in calculating the synthetic spectra, were taken from the VALD3 data base [13].

We used the observed spectra of the stars from the PolarBase data base obtained on the NARVAL spectrograph [14]. Here the resolution was R = 65000, the signal to noise ratio was S/N > 350, and the wavelength range was 3700-10480 Å. For our analysis of the chemical composition, it was important that the employed spectra cover not only the visible, but also the infrared range.

3. The light elements Li, C, N, and O

These light elements are often called key elements, given their key role in stellar evolution. We have determined the abundances of the 3 elements Li, C, and O in [1] from atomic lines of LiI, CI, and OI taking deviations from LTE into account. In the case of nitrogen, because of the absence of atomic lines of NI in the spectra of cold stars, as in [2], lines of molecular CN are used. Besides the abundance of N, the ratio $^{12}C/^{13}C$ of the carbon isotopes was also determined from lines of CN.

3.1. The abundance of lithium. Lithium is known to be one of the most sensitive indicators of stellar evolution. The abundance of this element among the 9 giants was determined [1] by fitting a synthetic spectrum to the observed one in the region of the resonance lithium line LiI 6707.76 Å. This line was detected only in the spectra of 2 of the stars, β Gem and μ Leo; for them LTE lithium abundances of $\log\varepsilon(\text{Li}) = 0.73$ and 0.16, respectively, were obtained (with an error of ±0.06 dex). For the other 7 giants it was possible only to estimate an upper limit for $\log\varepsilon(\text{Li})$. The values of $\log\varepsilon(\text{Li})$ found in [1] were combined with non-LTE corrections Δ_{NLTE} of 0.19 dex for β Gem and 0.29 dex for m Leo; the values of Δ_{NLTE} were found by calculation [15].

Recently new non-LTE calculations for the LiI 6707.76 Å line for the red giants [16] have been done, which yielded a substantial revision (reduction) in the non-LTE correction to the lithium abundance. In particular, the value of Δ_{NLTE} is now only -0.02dex for β Gem. and +0.02dex for μ Leo. Since the non-LTE corrections Δ_{NLTE} for all the 9 giants turned out to be small compared to the errors in determining the abundances $\log\varepsilon(\text{Li})$, we neglect them, i.e., we finally accepted the lithium abundances obtained in [1] under LTE conditions for all the 9 giants.

3.2. The abundances of C and O. A non-LTE analysis of the abundances carbon and oxygen was made in [1] . A list of the CI and OI lines used was also given there; it includes both visible and infrared regions of the spectrum (up to the CI 9658.44 Å line). The non-LTE computational technique used here for the CI and OI lines

TABLE 3. Results Obtained for the CNO-Elements for the 9 Program Giants and the Giants EK Eri and OU And, Studied in [2].

Star	logε(C)	logε(N)	logε(O)	[N/C]	[N/O]	logε(C + N + O)	$^{12}C/^{13}C$
β Gem	8.12±0.05	8.42±0.04	8.71±0.05	0.92±0.06	0.57±0.06	8.96±0.08	17
α Ari	7.89±0.07	8.57±0.03	8.65±0.05	1.30±0.08	0.78±0.06	8.95±0.09	18
μ Leo	8.45±0.06	8.86±0.05	9.01±0.07	1.03±0.08	0.71±0.09	9.31±0.10	18
γ^1 Leo	7.75±0.10	8.22±0.04	8.46±0.10	1.09±0.11	0.62±0.11	8.71±0.15	8
ε CrB	7.88±0.11	8.62±0.04	8.65±0.09	1.36±0.12	0.83±0.10	8.97±0.15	9
HR 3145	7.84±0.11	8.33±0.05	8.52±0.10	1.11±0.12	0.67±0.11	8.79±0.16	-
β UMi	7.82±0.12	8.44±0.03	8.48±0.07	1.24±0.12	0.82±0.08	8.81±0.14	13
β Cnc	7.81±0.11	8.61±0.05	8.50±0.10	1.42±0.12	0.97±0.11	8.90±0.16	13
α Tau	7.73±0.10	8.50±0.06	8.37±0.08	1.39±0.12	0.99±0.10	8.78±0.14	13
EK Eri	8.15±0.07	8.17±0.06	8.81±0.07	0.64±0.09	0.22±0.09	8.97±0.12	17
OU And	7.90±0.15	8.40±0.10	8.80±0.12	1.12±0.18	0.46±0.16	8.98±0.21	-

was developed by one of the authors of this article (S.A.K.) and is described in Refs. 17 and 18. The resulting abundances of C and O are given in Table 3. It is clear that the amount of carbon in all the giants in Table 3 reveals a deficit relative to the solar abundance $\log\varepsilon_\odot(C) = 8.47$ which corresponds to a reduction the value of [C/Fe] from -0.2 to -0.5 dex. The oxygen abundance, on the other hand, does not manifest any sort of systematic deviation relative to its solar value, $\log\varepsilon_\odot(O) = 8.71$.

