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Do we really obtain reliable elemental abundances for supergiant stars? [⋆]

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Abstract. We discuss the problems of standard spectroscopic analysis of intermediate mass supergiants and propose the usage of Fe II lines for the microturbulent velocity and gravity determination, instead of Fe I lines that are usually applied for this aim, but more affected by non-LTE effects.

With the example of δ Cep (seven high-resolution and high signal-to-noise ratio spectra) we demonstrate that the proposed approach results in the following advantages:

- it removes the long-standing problem of the discrepancy between the spectroscopic and physical gravities (based on the estimated stellar masses and radii), resulting in a complete agreement between these values;
- it brings the abundances of some elements (among them carbon, nitrogen, oxygen) in accordance with the theoretically predicted atmospheric abundances for the supergiants of intermediate masses after the first dredge-up phase;
- it allows us to keep an ionization balance of some elements observed in two ionizational stages together with the Fe I/Fe II balance.

Key words: stars: abundances – stars: individual: δ Cep – stars: variables: Cepheids

1. Introduction

Cepheids are stars, whose investigation is of paramount importance for the critical testing of our knowledge about the detailed evolutionary characteristics of the intermediate mass stars. Numerous studies of the chemical composition of Cepheids and non-variable yellow supergiants showed that the observational results agree qualitatively with the theoretical predictions (see, e.g. Luck & Lambert 1981, Luck & Lambert 1985, Luck 1994, Andrievsky et al. 1996, Kovtyukh et al. 1996). However, a more detailed investigation indicates that there are still some contradictions between the theory and observations that are not completely understood and have not been explained to date. One can mention the papers by Luck & Lambert (1985), Luck et al. (1998), where the problem was posed and some attempts to solve it were undertaken. The problem itself arises from the following observational results:

1. The considerable oxygen deficiency observed in the intermediate mass ($M \leq 10M_\odot$) supergiants is not explained by the standard dredge-up scenario.
2. The observed carbon deficiency is often greater than the theoretically predicted one for these stars.
These contradictions are likely to be connected with more general problems of the stellar spectroscopic analysis.
3. Spectroscopic gravities (based on Fe I/Fe II balance) appear to be systematically lower than those determined from the stellar physical parameters.
4. For the great majority of the elements that presented in the spectrum by two ionization stages, the ionization balance is not reached when the gravity is determined using Fe I and Fe II lines.

Luck & Lambert (1985) were the first to clearly point out that for intermediate mass supergiants so-called “physical” (or “theoretical”) gravities, whose determination is based on the masses and radii, are not consistent with the “spectroscopic” gravities found by keeping the Fe I/Fe II ionization balance. These authors have emphasized that the difference between the spectroscopic and theoretical gravities is well correlated with the determined carbon and oxygen abundances. Remarkable oxygen deficiency appears in the case, when spectroscopically determined gravities $\log\, g^{sp}$ are less than theoretically estimated by a factor of 2 or more (see Fig. 11 from that paper). Oxygen abundance can be changed to approximately solar value only if $\log\, g^{ph}$ instead of $\log\, g^{sp}$ is used in the analysis, but this immediately leads to a significant imbalance in the ionization equilibrium for metals. Such a disequilibrium cannot be removed by any reasonable $T_{\rm eff}$ changes. The problems of the spectroscopic analysis are clearly seen, first of all, in the resulting abundances of carbon and oxygen, which are the elements of great importance from the evolutionary point of view. In their concluding remarks, Luck & Lambert (1985) speculate that the oxygen underabundance found for intermediate mass stars can be explained by either a specific chemical composition of their progenitors, or systematic errors attributed to traditional spectroscopic abundance analysis. We show below that the mentioned contradictions can be removed using a more realistic approach in the chemical

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[⋆] The Appendix is only available electronically with the On-Line publication at http://link.springer.de/link/service/00230/

composition analysis. For this aim we present the results of a detailed study of the elemental abundances in the atmosphere of the famous classical Cepheid δ Cep observed at seven different phases. This star was selected because 1) as a bright object, it enables one to obtain spectra of high quality, 2) as a star belonging to the class of pulsating variables, it gives a possibility to estimate its luminosity, mass, radius and effective temperature with rather high accuracy.

2. Observational material

Observations were carried out at Kitt Peak National Observatory with the coudé-fed telescope during 21–27.09.1995. The spectrograph was equipped with a 3070 × 1024 CCD camera. Seven high-resolution spectra (each of them is three spectra co-added, resolving power $R\ \approx$ 80000, S/N ≈150) were taken in the spectral region 5600–7800 Å(25 orders). The spectra of δ Cep were initially analysed by Fry & Carney (1997) for the determination of the iron content. Detailed description of the spectroscopic material and its preliminary reduction can be found in that work. Useful information concerning the spectra is also presented in Table 1 (see the first three columns).

Further work with the spectra (continuum level, wavelength calibration, equivalent width measurements, etc) was performed using the DECH20 package (Galazutdinov 1992). Equivalent widths of about 3400 lines were measured from the program spectra. Some lines were removed after the preliminary consideration. Thus, at the final step we used approximately 2700 lines. For the great number of them we had two estimates of the equivalent width W from adjacent orders. In all cases, the differences between independent estimates did not exceed 5–7%, being usually less than this value. It indicates the high quality of the spectra and high precision of the equivalent width determination, even for the lines located near the order edges. The final list of the lines and their equivalent widths are given in the Appendix. Note, that in the abundance analysis we did not use the lines having $W \geq 150$ mÅ.

3. General method of analysis

3.1. Numerical code

The WIDTH9 code and new grid of atmosphere models (Kurucz 1992) were used to derive the abundances. Although these models do not take into account the sphericity of the supergiant atmospheres, as well as possible increased helium content (that could be expected for Cepheids), they are commonly in use and this allows us to perform a correct comparison of the independently obtained results on elemental abundances.

3.2. Oscillator strengths

Special attention was given to oscillator strengths selected for abundance analysis. In this work we used so-called “solar” $\log\ gf$ values. They were derived by us using unblended solar lines (based on solar spectrum by Kurucz et al. 1984). The equivalent widths of selected solar lines were accurately measured using the software of Galazutdinov (1992). Then, for each line of the considered element we corrected the initially adopted $\log\ gf$ value to produce the solar elemental abundances (Grevesse et al. 1996) in the calculations. This was performed using the WIDTH9 code, solar atmosphere model from Kurucz's grid with the microturbulent velocity of 1 km s^{-1}. Oscillator strengths adopted for the further analysis are collected in the Appendix.

