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Oxygen abundance in halo stars from O I triplet

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Abstract. Oxygen abundance for 14 halo stars through the O I 7774 Å triplet have been derived from high resolution spectra ($R = 25,000$; $S/N > 100$) obtained with echelle-spectrometer of 6-m telescope of Special Astrophysical Observatory of the Russian Academy of Sciences. The effective temperature, metallicity and other parameters have been examined. For example, the effective temperature was found from H_α line wings and photometric indices. The abundance analysis was carried out using both LTE and non-LTE conceptions. For this aim, we have specified the oxygen atomic model.

The average [O/Fe] value appeared to be 0.61 ± 0.21 from the non-LTE determination. A trend of oxygen abundance increasing along with the iron abundance decreasing was found. The relation between [O/Fe] and [Fe/H] is linear: $[O/Fe] = -0.370 \times [Fe/H] + 0.047$. In addition to the sample of our program stars, we also involved in the analysis, 24 targets from Cavallo et al. (1997). For their original results we have determined the necessary non-LTE corrections.

Our data are compared with the results of other works (Tomkin et al., 1992; King & Boesgaard, 1995; Boesgaard et al. 1999).

Key words: atomic processes – line: formation – line: profiles – methods: numerical – stars: abundances – stars: atmospheres

1. Introduction

The oxygen abundance in metal - poor stars is one of the key parameters for the study of the Galaxy's early history. Yields of oxygen and iron due to a massive star exploding as a supernovae of type II and one of the intermediate-mass stars exploding as type Ia supernovae, are different (Woosley & Weaver 1986). Time scales of these events are also different (for the stars of $M > 10M_\odot$ it is about $t = 2 \cdot 10^7$ yr, for stars of smaller mass $1 < M < 10M_\odot$; $t = 10^8 \div 10^9$ yr). Therefore, the relation between the abundance of oxygen and iron play a significant role for models of galactic chemical evolution (Wheeler et al. 1989) and galaxy formation (Gilmore et al. 1989). Oxygen is an element which is not processed during stellar evolution and nucleosynthesis in the CNO cycle. Hence the O abundance derived from spectral analysis of dwarfs and giants is a good indicator of enrichment of the interstellar matter with oxygen. However, currently, the value of the O abundance in atmospheres of halo stars and the trend of oxygen abundance increasing along, with Fe abundance decreasing are still discussed. We will not include a complete review of papers on O abundance determination in metal-poor stars, nonetheless, we shall point out the principal discrepancies of obtained results.

One of the first works detecting the overabundance of oxygen relative to iron, was that of Conti et al. (1967). Later, for halo stars Sneden et al. (1979) obtained a [O/Fe] value higher than the solar one. Clegg et al. (1981) found the trend of oxygen with metallicity for metal-deficient disk stars. Abia & Rebolo (1989) using triplet O I 7774 for O abundance determination have identified a noticeably larger abundance of oxygen (from 0.7 up to 1.2 dex) and evidence of a trend with metallicity. At that time the works carried out with line 6300 Å for metal-poor giants revealed an oxygen overabundance of about $0.35 \div 0.40$ (Gratton & Ortolani, 1986; Barbuy, 1988; Sneden et al. 1991) and an absence of the noticeable trend. To explain this disagreement between the dwarfs and giants, Abia & Rebolo (1989) have proposed that oxygen is depleted in K giants by the mixing of CNO. But then the works on oxygen analysis in dwarfs using the line 6300 (Spite & Spite, 1991; Spiesman & Wallerstein, 1991) have confirmed a value of [O/Fe] = $0.4 \div 0.5$ dex and the lack of a trend. Bessell et al. (1991), by using a molecular singularity OH near UV- band, have also received the value of 0.4 dex.