3.3. The abundance of N and the ratio $^{12}C/^{13}C$. As in [2], when determining the abundance of nitrogen and the carbon isotope ratio $^{12}C/^{13}C$ from lines of the CN molecules, we examined the spectral interval 7985-8025 Å. Here we observed a series of lines of ^{12}CN containing the isotope ^{12}C, as well as the ^{13}CN 8004.7 Å multiplet with the isotope ^{13}C. In this interval we calculated a synthetic spectrum of the star which was then fit to the observed spectrum. With this fit the abundance of carbon was fixed (it is determined above), while the nitrogen content was varied.

The found abundance of nitrogen, $\log\varepsilon(N)$, and the ratio, ^{12}Ñ/^{13}Ñ of the carbon isotopes, are shown in Table 3. which collects all the data we have obtained on the CNO-elements. Here the giants EK Eri and OU And which were studied [2] by the same technique are presented, along with the 9 program stars. It is clear that the abundance of nitrogen for all the giants in Table 3 manifests an excess relative to the solar abundance $\log\varepsilon_\odot(N) = 7.85$, which corresponds to excess values of $[N/Fe] = 0.54 - 1.12$.

As for the ratio $^{12}C/^{13}C$, the lower values of $^{12}C/^{13}C = 8 - 18$ for most of the giants in Table 3 (for the sun $^{12}C/^{13}C = 89$) show undoubtedly that these giants have passed the FDU phase. The ratio $^{12}C/^{13}C$ could not be determined for the stars HR 3145 and OU And. As noted in [2], in the case of OU And the reason was the relatively rapid rotation and elevated effective temperature of this star, but the high value of [N/C] = 1.1 found for OU And may serve to confirm that this giant has also passed through the FDU phase. In the case of HR 3145, we had access to the only observable IR spectrum which at the site of the ^{13}CN 8004.7 Å multiplet manifested strong blending, possibly to a tellurium line. However, also for HR 3145 the value of [N/C] = 1.1 is just as high as for OU And, demonstrating passage through the FDU phase. It should be noted that in [1] for 7 of the 9 giants, values of $^{12}C/^{13}C$ found previously by other authors were reported (from an analysis of the equivalent widths of CN lines, and without the aid of synthetic spectra, as in our work). A comparison of these data with Table 3 reveals good agreement.

4. A correlation between [N/C] and [N/O]

It has been long known for the red giants that there is an anticorrelation between the abundances of nitrogen and carbon. As shown in [1] 7, in the case of the more massive A-, F-, and G-supergiants the "nitrogen-carbon" anticorrelation reflects the dependence of the evolutionary changes in the abundances of N and C on the initial rotation velocity of stars. The theory predicts that a clearer indicator of the evolution may be the relationship between the quantities [N/C] and [N/O].

Figure 1 shows the relationship between [N/C] and [N/O] for the 9 program stars, as well as for the magnetic giants EK Eri and OU And studied in [2] . A distinct, clearer correlation is observed between these quantities, with [N/C] varying from 0.64 (EK Eri) to 1.4 (β Cnc and α Tau), i.e., it increases by almost 0.8 dex. The correlation is well approximated by a linear dependence, which confirms the dashed line drawn by a least squares method.

It is interesting to compare the relationship between [N/C] and [N/O] for the red giants, stars of comparatively low mass ($M/M_\odot = 1.2 - 2.8$, see Table 1), with an analogous dependence for the much more massive AFG-supergiants ($M/M_\odot = 4 - 20$). In particular, as can be seen from Fig. 5, in [1] 8, for most supergiants the quantity [N/C] varies from 0.4 to 1.6, which is somewhat wider than the variation of [N/C] in Fig. 1.

Figure 1 also shows the theoretical dependence of [N/C] on [N/O], that follows from the calculations [19] for the model of a rotating star with a mass of $2.5\,M_\odot$ (the thin continuous curve). The results of calculations for the post-FDU phase (the end of helium burning) are shown. The nodal points on this curve correspond to different values of Ω_0/Ω_{crit}, where Ω_0 is the initial angular rotation speed and Ω_{crit} is the critical rotation speed. We note that the variations in Ω_0/Ω_{crit} from 0 to 0.9 correspond to variations in the initial rotation speed at the equator from 0 to 316 km/s (see [1] 9).

We can see that calculations for the model with $M = 2.5\,M_\odot$ cannot describe the observed dependence of [N/C] on [N/O] quantitatively. It is important that for most giants the observed high values of [N/C] and [N/O] according to the theory can only be reached at a high initial rotation speed that approaches or even exceeds a critical velocity.