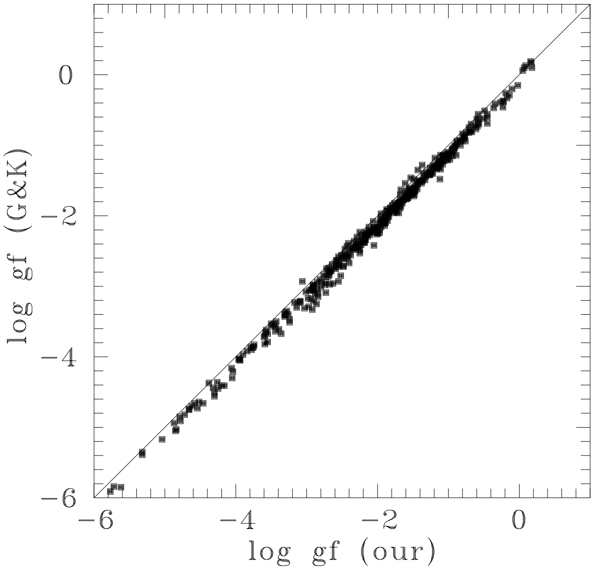

Fig. 1. Comparison of our oscillator strengths with $\log\ gf$ of Gurtovenko & Kostyk (1989).

A comparison of our oscillator strengths for 415 common Fe lines with $\log\ gf$ of Gurtovenko & Kostyk (1989) shows a small systematical difference (about 0.1 dex). This difference is easily explained taking into account the difference in the adopted solar iron abundance (Gurtovenko & Kostyk used $\log\ A(\mathrm{Fe}) = 7.64$, while we employed 7.50). The result of the comparison is given in Fig. 1.

In their fundamental spectroscopic study of 23 galactic Cepheids, Fry & Carney (1997) found a similar small difference comparing their “solar” $\log\ gf$ values with those of Gurtovenko & Kostyk (1989). Finally, we have compared $\log\ gf$ for 101 common lines with Fry & Carney (1997) and found an excellent agreement (see Fig. 2). It should be mentioned that our oscillator strengths were also compared with the compilative $\log\ gf$ data used by Luck (1996) in his studies and no significant differences were found.

4. Determination of atmospheric parameters: standard approach

4.1. Effective temperature

A comprehensive comparative analysis of the different determinations of the T_{eff} value for δ Cep was given by Fry & Carney (1997). It was shown that the obtained values are in good agreement with the independent results of Fernley et al. (1989) based

Table 1. Observations and atmospheric parameters

Sp	HJD,2440000+	ϕ	$T_{\rm eff}$(KS)	log g^{ph}	$T_{\rm eff}$	log g^{S}	$V_{\rm t}{}^{S}$	log g^{NS}	$V_{\rm t}{}^{NS}$
Sp 1	9981.80869	0.443	5710	1.96	5640	1.5	2.7	2.0	3.2
Sp 2	9982.80209	0.628	5540	1.99	5550	1.6	3.2	2.0	3.7
Sp 3	9983.77479	0.809	5660	2.04	5675	1.5	3.5	2.0	3.8
Sp 4	9984.81440	0.002	6650	2.05	6650	1.7	3.0	2.2	3.5
Sp 5	9985.82009	0.190	6150	1.97	6050	1.6	2.6	2.1	3.1
Sp 6	9986.75476	0.364	5800	1.94	5700	1.5	2.6	2.0	3.1
Sp 7	9987.75601	0.551	5600	1.97	5580	1.6	2.5	2.1	3.0

Phases are calculated with the elements from Kiss (1998); $T_{\rm eff}$(KS) – an estimate from Kiss & Szatmáry (1998) calibration using $uvby$ – photometry.

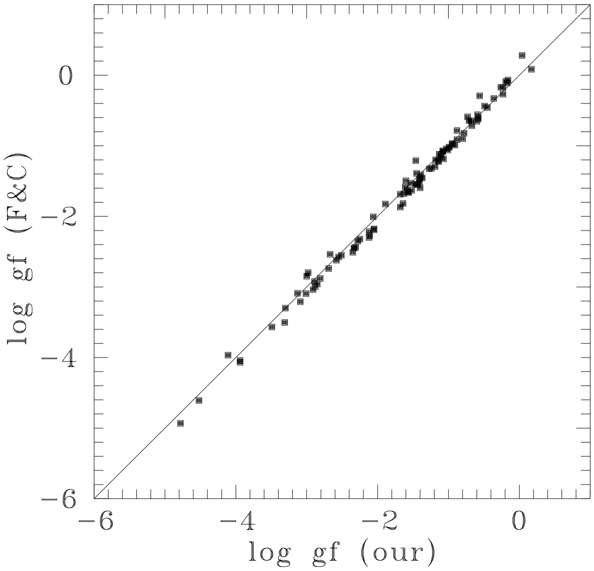

Fig. 2. Comparison of our oscillator strengths with those of Fry & Carney (1997).

on the infrared flux method and Evans & Teays (1996) based on spectrophotometry.

In the present paper we slightly modified the $T_{\rm eff}$ values for different phases. The new values differ from old estimates by no more than 100 K. To specify the temperature, we used standard condition where there is no dependence of the abundances derived from the individual Fe I lines upon line excitation potentials (see sixth column of Table 1).

Kiss & Szatmáry (1998) obtained very accurate $T_{\rm eff}$ -$(b-y)_0$ calibration that was also used for δ Cep photometric temperature determination. It is very important to note that applied photometrical data were obtained by Kiss (1998) at the same epoch when the spectroscopic observations were carried out. Our spectroscopic estimates of $T_{\rm eff}$ appeared to be in good agreement with $T_{\rm eff}$ determination based on Kiss & Szatmáry photometrical calibration (Δ $T_{\rm eff}$ is less than 100 K - see Table 1).

4.2. Microturbulent velocity

In order to derive the microturbulent velocity $V_{\rm t}$, we used the standard method which implies that there should be no dependence of iron abundance obtained from the individual Fe I lines upon their equivalent widths (see Fig. 3). Results of $V_{\rm t}$ determination for all the phases are presented in Table 1 (the mark "S" denotes standard approach).