Spiesman & Wallerstein (1991) have explained the existing discrepancies by systematic errors in the abundance analysis and possible deviations from LTE in the case of triplet O I. Some authors investigated the problem. Kiselman (1991) has performed NLTE analysis of triplet 7774 and received significant NLTE corrections (up to 0.4 dex) and an agreement between the O abundances obtained from the lines 6300 and 7774. However, Takeda (1994) also carried out the NLTE analysis and found that NLTE effects are smaller for metal-poor stars (mean value is 0.1 dex). Tomkin et al. (TLLS) (1992) made a careful investigation of the O abundance determination in the atmospheres of subdwarfs through triplet O I with NLTE corrections and forbidden line [O I] 6300. Their O abundance is lower than that of Abia & Rebolo (1989) by 0.2 dex in average. They determine

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Send offprint requests to: S.A. Korotin an average triplet O I line-based [O/Fe] value of $+0.8 \pm 0.2$ and the [O/Fe] value of 0.5 ± 0.1, based on OH and [O I] lines, the average difference between the NLTE and LTE abundances is -0.03 dex for oxygen.

Another origin of discrepancies may be that O/Fe ratios are very sensitive to the temperature in the stellar models (Nissen & Edvardsson, 1992). King (1993) has determined a reduction in the temperature of subdwarfs of 150-200 K and has received O abundances close to those from the 6300 and 7774 lines. This approach was subject to criticism by Balachandran & Carney (1996). Boesgaard & King (1993) have determined abundances of oxygen in halo dwarfs, their parameter scale was close to that of Abia & Rebolo (1989). They have determined the mean [O/Fe] ratio as 0.2 dex lower, on average, than that obtained by the above mentioned authors.

Then, King & Boesgaard (1995) have considered again systematic effects in oxygen abundances derived from the 6300 Å [O I] and 7774 Å O I lines in an example of metal-rich F and G dwarfs and found that for $T_{\rm eff} < 6200 \div 6300K$ there is no systematic difference. This agreement in O abundances at cooler $T_{\rm eff}$ is in conflict with that of others and they suggest that the discrepancy may be caused by the difference in atmosphere models. In 1997, the work of Cavallo et al. (1997) on the definition of O abundances from the triplet 7774 without NLTE corrections was published. They found the averaged value [O/Fe] = $+0.79 \pm 0.29$ and evidence of the trend. Gratton et al. (1997), from a sample of about one hundred dwarfs with metal abundances in the range $-2.5 < [O/Fe] < 0.2$, obtained that O and alpha- elements are overabundant by 0.3 dex (including corrections for departures from LTE). Oxygen abundances in unevolved metal-poor stars ($-3.0 < [Fe/H] < -0.3$) from near-ultraviolet OH lines were performed by Israelian et al. (1998). For four stars from their sample the authors derived the oxygen abundances through the [O I] 6300 line (using the equivalent widths from the literature) and found that oxygen abundances are consistent with those based on OH lines. For metallicities in the range $-3 < [Fe/H] < -1$ they obtained that [O/Fe] versus metallicity hase a slope of about -0.31 ± 0.11. Boesgaard et al. (1999) have measured O in 24 unevolved stars with Keck HIRES observations of the OH lines in the UV region. They derived low metallicities, ($[Fe/H] < -3$), that $[O/Fe] > +1.0$, and they analysed also the relation between O and [Fe/H] and found that the slopes for the thin disk, thick disk, and halo can be represented by the same relationship.

The purpose of our work is the determination of the O abundances in atmospheres of metal-poor stars through the 7774 triplet with NLTE corrections based on high-resolution spectra and a careful analysis of the basic stellar parameters.