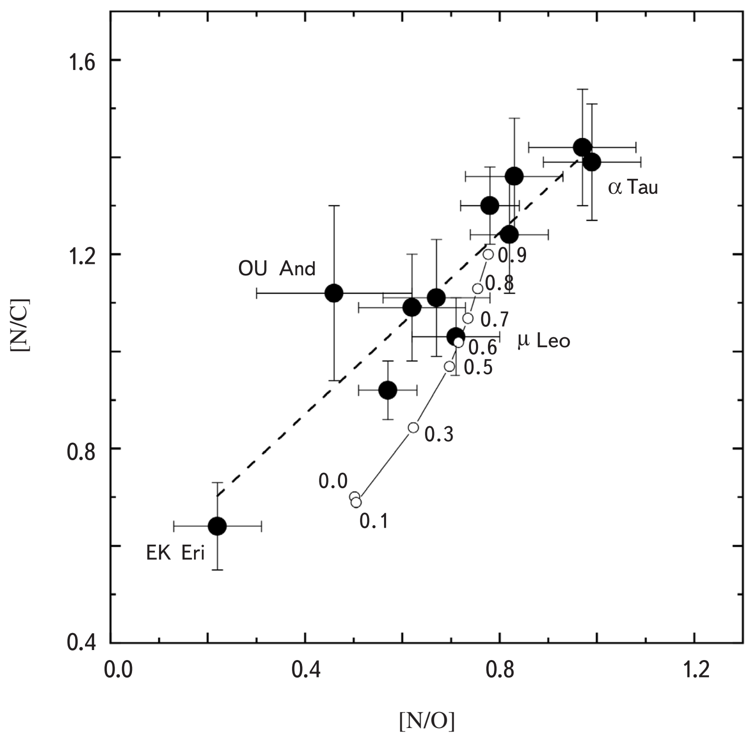

Fig. 1. The correlation between [N/C] and [N/O] for the 9 program stars, as well as the magnetic giants EK Eri and OU And [2]. The dashed line was produced by a least squares method. The thin curve shows the results of calculations for a model of a rotating star with $M = 2.5\,M_{\odot}$ [18]. Near the nodal points for this curve the values of the relative initial angular rotation velocity are indicated.

In particular, the theory cannot explain the high values of [N/C] = 1.0 - 1.4 obtained for most giants. This discrepancy is discussed below.

5. The combined abundance of C+N+O

An important prediction of the theory concerns the combined abundance of C+N+O, in particular: despite the substantial variation in the individual amounts of the elements C, N, and O during the process of the star's evolution, the sum of the abundances of C+N+O must remain unchanged from the moment of the start of the evolution. This means that in red giants this quantity must be the same as at the onset of their evolution.

Values of the combined abundance $\log\varepsilon(\mathrm{C+N+O})$ are given in Table 3. Figure 2 is plotted using them to show the dependence of $\log\varepsilon(\mathrm{C+N+O})$ on the metallicity index [Fe/H].

Figure 2 is noteworthy for a compact group of points corresponding to five giants with normal metallicity $[\mathrm{Fe/H}] = \pm 0.1$ and with very close values of $\log\varepsilon(\mathrm{C+N+O}) = 8.95 - 8.98$ (with an average of 8.97), which are

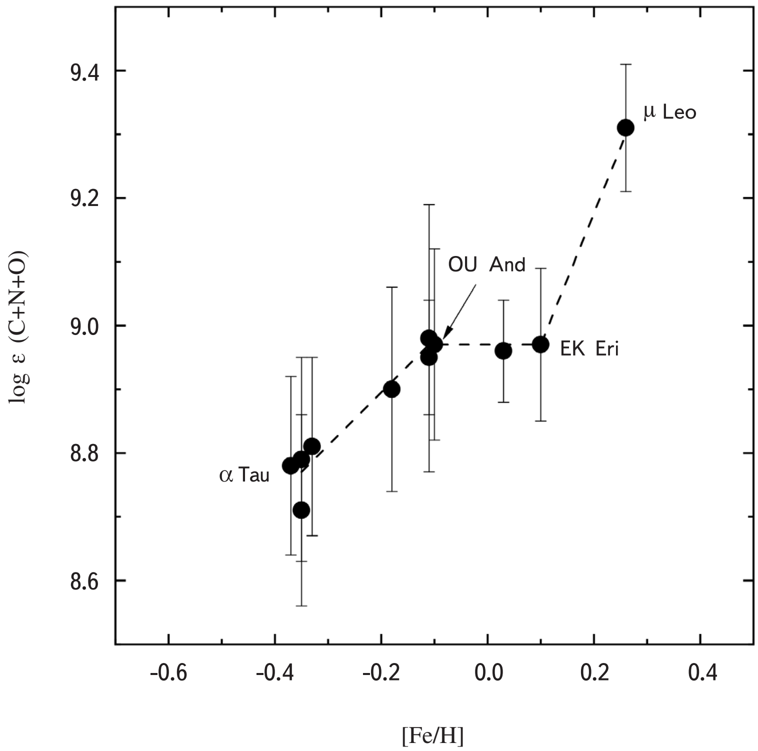

Fig. 2. The combined abundance of C+N+O as a function of the metallicity index [Fe/H]. The broken dashed line approximates the observed trend.

practically the same as the solar value 8.94 [4]. This result is important for two reasons.