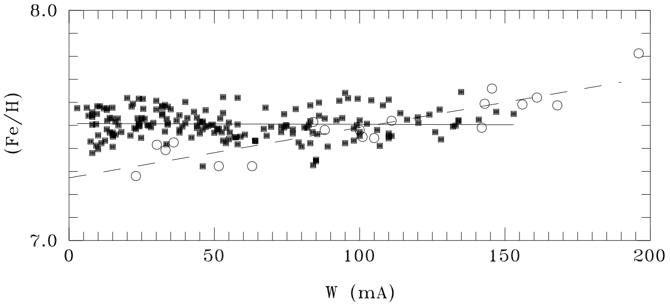

Fig. 3. Sp1: ϕ=0.443. Standard approach: $V_{\rm t}$ is determined using Fe I lines ($filled\ squares$); for reference, the result for Fe II lines is indicated by $open\ circles$.

It should be noted that visible dependence between the iron abundance derived from the individual Fe I lines and the corresponding equivalent widths appeared when the $V_{\rm t}$ parameter was changed by approximately $\pm$ 0.2 km s^{-1}or greater.

Our mean $V_{\rm t}$ value found for δ Cep from the seven spectra is exactly the same as determined by Fry & Carney (1997) within the quoted error.

4.3. Gravity

In the standard calculations we kept the condition of the Fe I/Fe II ionization balance for all the phases. It enabled us to determine the log g value and its variation during the pulsational cycle. The amplitude of the log g variation was surprisingly small (see Table 1, log g with a mark "S").

5. Traditional approach of abundance analysis and its demerits

As usual, Fe I lines are practically always used for microturbulence velocity determination, sometimes for effective temperature specification, and together with Fe II lines for gravity determination. The number of unblended Fe I lines of different excitation potentials of the lower level and with equivalent widths spanning the interval from 0 to 200 mÅ is rather large in the spectra of yellow supergiants, making them a very attractive tool for determination of the stellar atmospheric parameters.

Up to now, the majority of the investigators used Fe I lines for this purpose. Nevertheless, there is accumulating evidence, that the lines of neutral elements (iron, in particular) should be used with caution.

As was pointed out by Lyubimkov & Boyarchuk (1983, 1985) and Rentzsch-Holm (1996), the NLTE effects for Fe I lines are very pronounced and depend upon the equivalent width (although, in the latter work only the stars with $T_{\rm eff}$=7000 K−12000 K and $\log\, g$=3.5−4.5 were examined, there is no doubt that NLTE corrections should increase along with the gravity decreasing). According to Lyubimkov & Boyarchuk (1983), the NLTE corrections to the iron abundance in $F0$ supergiants achieve about 0.6 dex, when lines with $W \approx$ 200 mÅ are used, and 0.1–0.2 dex in the case of lines having $W \approx$ 50 mÅ.

At the same time, Fe II lines are practically not sensitive to the departure from LTE. Severe overionization of Fe II is unlikely in $F - G$ supergiants, while for Fe I atoms it can be expected. Recently this conclusion was confirmed by the calculations of statistical equilibrium for Fe I/ Fe II in the atmosphere of late-type stars (Thevenin & Idiart 1999). Accurate atomic models for neutral and ionized iron were applied to investigate the NLTE effects in iron abundance for various stellar parameters. The authors found that particularly in the case of metal deficient stars, surface gravities derived by LTE analysis are in significant error.

Generally this problem exists not only for intermediate mass supergiants. Steenbock (1985) showed that deviations from the LTE for neutral iron affect the stellar parameters found from the spectroscopic analysis, particularly in the evolved giants such as Pollux. The NLTE effects in metal-poor stars and their spectral manifestations were explored by Gehren et al. (1991).

Fuhrmann et al. (1997) proposed the use of pressure-broadened Mg Ib lines to derive the gravity parameter for F and G stars. These lines appear to be more reliable tracers compared to the ionization equilibrium condition for Fe I/Fe II, which is susceptible to overionization effects. They demonstrated that the strong line method circumvents the long-standing problem of gravity discrepancy. The same conclusion about the systematic errors in the standard spectroscopic LTE analysis based on the keeping of iron ionization equilibrium was also drawn in the work by Fuhrmann (1998). It was found that for neutral iron lines formed in the atmospheres of some stars, much stronger deviations are expected than for the corresponding lines in the solar photosphere. While no such influence was found for the Fe II lines, one can suspect that the different behaviour of Fe I and Fe II lines would cause a noticeable change in the $\log\, g$ value if it is determined from the Fe I/Fe II balance.

If the NLTE corrections progressively depend upon the equivalent widths, then we should expect a monotonous decreasing of the iron abundance derived from the Fe I lines along with an increase of their equivalent widths. Standard spectroscopic analysis implies that the microturbulence parameter is determined by avoiding any dependence of the resulting abundances from individual lines upon their equivalent widths. If Fe I lines are used, then taking into account their anomalous behaviour, one can suspect that one will inevitably obtain an artificially decreased $V_{\rm t}$ value in order to equalize the abundances resulting from the stronger and weaker lines of the neutral iron. Such an incorrectly determined microturbulence parameter can then affect the gravity determination and finally introduce an error in the elemental abundances.

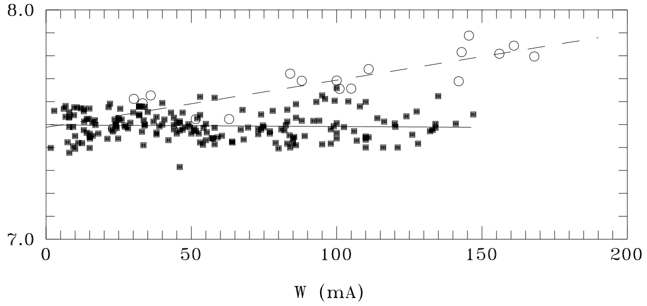

Fig. 4. Sp 1: abundance result for individual Fe I and Fe II lines when $V_{\rm t}$ is determined using Fe I lines. Symbols are the same as on Fig. 3.

Let us consider the δ Cep example. Starting the analysis with the preliminary estimated $T_{\rm eff}$ (photometry) and $\log\, g$ (e.g., physical gravity) values, we have to specify the model parameters (in the main it refers to the gravity value). With $V_{\rm t}$ value derived by using only Fe I lines (≈ 3 km s^{-1}, see Table 1), Fe II lines produce an apparent iron overabundance (Fig. 4).

To equalize the mean abundance results from Fe I and Fe II lines (i.e., to preserve the Fe I /Fe II ionization balance), we are forced to decrease the model gravity by approximately 0.5 dex compared to the physical one. Thus, the averaged abundances from Fe I and Fe II lines become more or less similar (see Fig. 3), but at the same time the discrepancy between spectroscopic and physical gravity values appears.