2. Observations and reductions

The program stars were selected from the survey of Carney et al. (1994) of stars with large proper motions and from Bartkevicius (1980). This list of stars includes those with ($2 < \log g < 5$) and metallicities in the range $-2.5 < [Fe/H] < -0.5$. Basic data for investigated stars are given in Table 1. B-V were taken from SIMBAD database; M_v^* – absolute magnitudes are from Klochkova et al. (1996); M_v – absolute magnitudes were calculated using HIPPARCOS parallaxes. The spectra were obtained at 6-m telescope using the echelle spectrometers LYNX (Panchuk et al. 1993) equipped with a 530×580 pixel CCD and PFES (Panchuk et al., 1998) equipped with a 1040×1170 pixel CCD in the spectral ranges $5200 \div 8800$ ÅÅ and $5500 \div 8700$ ÅÅ within an extensive program of spectroscopic research of stars with large proper motions. The spectral resolution was R=25 000; the signal/noise ratio exceeded 100. The processing of two-dimensional echelle frames (dark frame subtraction, removal of the cosmic hits, wavelength calibration, extraction of one-dimensional echelle orders) was done using the code DECH20 (Galazutdinov, 1992) and the system ESO-MIDAS. The continuum level drawing and equivalent width measurements were carried out through the program DECH20 (Galazutdinov, 1992). A fragment of the HD 175305 spectrum in the vicinity of O I 7774 triplet is shown in Fig. 1. Equivalent widths of the lines were measured by means of a gaussian fitting. To check the measured equivalent widths, we have made a comparison of our results for HD 175305 with those obtained by Gratton & Sneden (1986) with a coude spectrometer on the 2.7-m McDonald Observatory telescope. The mean difference between them is (EW$_{SAO}$-EW$_{McDonald}$) = -0.32 $\pm$0.61mÅ (σ=2.71mÅ) for 21 lines. We also made a comparison of the equivalent widths for BD $+23°3912$ measured in this work EW$_{MKKP}$, with those from work of Tomkin et al. (1992) EW$_{TLLS}$, shown in Fig. 2. The equivalent widths of O I triplet lines are given in Table 6.

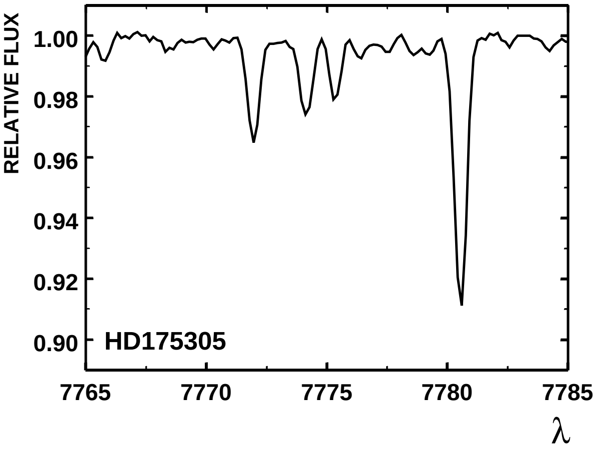

Fig. 1. The O I 7774 region of the HD 175305

3. Atmospheric parameters

The atmospheric parameters and elemental abundances for some program stars were derived early in the work of Klochkova et al. (1996). We specified the atmospheric parameters and [Fe/H] of our program stars. As shown in the recent studies (see in detail, Cavallo et al.,1997; Israelian et al., 1998; Boesgaard et al., 1999; Gratton, 1999) the choice of the effective temperature is extremely important for metal-poor stars and also for determi-

Table 1. The main characteristics of the program stars.

Star					$T_{\rm eff}$		Adopted			
		V	B-V	M_v	(B-V)	(H_α)	[Fe/H]	$T_{\rm eff}$	log g	V_t
HD 245	G265-1	8.37	0.65	0.63^*	5394	5500	-0.66	5500	3.7	1.5
HD 64090	G90-25	8.28	0.61	0.61^*	5382	5370	-1.76	5370	4.0	2.5
HD 65583		6.94	0.73	5.84	5409	5500	-0.64	5500	5.0	1.2
HD 103912	G122-57	8.36	0.86		4928	5000	-0.61	5000	3.0	1.0
HD 157948	G182-7	8.10	0.76	0.64	5258	5250	-0.55	5250	4.0	2.0
HD 175305		7.20	0.76	0.46	4991	5000	-1.44	5000	2.5	1.4
HD 219715		9.17	0.75		5068	5000	-1.10	5000	2.5	1.2
BD+13°13	G30-52v	8.59	0.81	5.40	4969	5000	-0.75	5000	3.0	2.7
BD+17°4708	G126-62	9.47	0.43	0.67^*	5943	6000	-1.65	6000	4.0	2.0
BD+23°3130	G170-47	8.95	0.64	0.57^*	5229	5150	-2.51	5150	2.0	2.0
BD+23°3912		8.90	0.51	3.75^*	5780	5750	-1.39	5750	3.7	1.3
BD+26°4251	G188-22	10.05	0.49	0.69^*	5844	5860	-1.42	5860	3.5	1.7
BD+59°2407	G231-52	10.34		6.27		5750	-1.57	5750	4.0	2.5
BD+66°0268	G246-38	9.91	0.65	0.58^*	5210	5250	-2.10	5250	4.2	2.5