First, a prediction of the theory is confirmed: giants with normal (solar) metallicity retain their initial (solar) combined abundance of C+N+O. Second this result can be regarded as an objective criterion for the accuracy of our results regarding the CNO-elements. The small difference of 0.03 dex in the values of $\log\varepsilon(\mathrm{C+N+O})$ among the five stars cannot be random: on this basis we consider the actual error in the abundances of C, N, and O that we found is probably no more than ±0.05 dex.

The other compact group in Fig. 2 is made up of 4 giants with reduced metallicity; for them the index [Fe/H] lies between -0.33 and -0.37, and the values of $\log\varepsilon(\mathrm{C+N+O})$ between 8.71 and 8.81 (8.77 on the average, which is 0.17 dex below the solar value).

The dashed line in Fig. 2 approximates an obvious trend in $\log\varepsilon(\mathrm{C+N+O})$ with the metallicity index [Fe/H]. Here a special position is occupied by the giant m Leo with an elevated index [Fe/H] = +0.26 and a high value of $\log\varepsilon(\mathrm{C+N+O}) = 9.31$, which is 0.37 dex higher than on the sun. The question arises of how reliable is the large value of $\log\varepsilon(\mathrm{C+N+O})$ for μ Leo? As already noted, when determining the abundances of elements for cold stars the results are especially sensitive to errors in the effective temperature T_{eff}. The accuracy of determining T_{eff} in the

TABLE 4. The Parameters T_{eff} and log$g$ Found in [1] for the Giant μ Leo Compared to Data from other Authors.

T_{eff}	log$g$	Ref., year
4475	2.50	[1], 2021
4474	2.51	[8], 2015
4471	2.45	[20], 2015
4461	2.65	[21], 2019

case of μ Leo is high; Table 4 may serve as confirmation, where for μ Leo, we show our values of T_{eff} and log$g$, as well as the results of other authors obtained in recent years. We can see that there is excellent agreement in the values of T_{eff} (as well as of log$g$). Thus, the elevated value of $\log\varepsilon(\mathrm{C+N+O})$ for μ Leo is confirmed.

6. The heavy elements

We refer to the chemical elements heavier than iron as heavy elements. We examined 12 such elements from Cu to Hf; eight of them (from La to Er) are rare earths, (RE), three of them are lighter than the RE (Cu, Rb, and Ba), and one is heavier than the RE (Hf). Previously [2], as a control we determined the abundances of these elements for the sun, using the same spectral lines as in this paper. It was shown that these abundances are in agreement with the latest data for the sun [4] (see Table 7 in [2]).

The analysis of the abundance of the heavy elements in this paper was carried out by the method described in [2] . In particular, the abundances of copper, rubidium, and barium were determined without assuming LTE and we applied an LTE approach for the rare earths (RE) and hafnium.

The abundances of all the elements, including the heavy elements, are listed in Table 5. The last column gives the contemporary data for the sun [4]; here the refined abundance for lithium is taken from [1] 6. Here we have not indicated the errors in the elemental abundances, except for the sun, since including these errors would have nearly doubled the size of the table. Besides, for the CNO elements the errors are already given in Table 3, while for Li the error of ±0.06 dex in the case of two of the stars with detected lithium (β Gem and μ Leo) was given in [1] . The errors in the abundance of iron are shown in Refs. 1 and 2 (we note that the errors in the abundance of Fe range from ±0.05 to ±0.09 dex). For the heavy elements the typical error is ±0.10 dex.

In the discussion of Fig. 2 above, we separated the study of the giants into three groups depending on their metallicity [Fe/H]. In the group with normal metallicity [Fe/H] = ±0.1, we included three of the program giants (β Gem, α Ari, and ε CrB), as well as the two magnetic giants studied in [2], EK Eri and OU And. We have already

TABLE 5. Abundance of Elements $\log\varepsilon(\mathrm{El})$ in the Atmospheres of the 9 K-Giants Compared with Data for the Sun [4] (for Solar Abundance of Li see [6])