As was already mentioned, such a problem was discussed by Luck & Lambert (1985) and, for example, by Luck (1994), Luck et al. (1998). In the latter work, where the sample of LMC and SMC supergiant stars was investigated, the authors found high disaccord between physical and spectroscopic $\log\, g$ values for the supergiants having physical gravities less than 1 dex (see Fig. 4 from that work). The difference between the two values in some cases achieved 1−1.5 dex. This fact clearly signals that something is wrong in the traditional spectroscopic analysis of the intermediate mass supergiants. We believe that this problem will be more severe in the case of very luminous supergiants and those having metal deficient atmospheres, where departure from LTE and additional overionization of the neutral species are very likely.

Hill et al. (1995) analysed several F supergiants from LMC and also concluded that atmospheric parameters derived with a law of overionization gave the gravity increased by 0.6 dex, and microturbulent velocity increased by 0.5 km s^{-1} compared with the parameters determined in pure LTE approach. Moreover, the gravity determined in this way appeared to be close to the value which can be derived from photometry.

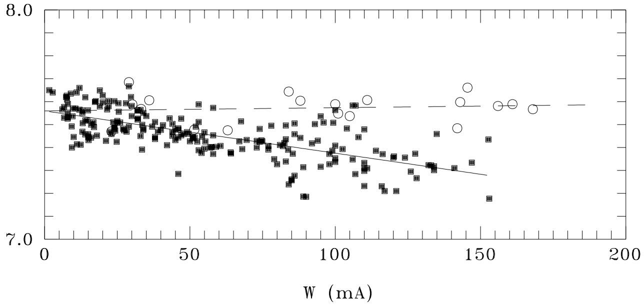

Fig. 5. Sp 1: to microturbulence parameter determination using only Fe II lines (non-standard approach). Symbols are the same as on Fig. 3.

6. Determination of atmospheric parameters: non-standard approach

Microturbulent velocity in this case has been found using only Fe II lines (see Fig. 5), which are not suspected to be strongly affected by the NLTE effects. It is not surprising that with this microturbulent velocity ($V_{\rm t} \approx$ 3.4 km s^{-1}, which is $\approx$ 0.5 km s^{-1} greater than that determined by analysing only Fe I lines), the Fe I lines give a progressively lower abundance. We believe, that in this case more or less realistic iron abundance based on Fe I lines should be refered to equivalent width W = 0 mÅ. *Only this* formally extrapolated abundance from the sample of neutral iron lines must then be compared with the mean result from all investigated Fe II lines in order to specify the $\log\ g$ value.

It is clear, that with a higher $V_{\rm t}$ value, the mean iron abundance derived from Fe II lines will be lower and Fe I/Fe II ionization balance will take place at greater gravity than it is expected from the standard analysis. Using this method, we have found that $\log\ g$ falls in the region 2.0−2.2 dex for δ Cep. Results of $V_{\rm t}$ and $\log\ g$ determination for different phases are given in Table 1 with the mark "NS" (non-standard approach).

It is worth estimating an independent $\log\ g$ value from the combination of empirical "mass-period" calibration (Turner 1996):

$$\log\ (M/M_{\odot}) = 0.41 + 0.50 \log\ P, \tag{1}$$

that was obtained for cluster Cepheids using B stars of well-known masses, and the "period-luminosity" relation (Gieren et al. 1998):

$$\langle M_v \rangle = -1.294–2.769 \log\ P \tag{2}$$

Using the following formula:

$$\log\ g = \log{(M/M_{\odot})} - 10.61 - \log{(L/L_{\odot})} + 4\log\ T_{\rm eff}, \tag{3}$$

we calculated physical gravity values for different phases (see the fifth column of Table 1) supposing that δ Cep has a mass $M = 6M_{\odot}$. While using the expression for the physical gravity, we have taken into account the luminosity variation during the pulsation. The luminosity values for the phases of interest were found using the mean M_v value (Eq. 2), corresponding m_v values (Kiss 1998) and bolometrical corrections $B.C.$ calculated for different effective temperatures at the different phases ($B.C.$ are taken from Straizys 1982).

At the present time, Cepheid masses are probably known with uncertainty not greater than $\pm$ 1 $M_{\odot}$. If so, then the gravity is uncertain by about $\pm$ 0.1 dex for $M = 6M_{\odot}$. This estimate shows that for δ Cep the difference between physical $\log\ g$ value and spectroscopically determined (in the standard approach) $\log\ g^{ph}$ $-\log\ g^{sp}$ = 0.5 is significant, i.e. exceeds the probable errors of both gravity values.

It is also important to take into account the correction to physical gravity caused by dynamical effects in δ Cep atmosphere. In this case the effective gravity value can deviate from that estimated with the help of Eq. (3). In fact, correction for δ Cep is small (about -0.06 dex) for the time interval 0.15−0.70 P, but can achieve significant value (more than +0.15 dex) between ϕ = 0.8−1.0 (note that we do not have any observations relevant to this phase interval).

At present we cannot answer the question whether the changes in the physical gravity value caused by the additional dynamic acceleration in the pulsating atmosphere can be detected by spectroscopic analysis similar to that performed in this work. We suppose that this problem requires a special consideration using high-resolution spectra spaced with small time steps within the pulsational period.

Breitfellner & Gillet (1993) obtained the surface gravity variation for δ Cep using very precise radial velocity curve and angular diameter variation determined by Fernley et al. (1989). They found that $\log\ g$ varies from 2.01 to 2.12 reaching the maximum at the phase 0.9. The mean gravity value (assuming the mean radius of δ Cep estimated by Fernley et al. 1989, i.e, 37.28 $R_{\odot}$) is 2.05. Even with Turner's (1988) radius estimate 43 $R_{\odot}$ one has $\log\ g$= 1.93 for 5.7 $M_{\odot}$ (this mass value was adopted by Breitfellner & Gillet).

As one can see, the result of Breitfellner & Gillet (1993) is very close to our estimate based on the non-standard approach. Note also, that according to Breitfellner & Gillet the amplitude of gravity variation is really small (about 0.1 dex). Therefore, any reported $\log\ g$ variations within the range more than 0.2, in fact, do not reflect the real pulsational radius changes, but rather testify to problems of the standard spectroscopic analysis.