Z	Element	β Gem	α Ari	μ Leo	γ^1 Leo	ε CrB	HR 3145	β UMi	β Cnc	α Tau	Sun
3	Li	0.72	≤ -0.12	0.16	≤ -0.24	≤ -0.27	≤ -0.43	≤ -1.05	≤ -0.63	≤ -1.15	0.96±0.05
6	C	8.12	7.89	8.45	7.75	7.88	7.84	7.82	7.81	7.73	8.47±0.06
7	N	8.42	8.57	8.86	8.22	8.62	8.33	8.44	8.61	8.50	7.85±0.12
8	O	8.71	8.65	9.01	8.46	8.65	8.52	8.48	8.50	8.37	8.71±0.04
26	Fe	7.51	7.37	7.74	7.13	7.38	7.13	7.15	7.30	7.11	7.48±0.04
29	Cu	4.30	4.13	--	4.00	3.97	3.85	4.16	4.09	4.05	4.18±0.05
37	Rb	2.39	2.25	2.75	2.12	2.27	2.10	2.21	2.10	2.24	2.47±0.07
56	Ba	2.19	2.20	2.35	2.00	2.19	1.74	2.28	2.46	2.14	2.25±0.07
57	La	1.15	1.09	1.23	0.91	0.98	0.82	0.97	1.11	0.82	1.11±0.04
59	Pr	0.71	0.68	0.85	0.55	0.57	0.54	0.50	0.69	0.50	0.72±0.04
60	Nd	1.51	1.48	1.56	1.27	1.39	1.09	1.38	1.46	1.03	1.42±0.04
62	Sm	1.00	0.93	1.1	0.77	0.83	0.74	0.85	0.93	0.75	0.95±0.04
63	Eu	0.55	0.49	0.81	0.42	0.45	0.37	0.43	0.51	0.30	0.52±0.04
64	Gd	1.12	1.09	1.17	0.94	1.01	0.88	0.94	0.96	0.87	1.08±0.04
66	Dy	1.11	1.20	1.22	0.92	0.88	0.77	0.64	0.80	0.56	1.10±0.04
68	Er	0.93	0.80	0.86	--	--	0.60	0.89	--	0.74	0.93±0.05
72	Hf	0.94	0.75	0.92	0.59	0.60	0.48	0.53	0.55	0.40	0.85±0.05

discussed the chemical composition of three stars from this group. β Gem, EK Eri, and OU And in [2] . In particular, it was shown that for the heavy elements from Fe to Hf the found abundances typically differ from those for the sun within the limits of error. Analyzing the data from Table 5, we arrive at the same conclusion with regard to the two remaining stars from this group, α Ari and ε CrB.

Thus, for the group of giants with normal metallicity the result is entirely expected: they have essentially the solar abundance of the heavy elements. The chemical composition of the giants with low metallicity (for them [Fe/H] is between -0.33 and -0.37) can be evaluated from Fig. 3, which shows the difference [El/H] in the abundances between a star and the sun for all the elements that were studied from Li to Hf. In order to reduce to a minimum the size of this figure for the two coldest stars in this group, β UMi and α Tau, an elevated upper limit of the abundance of lithium $[\mathrm{Li/H}] \le -1.00$ is indicated, while the actual limit is $[\mathrm{Li/H}] \le -2.01$ and -2.11 for β UMi and α Tau, respectively (see Table 5).

Data on the chemical composition of m Leo, the giant with an elevated metallicity $[\mathrm{Fe/H}] = +0.26$ that

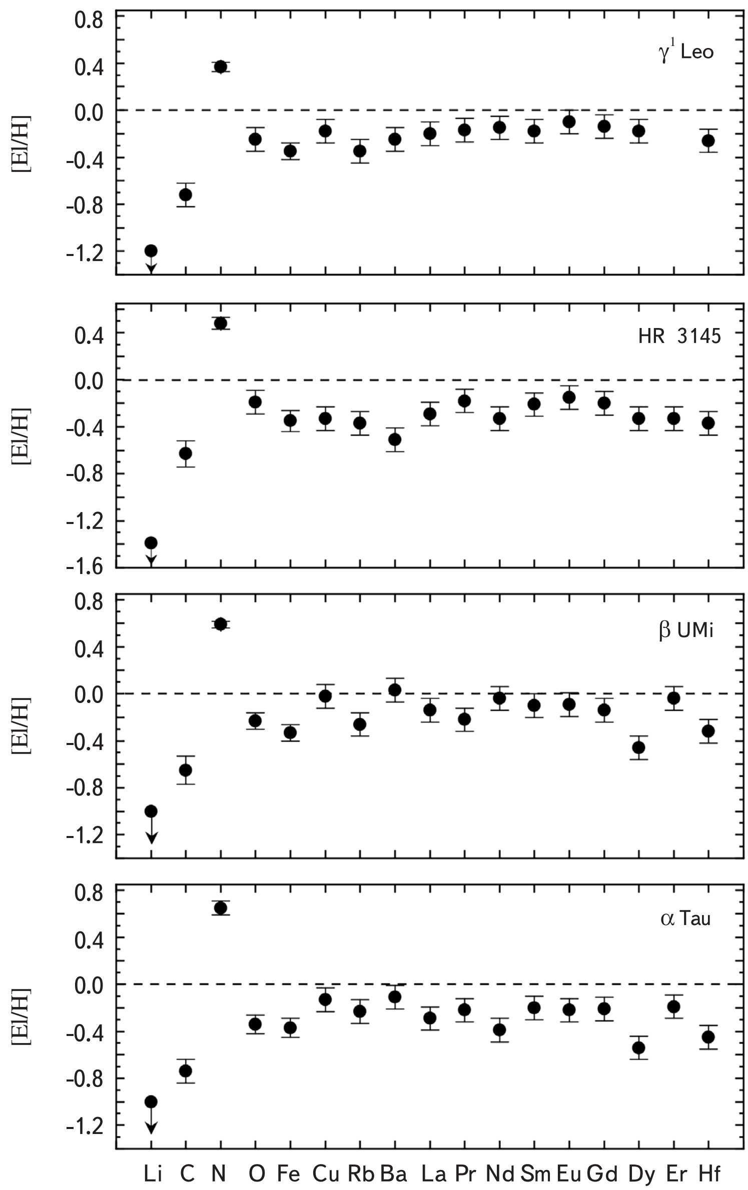

Fig. 3. The abundance of the elements (relative to the sun) in the atmospheres of the 4 giants with reduced metallicity indices [Fe/H] = -(0.33-0.37).

manifests an anomalously high combined abundance of C+N+O (Fig. 2) may supplement the overall picture. In Fig. 4 we show the abundances of the elements [El/H] relative to the sun for this star. We can see that the abundances of the RE-elements differ from the solar values considerably less than the abundance of iron.

The number of lines that we have used in analyzing any kind of rare-earth element depends on the element itself and on the specific star. The largest number of lines (12-19) was invoked to analyze the abundance of Nd. The smallest number of lines could be used for Dy and Er: only 2-3 lines for Dy and 1-2, for Er (the only exception was the giant β Gem with 4-5 lines). Thus, we regard the found abundances of Dy and Er as less reliable.

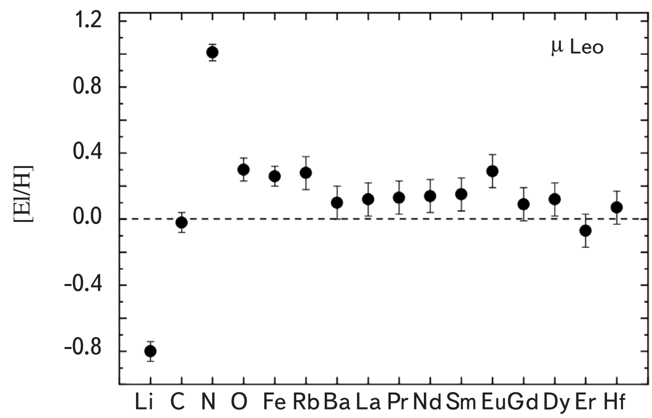

Fig. 4. The abundance of elements (relative to the sun) in the atmosphere of the giant μ Leo with an elevated metallicity index [Fe/H]=+0.26.

Figure 5 shows the value of [RE/Fe], the average value of [El/Fe] for 6 RE-elements from La to Gd, as a function of [Fe/H] (the results for Dy and Er were not included). A distinct trend can be seen in [RE/Fe] with increasing [Fe/H], where the value of [Re/Fe] decreases from +0.2 to -(0.11-0.15) dex as [Fe/H] increases from -0.35 to 0.10-0.26 dex. Thus, as [Fe/H] increases by 0.6 dex the value of [RE/Fe] falls by roughly 0.3 dex.

We recall that our analysis of the abundances of the RE-elements was made assuming LTE. Is it possible that

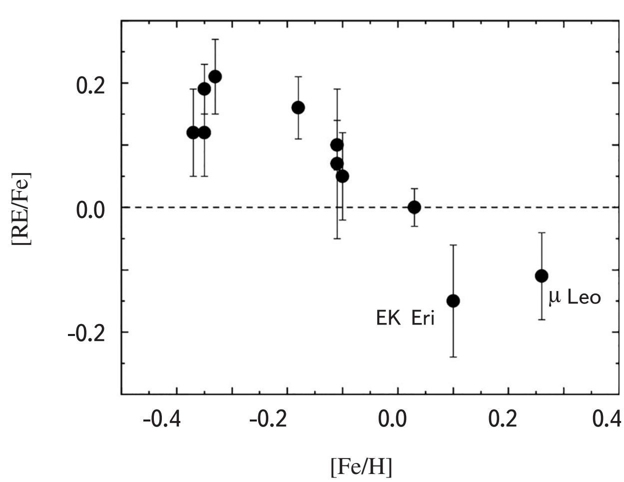

Fig. 5. The average value of [El/Fe] for the RE-elements as a function of the metallicity index [Fe/H].

the dependence shown in Fig. 5 was explained by non-LTE effects that were not taken into account? It should be noted that the lines of the RE-elements in the spectra of the stars studied here are generally very faint and are formed deep in their atmospheres. For stars with near-solar metallicity at these depths the electron density is high and collisions with them ensure a level population in the atoms in accordance with LTE. This makes it possible to hope that possible non-LTE effects are fairly small for them. This proposition is partly confirmed by non-LTE calculations for Pr II [22], Nd II [23], and Eu II [24] for the sun, which imply that use of an LTE-analysis may introduce an error in the determined abundance of no more than ±0.03 dex. This value is an order of magnitude smaller than the change in [RE/Fe] of 0.3 shown in Fig. 5. For a final resolution of the problem, direct non-LTE calculations of the lines of RE-elements for cold giants similar to ours are desirable.