7. Some remarks on $V_{\rm t}$ variation and projected rotational velocity

Gillet et al. (1998) used 288 high-resolution spectroscopic profiles of the unblended Fe I 5576.09 Å absorption line to determine the turbulence variation in δ Cep atmosphere. Earlier, Breitfellner & Gillet (1993) presented their results for the entire pulsation cycle with particular emphasis on the interpretation of the behaviour of line width. Fokin et al., (1996) have discussed these results. All these works give the following picture of $V_{\rm t}$ variation: it is relatively constant during ϕ = 0.0–0.4 with a slow increase towards ϕ=0.7. The maximum takes place between ϕ = 0.8–0.9, i.e., at the minimum of the radius and maximum $\log\ g$. The lack of the spectra exposed at these phases in our disposal prevents the evaluation of the full amplitude of

Table 2. Phased elemental abundances for δ Cep and averaged data (standard approach)

	Sp1			Sp2			Sp3		
Ion	[M/H]	σ	N	[M/H]	σ	N	[M/H]	σ	N
C I	-0.40	0.15	10	-0.25	0.02	2	-0.37	0.15	2
N I	0.27	0.11	2	0.32	0.23	2	-	-	-
O I	-0.14	0.05	3	-0.07	0.01	2	-	-	-
Na I	0.23	0.07	3	0.23	0.04	2	0.18	0.04	2
Mg I	0.03	0.18	4	0.09	0.06	2	-0.10		1
Al I	0.18	0.10	5	0.18	0.19	2	0.16	0.26	2
Si I	0.14	0.09	32	0.11	0.08	21	0.07	0.11	15
Si II	-0.22	0.14	2	-0.25	0.25	2	-	-	-
S I	0.05	0.25	5	0.23	0.11	3	0.32	0.10	3
Ca I	0.03	0.10	9	0.04	0.13	6	0.05	0.04	2
Sc II	-0.02	0.14	6	-0.02	0.06	4	-	-	-
Ti I	0.07	0.13	30	0.01	0.11	23	0.08	0.18	8
Ti II	-0.08	-	1	0.01	-	1	-0.15	-	1
V I	-0.00	0.14	23	0.01	0.15	21	-0.11	0.17	9
V II	-0.26	0.06	2	-0.23	0.13	2	-0.42	0.21	2
Cr I	-0.00	0.14	16	0.08	0.31	13	-0.09	0.09	7
Mn I	0.03	0.16	5	-0.01	0.15	5	0.05	0.05	3
Fe I	0.01	0.07	209	0.03	0.09	165	-0.01	0.08	108
Fe II	-0.02	0.11	18	0.01	0.13	15	0.01	0.18	11
Co I	-0.09	0.12	14	-0.07	0.09	9	-0.33	0.13	4
Ni I	-0.02	0.09	59	-0.04	0.11	45	-0.05	0.13	28
Cu I	0.10	0.08	2	0.03	0.11	2	0.01	0.49	2
Zn I	0.01	-	1	0.37	-	1	-	-	-
Y II	0.12	0.06	2	0.19	0.01	2	0.06	0.07	2
Zr II	-0.18	-	1	-0.15	-	1	-0.37	-	1
Ru I	-0.08	-	1	-0.43	-	1	-	-	-
La II	-0.01	0.13	2	0.04	-	1	-	-	-
Ce II	-0.15	0.09	2	-0.09	0.05	2	-0.23	-	1
Nd II	-0.18	0.05	2	-0.16	0.00	2	-0.27	-	1
Eu II	-0.12	0.22	2	-0.05	0.18	2	-0.23	0.30	2

Table 2. (continued)

	Sp4			Sp5			Sp6		
Ion	[M/H]	σ	N	[M/H]	σ	N	[M/H]	σ	N
C I	-0.42	0.22	4	-0.16	0.10	2	-0.34	0.14	10
N I	0.40	0.11	2	0.31	0.06	2	0.39	0.00	2
O I	-0.19	0.11	3	-0.09	0.04	2	-0.07	0.04	2
Na I	0.21	0.02	3	0.28	0.03	3	0.27	0.05	3
Mg I	0.00	0.08	4	0.01	0.15	3	0.09	0.14	4
Al I	0.12	0.12	4	0.06	0.05	2	0.16	0.05	5
Si I	0.14	0.10	26	0.15	0.09	24	0.17	0.09	31
Si II	-0.35	-	1	-0.16	-	1	-0.05	-	1
S I	0.12	0.33	5	0.40	0.20	3	0.20	0.27	5
Ca I	0.05	0.13	8	0.08	0.13	9	0.01	0.10	8
Sc II	0.04	0.20	8	0.12	0.18	7	0.03	0.16	7
Ti I	0.20	0.15	12	0.14	0.21	23	0.08	0.15	28
Ti II	-0.15	-	1	-0.08	-	1	-0.17	-	1
V I	0.21	0.11	7	0.12	0.17	19	-0.00	0.07	19
V II	-0.22	-	1	-0.08	0.03	2	-0.24	-	1
Cr I	0.28	0.23	12	0.19	0.28	17	0.08	0.12	15
Mn I	0.05	0.04	3	0.09	0.05	3	0.02	0.06	4
Fe I	0.02	0.09	167	0.04	0.11	185	0.03	0.06	167
Fe II	-0.00	0.13	14	0.06	0.17	15	0.04	0.11	17
Co I	-0.03	0.09	3	-0.21	0.10	6	0.03	0.11	12
Ni I	-0.01	0.09	39	0.01	0.10	45	0.00	0.06	51
Cu I	0.27	-	1	0.26	0.05	2	0.10	0.01	2
Zn I	0.13	-	1	0.19	-	1	0.11	-	1
Y II	0.11	0.03	2	0.18	0.01	2	0.11	0.04	2
Zr II	-0.06	0.12	2	-0.15	-	1	-0.16	-	1
Ru I	-	-		0.14	-	1	-0.06	-	1
La II	0.02	-	1	0.12	-	1	0.05	0.09	2
Ce II	-0.13	-	1	0.14	0.46	2	-0.16	0.10	2
Nd II	-0.21	0.01	2	-0.10	0.03	2	-0.20	0.02	2
Eu II	-0.03	0.05	2	-0.04	0.12	2	-0.06	0.16	2

the $V_{\rm t}$ parameter variation, but the general tendency of the increase of microturbulence towards the light maximum is seen.