7. Discussion

An important result that we obtained for the 9 giants with planets that were studied is that they have all experienced deep convective mixing in the FDU phase. This fact is important precisely for discussing their chemical composition. To this discussion we have added the two magnetic giants, EK Eri and OU And, which we studied in [2] by the same method (they have also passed through an FDU phase, see [2]).

Lithium, the lightest element in our list, was not found for 7 of the 11 giants that were examined. This result is fully to be expected for such post-FDU objects; in fact, because of deep mixing of lithium from the atmosphere lithium from the stellar atmosphere was carried into deep and hot layers of the star where it was completely burnt up. However, for four of the giants (β Gem, μ Leo, EK Eri, and OU And) lithium was observed, which conflicts with the standard theory of stellar evolution. Yet another obscure fact is that for three of these four giants (βGem, EK Eri, and OU And) a magnetic field was found, which should not exist in post-FDU objects after deep mixing.

As we noted in [2], these two mysterious phenomena may have a single explanation. It involves hypothetical capture by a star (even after completion of the FDU phase) of a giant planet with a mass several times that of Jupiter.

Calculations [25] have shown that as a result of falling on a red giant of a planet with a mass up to M_J (where M_J is the mass of Jupiter) the lithium content on the surface of the star can be raised to $\log\varepsilon(\mathrm{Li}) \approx 2.2$. Thus, the values of $\log\varepsilon(\mathrm{Li}) = 0.16 - 1.52$ which we have found in the above four giants are entirely explainable in terms of this hypothesis. It is important that the capture of a planet, besides an increase in the abundance of lithium, leads to a significant rise in the rotation speed of a red giant. According to [2] 6, one consequence of this is the triggering of a dynamo mechanism and the appearance of a magnetic field.

For red giants in which planets are already detected, this sort of hypothesis appears to be quite realistic. Here it should be taken into account that in forming planetary systems, migration of planets takes place, for which the falling of one of the planets from a central star is entirely probable. According to the estimate of [2] 7, capture of planets by red giants takes place quite often in the galaxy, roughly 3 events per year.

On going from lithium to a discussion of the group of CNO-elements it is necessary to stop at the discrepancy between observations and theory regarding the dependence of [N/C] on [N/O]. According to Fig. 1, calculations of the model of a star with rotation cannot explain all the observed range of these two quantities. In addition, the high values of [N/C] = 1.0 - 1.4 for most of the giants observed in Fig. 1 according to the calculations of [1] 9 can be obtained only for initial rotation speeds greater than 150 km/s, which conflicts with observations of stars with masses of 1-3 $M_{\odot}$.

For more than two decades the hypothesis of additional nonconvective mixing (extra mixing) in red giants following FDU has been under discussion in the literature, in order to explain several features of the observed abundances of the light elements Li, C, N. and O in these stars which cannot be explained in terms of the standard theory. For example, the idea of "extra mixing" was invoked in [2] 8 to explain the low ratio of the carbon isotopes $^{12}C/^{13}C$ in these stars, and in [2] 9 for analyzing the quantity [C/N] for a large number of giants with different metallicity. Evidently, this idea is necessary to explain the dependence of [N/C] on [N/O] that we have obtained.

In Fig. 1 the giant EK Eri, for which a magnetic field was observed, occupies an especially low position. This example shows that the chemical composition of magnetic red giants merits special attention.

Yet another interesting result regarding the CNO-elements concerns the combined abundance of C+N+O. We found that, in full accord with the theoretical prediction, for the 5 giants with normal (solar) metallicities [Fe/H] = ±0.1 dex, the obtained values of $\log\varepsilon(\mathrm{C+N+O}) = 8.95 - 8.98$ actually coincide with the solar value 8.94. In other words, despite the variations in the individual abundances of C and N during the evolutionary process, especially after the FDU phase, the sum C+N+O remains unchanged from the moment the star is formed.

The dependence of the combined abundance of C+N+O on the metallicity index [Fe/H] (Fig. 2) is of special interest. It was found from the 11 stars, among which the giant m Leo with an elevated metallicity [Fe/H]= + 0.26 and an extraordinarily high value of $\log\varepsilon(\mathrm{C+N+O}) = 9.31$, occupies a special position. We believe that to confirm and refine this dependence it is necessary to substantially increase the number of stars that are examined, adding giants with metallicity [Fe/H] < -0.4, as well as some stars with [Fe/H] from 0.2 to 0.4, where, thus far, we only have the giant μ Leo. If the dependence of the sum C+N+O on [Fe/H] is confirmed, this will mean that it took place already in that initial interstellar matter from which the stars being examined were formed. Then an explanation of this phenomenon will be sought in modern models of the chemical evolution of the galaxy.

Regarding the relatively heavy elements there is interest in the anticorrelation we have found between the average abundances of the RE-elements and the value of [Fe/H] (Fig. 5). An analogous anticorrelation was found earlier [30] for the RE-elements Nd, Sm, and Eu in studies of several hundred F- and G- dwarfs with [Fe/H]= +0.4 to -1.4 (see Fig. 2 in [30]). In this range, it turns out that there is significant reduction in the values of [El/Fe] with the rise in the two magnetic giants, EK Eri and OU And, which were studied in [2] by the same method (they have also passed through an FDU phase, see [2]).

In the modern models of the chemical evolution of the galaxy, the main role in formation of the RE-elements is assigned to the r-process and the s-process. The role of these two processes in stellar nucleosynthesis and the chemical evolution of the galaxy is examined, e.g., in [32]; the role of the r-process is discussed in detail in the review of [33]. We emphasize that the dependence of [RE/Fe] on [Fe/H] shown in Fig. 5 is not connected in any way with the evolution of the studied giants, but only reflects the initial chemical composition of these stars (or, in other words, the chemical composition of the interstellar medium from which they were formed).

8. Conclusion

In this paper we have studied the chemical composition of 9 K-giants with planets lying within 100 pc of the sun. Here we have used the fundamental parameters of the stars which we found previously [1]. Only for the giant μ Leo, we reanalyzed anew the FeI lines and refined the iron abundance and the microturbulence parameter V_t.

We determined the abundances of 17 chemical elements from lithium (Z = 3) to hafnium (Z = 72). Here the analysis of the lines of a number of elements was done without assuming LTE (local thermodynamic equilibrium). Recently we used the same method [2] to study the giants EK Eri and OU And, for which substantial magnetic fields have been observed and which were identified as probable successors to magnetic Ap-stars. In analyzing the elemental abundances obtained in this paper, we supplemented them with the results found in [2] for EK Eri and OU And.

We have shown that all 9 of the program K-giants have passed through deep mixing in an FDU (First Dredge-Up) phase. For most of the giants this indicates a low ratio $^{12}C/^{13}C = 8-18$ of the carbon isotopes, which we found from lines of the CN molecule. For the star HR 3145, where it was not possible to determine $^{12}C/^{13}C$, proof is provided by the high ratio N/C (greater than the solar value by 1.1 dex), which is typical for post-FDU objects. It was concluded earlier that the stars EK Eri and OU And are also post-FDU objects.

Lithium, which is a sensitive indicator of stellar evolution was not found in 7 of the 11 giants examined here. The absence of lithium in the atmospheres of stars that have undergone deep mixing in an FDU-phase is an entirely expected result. However, for 4 of the giants that had also passed through the FDU phase, we detected lithium. In 3 of these 4 stars other authors a magnetic field was detected previously simultaneously by other authors. These two effects, the presence of lithium in the atmosphere and the existence of a magnetic field are utterly unexpected for post-FDU giants in terms of the standard theory and these days find a general explanation in terms of a unified hypothesis: capture (engulfment) of a stellar planet with a mass several times that of Jupiter.

For the group of CNO-elements, we found two relationships that are of interest. The first is a clearly distinct correlation between [N/C] and [N/O],,which is an observed manifestation of stellar evolution. A comparison of the observed dependence with a theoretical model accounting for rotation has shown that the theory cannot explain the high values of $[N/C] = 1.0 - 1.4$ which we obtained for most of the giants examined here. Here it is evidently necessary to invoke an hypothesis of additional nonconvective (extra) mixing, which has been discussed in the literature for more than two decades.

The second relationship concerns the combined abundance C+N+O, which according to the theory should not vary during the time a star is formed. We have shown that for giants with near-solar abundances $\log\varepsilon(C+N+O) = 8.95 - 8.98$ (8.97 on the average) actually coincide with the solar abundance, 8.94. A trend has been found in the value of $\log\varepsilon(C+N+O)$ with increasing [Fe/H] but confirming it requires an extension of the list of values of [Fe/H] and, therefore, an extended list of giants to be examined. The large value of $\log\varepsilon(C+N+O)=9.31$ for the giant m Leo, which has a high metallicity [Fe/H] = +0.26, merits separate attention.

An anticorrelation has been found between [RE/Fe], the average abundance of the rare-earth elements La, Pr, Nd, Sm, Eu, and Gd (relative to Fe), and the metallicity index [Fe/H]. It agrees well with data for the F- and G- dwarfs in the vicinity of the sun and reflects the initial chemical composition of the giants studied here.

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