Van Paradijs (1971) performed a curve-of-growth analysis of δ Cep covering the pulsation cycle and also found the variation of the microturbulent velocity. For the phases close to those of Van Paradijs, our $V_{\rm t}$ values are about 1 km s^{-1} lower than those obtained by Van Paradijs. This discrepancy can be interpreted by the different resolving power of the spectroscopic instruments and differences of the methods used.

Using unblended lines we have also estimated the projected rotational velocity for δ Cep as $v \sin i \leq 9.0$ km s^{-1}. This value agrees well with that determined by Fokin et al. (1996), who give 7.5 km s^{-1}.

8. Abundance results

Below we present a short description of the abundance results based on both applied approaches.

8.1. Standard approach

With atmospheric parameters specified by the usual way we calculated abundances for 26 elements (see Table 2), but in this section we will briefly mention only C and O abundances.

Our value of the relative carbon abundance obtained with standard approach [C/H]=-0.31 ± 0.12 is exactly the same as that derived by Luck & Lambert (1992): [C/H]=-0.33. For oxygen, those authors found the relative abundance [O/H]=-0.18. Our analysis yielded similar value [O/H]=-0.10 ± 0.04.

8.2. Non-standard approach

In Table 3 we give the abundances for seven phases and averaged values obtained using the non-standard approach. First of all, it should be noted that there are no noticeable differences between the results from the different spectra exposed at different phases. As has been already mentioned, the abundance based on Fe I lines is referred to W=0 mÅ (see Fig. 5). It was found using a formal extrapolation procedure and in this specific case the σ value represents the scattering with respect to the extrapolating line. The same procedure was adopted for determination of the

Table 2. (continued)

	Sp7			Averaged		
Ion	[M/H]	σ	N	[M/H]	σ	n
C I	-0.21	0.03	2	-0.31	0.12	2-10
N I	0.11	0.10	2	0.30	0.10	2
O I	-0.06	0.01	2	-0.10	0.04	2-3
Na I	0.27	0.00	3	0.24	0.04	2-3
Mg I	0.01	0.06	3	0.02	0.11	1-4
Al I	0.17	0.09	2	0.15	0.12	2-5
Si I	0.12	0.10	23	0.13	0.09	15-32
Si II	-0.13	0.22	2	-0.20	0.20	1-2
S I	0.23	0.21	3	0.22	0.21	3-5
Ca I	0.05	0.06	8	0.04	0.10	2-9
Sc II	0.06	0.20	6	0.04	0.16	4-8
Ti I	-0.00	0.14	26	0.08	0.15	8-30
Ti II	-0.01	-	1	-0.09	-	1
V I	-0.02	0.14	21	0.03	0.14	7-23
V II	-0.22	0.06	2	-0.24	0.10	1-2
Cr I	0.02	0.15	16	0.08	0.19	7-17
Mn I	-0.04	0.15	4	0.03	0.09	3-5
Fe I	0.01	0.08	159	0.02	0.08	108-209
Fe II	0.01	0.15	17	0.02	0.14	11-18
Co I	-0.16	0.14	10	-0.12	0.11	3-14
Ni I	-0.04	0.10	47	-0.02	0.10	28-59
Cu I	0.11	0.20	2	0.12	0.08	1-2
Zn I	0.24	-	1	0.17	-	1
Y II	0.20	0.02	2	0.14	0.03	2
Zr II	-0.17	-	1	-0.18	0.12	1-2
Ru I	-0.02	-	1	-0.09	-	1
La II	-0.04	0.18	2	0.03	0.13	1-2
Ce II	-0.09	0.09	2	-0.15	0.08	1-2
Nd II	-0.15	0.06	2	-0.18	0.03	1-2
Eu II	-0.07	0.22	2	-0.09	0.18	2

n – minimal and maximal number of used lines

Table 3. Phased elemental abundances for δ Cep and averaged data (non-standard approach)

	Sp1			Sp2			Sp3		
Ion	[M/H]	σ	N	[M/H]	σ	N	[M/H]	σ	N
C I	-0.24	0.15	10	-0.16	0.03	2	-0.22	0.15	2
N I	0.43	0.11	2	0.41	0.23	2			
O I	0.04	0.06	3	0.05	0.04	2			
Na I	0.13	0.02	3	0.17	0.01	2	0.17	0.00	1
Mg I	-0.04	0.22	4	0.09	0.00	1	-0.19	0.00	1
Al I	0.15	0.08	5	0.15	0.17	2	0.12	0.25	2
Si I	0.10	0.08	32	0.06	0.05	19	0.07	0.14	17
Si II	-0.01	0.14	3	-0.03	0.31	3			
S I	0.16	0.24	5	0.29	0.10	3	0.43	0.09	3
Ca I	-0.08	0.10	9	-0.06	0.11	5	-0.00	0.01	2
Sc II	0.03	0.08	5	0.08	0.07	3			
Ti I	0.03	0.11	29	-0.02	0.11	23	0.04	0.18	8
Ti II	0.07	0.00	1	0.12	0.00	1	0.02	0.00	1
V I	-0.02	0.14	23	-0.01	0.15	21	-0.08	0.24	10
V II	-0.08	0.07	2	-0.10	0.14	2	-0.24	0.21	2
Cr I	-0.02	0.13	16	0.05	0.31	13	-0.02	0.28	8
Mn I	-0.05	0.21	5	-0.10	0.16	5	-0.04	0.05	3
Fe I	0.05	0.07	112	0.04	0.08	68	0.12	0.06	42
Fe II	0.07	0.07	16	0.09	0.08	12	0.05	0.14	6
Co I	-0.11	0.13	14	-0.09	0.09	9	-0.36	0.12	4
Ni I	-0.03	0.10	59	-0.03	0.08	42	-0.07	0.13	27
Cu I	0.03	0.03	2	-0.03	0.06	2	-0.03	0.03	2
Zn I	0.02	0.00	1	0.35	0.00	1			
Y II	0.28	0.05	2	0.31	0.01	2	0.23	0.08	2
Zr II	0.01	0.00	1	-0.00	0.00	1	-0.18	0.00	1
Ru I	-0.09	0.00	1	-0.44	0.00	1			
La II	0.16	0.14	2	0.18	0.00	1			
Ce II	0.05	0.09	2	0.06	0.05	2	-0.04	0.00	1
Nd II	0.01	0.05	2	-0.02	0.00	2	-0.09	0.00	1
Eu II	0.05	0.19	2	0.08	0.16	2	-0.06	0.29	2

nickel abundance based on Ni I lines, the number of which is sufficiently great (see the discussion below).

Carbon. This element is apparently deficient in δ Cep atmosphere. Such a deficiency implies that δ Cep has already passed the red supergiant phase.

In their pioneer work Luck & Lambert (1981) detected observed anomalies of the CNO abundances in galactic $F-G$ supergiants which are regarded as having passed the first dredge-up phase. All the subsequent spectroscopic studies confirmed these results, but they also brought to light the apparent discrepancy between the theory and observations. Theoretically expected carbon deficiency appeared to be less than that observed, while the remarkable oxygen deficiency observed in supergiants was not theoretically predicted at all.

With the new approach we have found that for δ Cep the relative carbon abundance [C /H] = -0.21. It agrees well with the theoretical prediction for the star suffered the first dredge-up (for example, Schaller et al. 1992 give [C /H] = -0.17 after the first dredge-up for the star of 6 $M_\odot$; this theoretical value was interpolated between results for two models of 5 $M_\odot$ and 7 $M_\odot$ of the solar metallicity).

Nitrogen. While carbon appears to be deficient, nitrogen abundance has a tendency to be increased. This is in good agreement with the theoretical prediction concerning CN anomalies after the dredge-up phase. Our result is [N /H] = +0.43, while from the calculations of Schaller et al. (1992) one can obtain [N /H] = +0.42. As an independent confirmation, one can also mention the theoretical result for a star of 5$-$7 $M_\odot$ obtained by El Eid & Champagne (1995). They give [N /H] = 0.41$-$0.43.

Oxygen. The relative oxygen abundance derived by us is [O /H] = +0.06. Schaller et al. (1992) predict [O /H] = -0.03 after the first dredge-up. We can state that within the standard error of abundance analysis these values are in the close agreement.

8.3. Short conclusion on CNO abundances

The problem with a discrepancy between the theory and observations concerning CNO abundances is probably due to the wrong estimate of the gravity value, which is the result of V_t parameter underestimation. The lines of C, N and O available for the analysis are usually weak in the supergiant spectra (we

Table 3. (continued)

	Sp4			Sp5			Sp6		
Ion	[M/H]	σ	N	[M/H]	σ	N	[M/H]	σ	N
C I	-0.34	0.22	4	-0.03	0.09	2	-0.20	0.14	10
N I	0.48	0.09	2	0.45	0.06	2	0.53	0.00	2
O I	0.00	0.20	3	0.06	0.06	2	0.08	0.05	3
Na I	1 0.16	0.02	3	0.20	0.07	3	0.16	0.08	3
Mg I	1 -0.04	0.08	4	-0.03	0.19	3	-0.00	0.18	4
Al I	1 0.09	0.10	4	0.04	0.04	2	0.11	0.05	5
Si I	1 0.11	0.10	27	0.11	0.08	23	0.12	0.09	32
Si II	1 -0.23	0.00	1	-0.02	0.00	1	0.13	0.16	2
S I	1 0.13	0.30	5	0.44	0.18	3	0.29	0.25	5
Ca I	2 -0.05	0.08	7	-0.02	0.11	9	-0.08	0.13	9
Sc II	2 0.12	0.17	8	0.11	0.10	6	0.06	0.10	6
Ti I	2 0.08	0.06	8	0.04	0.12	15	0.05	0.16	29
Ti II	2 -0.01	0.00	1	0.05	0.00	1	-0.03	0.00	1
V I	2 0.12	0.03	4	0.07	0.09	16	-0.01	0.11	21
V II	2 -0.06	0.00	1	0.07	0.02	2	-0.07	0.00	1
Cr I	2 0.13	0.13	8	0.06	0.11	11	0.07	0.15	16
Mn I	2 0.00	0.04	3	-0.02	0.04	3	0.02	0.28	5
Fe I	2 0.03	0.12	179	0.06	0.13	189	0.08	0.13	224
Fe II	2 0.09	0.10	13	0.15	0.07	12	0.11	0.07	15
Co I	2 -0.04	0.09	3	-0.22	0.10	6	0.00	0.18	14
Ni I	2 0.01	0.08	36	0.03	0.09	42	0.03	0.13	58
Cu I	2 0.25	0.00	1	0.22	0.07	2	0.02	0.03	2
Zn I	3 0.11	0.00	1	0.16	0.00	1	0.09	0.00	1
Y II	3 0.26	0.02	2	0.32	0.00	2	0.26	0.03	2
Zr II	4 0.10	0.11	2	0.01	0.00	1	0.01	0.00	1
Ru I	4			0.13	0.00	1	-0.09	0.00	1
La II	5 0.15	0.00	1	0.27	0.00	1	0.20	0.10	2
Ce II	5 0.02	0.00	1	0.29	0.45	2	0.02	0.10	2
Nd II	6 -0.09	0.01	2	0.05	0.02	2	-0.04	0.02	2
Eu II	6 0.10	0.07	2	0.11	0.10	2	0.10	0.13	2

Table 3. (continued)

	Sp7			Averaged		
Ion	[M/H]	σ	N	[M/H]	σ	n
C I	-0.06	0.04	2	-0.21	0.12	2-10
N I	0.26	0.10	2	0.43	0.10	2
O I	0.11	0.03	2	0.06	0.08	2-3
Na I	0.14	0.07	3	0.16	0.04	1-3
Mg I	-0.07	0.13	3	-0.03	0.11	1-4
Al I	0.12	0.07	2	0.11	0.11	2-5
Si I	0.06	0.09	23	0.09	0.09	17-32
Si II	0.08	0.19	3	-0.01	0.13	1-3
S I	0.32	0.20	3	0.29	0.19	3-5
Ca I	-0.07	0.09	9	-0.05	0.09	2-9
Sc II	0.06	0.09	5	0.08	0.10	3-8
Ti I	-0.06	0.12	25	0.02	0.12	8-29
Ti II	0.13	0.00	1	0.05	-	1
V I	-0.06	0.13	21	0.00	0.13	4-23
V II	-0.04	0.07	2	-0.07	0.07	1-2
Cr I	-0.02	0.15	16	0.06	0.18	8-16
Mn I	-0.18	0.09	4	-0.05	0.12	3-5
Fe I	0.02	0.12	180	0.06	0.10	42-224
Fe II	0.10	0.11	16	0.09	0.09	6-16
Co I	-0.19	0.13	10	-0.10	0.12	3-14
Ni I	-0.01	0.12	47	-0.01	0.10	27-59
Cu I	0.01	0.13	2	0.06	0.05	1-2
Zn I	0.21	0.00	1	0.16	-	1
Y II	0.35	0.02	2	0.29	0.03	2
Zr II	0.01	0.00	1	0.00	0.11	1-2
Ru I	-0.06	0.00	1	-0.05	-	1
La II	0.13	0.18	2	0.18	0.14	1-2
Ce II	0.09	0.10	2	0.07	0.16	1-2
Nd II	0.03	0.05	2	-0.02	0.03	1-2
Eu II	0.09	0.19	2	0.07	0.16	2

n – minimal and maximal number of used lines

do not consider the strong O I 7771 Å absorption). Therefore abundances derived from these lines are practically not sensitive to V_t variation, but strongly depend upon $\log g$ changes. Artificially decreasing $\log g$, we force these lines, with high excitation potentials of the lower level, to produce larger equivalent widths in the calculations. This is clearly demonstrated in Fig. 6, where dependences between the calculated equivalent widths of selected CNO lines and model atmosphere gravity are shown (for reference, we also show the behaviour of a gravity sensitive line of an ionized atom, in this case Y II). $T_{\rm eff}$ was 6000 K for all the models of the different gravities.

It is quite understandable, that after the comparison of the observed equivalent width of a certain CNO line with a theoretical one calculated from a model with artificially lowered gravity, the conclusion is that the considered element is relatively deficient.

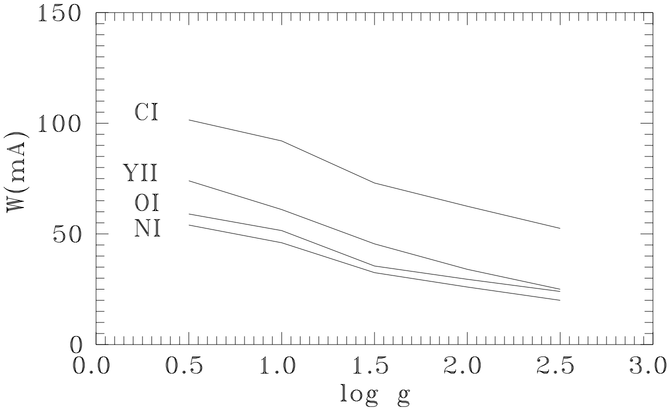

Fig. 6. Calculated equivalent widths of selected C I 6587.62 Å, N I 7468.31 Å, O I 6156.77 Å and Y II 6795.41 Å lines as a function of the adopted surface gravity.

8.4. *Other elements*

Surface Na abundance should also be altered after the first dredge-up phase (or even earlier - on the main sequence due to, e.g., turbulent diffusion), when Ne – Na processed material appears in the upper layers of the stellar atmosphere. Enhanced sodium is an ordinary feature of the atmospheres of supergiants. The theoretical ground of this phenomenon was discussed by Denissenkov (1988). Sasselov (1986) also explained the sodium overabundance in the supergiants as a result of Ne − Na cycle operation. Our result for δ Cep testifies about the modest sodium enrichment. We did not obtain a remarkable sodium overabundance, but this is exactly the same value that could be expected from the recent theoretical consideration (see, Table 2 from the work by El Eid & Champagne 1995).

The α - elements do not show any significant anomalies in the atmosphere of δ Cep with one possible exception for sulfur, which seems to be slightly overabundant (but the σ value is rather big).

The iron-group elements show the solar-like ratios (M/Fe). Note, that using the traditional approach we were not able to keep ionization balances for Si I/Si II, Ti I/Ti II, V I/V II together with preserving the Fe I/Fe II equilibrium (see Table 2). With the new approach the situation seems to be much better (see averaged abundance values from Table 3).

It should be noted that Lyubimkov & Boyarchuk (1983) concluded that the NLTE effects are important not only for iron itself, but also for iron-peak elements. Really, the analysis of the great number of Ni I lines in δ Cep spectra has shown that their behaviour resembles that of Fe I lines. Therefore, for Ni abundance determination we used the same method as for iron abundance determination based on Fe I lines (extrapolation of the "[Ni /H]-W" dependence for the sample of Ni I lines to value W=0 mÅ).

The number of available lines of other neutral species (Ca , Ti , Cr , etc) is not large, therefore there is no sense applying such a procedure. In this case, one can recommend the use of only the weakest lines (having W less than 50 mÅ) for abundance determination that could minimize the influence of the NLTE effects on the resulting abundances.

9. Conclusion

Above we showed that standard spectroscopic analysis of intermediate mass supergiant stars, based on determination of the atmospheric parameters with the help of numerous Fe I lines, produces some discrepancy with the theoretical expectation for surface gravity and abundances of some chemical elements. This discrepancy is likely due to a sensitivity of the lines of neutral iron to NLTE effects, which are ignored in the LTE analysis.

The use of Fe II lines, which are seen as being be free of significant influence from NLTE effects, allows one to avoid this problem giving physically more acceptable results.

One can then ask whether all previously obtained results on chemical abundances, at least for yellow supergiants, are wrong. Fortunately, the situation seems to be not so dramatic. The differences discussed between the two considered approaches become noticeable when the internal errors of the analysis are small (say, about 0.1 dex, which is rarely reached in the quantitative analysis).

This is relevant to spectroscopic studies based on high quality observations (high resolution and high signal-to-noise spectra). As one can see from Tables 2 and 3 (averaged data), despite the significant differences in the microturbulence parameter and surface gravity values, both applied methods give similar results for some elements. Let us consider iron, in particular. In fact, both methods produce nearly the same mean iron abundance, which is actually close to the value given by the weakest Fe I lines. Nevertheless, adopting the standard approach we underestimate the microturbulent velocity and artificially decrease the spectroscopic gravity. In the case of non-standard approach we reach practically the same iron abundance by analysing the Fe II lines and only the weakest (formally having W=0 mÅ) lines of neutral iron (both the line samples are regarded to be free of the NLTE influence). Being physically more grounded, the second method gives the following advantages:

- it removes so-called problem of the spectroscopic gravities, fitting them to the gravities based on the estimated stellar masses and radii;
- it brings the abundances of some elements (among them carbon, nitrogen, oxygen) in accordance with the theoretical prediction for the stars of intermediate masses;
- it allows us to keep an ionizational balance for some elements seen in two ionization stages together with Fe I/Fe II balance. In the next papers we plan to report similar results obtained for some Cepheids having reliably determined physical characteristics.

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