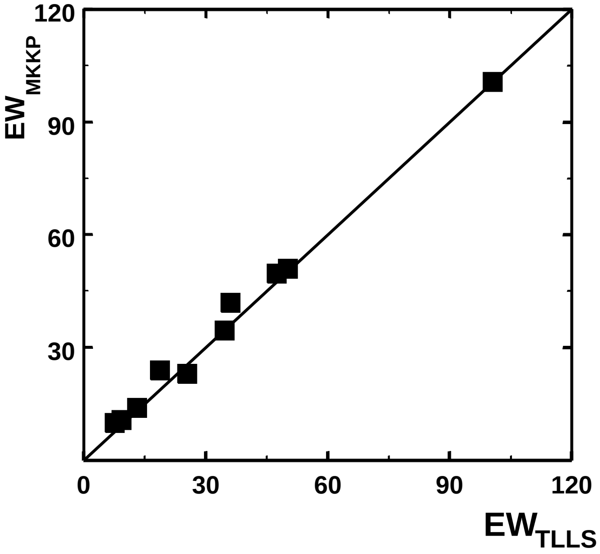

Fig. 2. Comparison of the equivalent widths in mÅ for BD $+23°3912$ measured in this work EW_{MKKP}, with those in the work (Tomkin et al. 1992) EW_{TLLS}

nation of the oxygen abundance. There exist some approaches for the $T_{\rm eff}$ determination:

1) direct method based on the bolometric fluxes and angular diameters, and semi-direct method, which requires also the atmosphere models, for example, IRFM Infrared Flux Method (Blackwell et al. 1990, for metal-poor stars-Magain 1987; Arribas & Martinez-Roger 1987, 1989; Alonso et al., 1994, 1996; Gratton et al. 1996);

2) method based on spectroscopic analysis of Fe I lines; this method is independent of the photometric indices, calibration and the interstellar reddening;

3) Balmer line profiles (for metal-poor dwarfs - Fuhrmann et al. 1993, 1994), because the far wings of H_α are quite independent from the gravity, metallicity and convection of the atmosphere model (Gratton et al. 1996) Having in our disposal spectra containing the H_α line and taking into account the above mentioned remark, we considered this hydrogen line as a basic criterion of the $T_{\rm eff}$ choice for program stars. An additional reason to apply the H_α line is the following. Having determined the effective temperature from this line, we avoid the problem of the interstellar reddening and also take into account the individual characteristics of the atmosphere of concrete star. A comparison between observed H_α profile for star BD $+59°2407$ (G231-52) and synthetic profile computed by STARSP code (Tsymbal, 1996) with $T_{\rm eff}$ = 5750 K, $\log g$ = 4, [Fe/H] = -1.5 is given in Fig. 3. The mean error of $T_{\rm eff}$ determination in our case is ±100 K. We also determined $T_{\rm eff}$ from the B-V colour by using the calibration of Alonso et al. (1994) which takes into account the metallicity. The effective temperatures obtained by these methods are given in Table 1. As one can see from Table 1, there is a good agreement between the temperature values determined by different methods. The mean difference equals 17 ± 55 K which is within the errors of determination. In Table 2 our $T_{\rm eff}$ values are compared with those obtained by other investigators. Generally, there is rather good agreement. Only in two cases the difference achieves 200 K. It should be noted that such an uncertainty can cause an error in the oxygen abundance of about 0.15 dex that cannot significantly affect the resulting conclusions.

To specify $\log g$, V_t and [Fe/H], we selected and measured 20 Fe I lines and 5 Fe II lines in the region $6200 \div 6500$ ÅÅ. In Table 3 the atomic parameters of the Fe lines are given. Also for each line we show the resulting abundance. Note, that adopted solar iron abundance is (Fe/H) = 7.55. The surface gravities were estimated from the condition of ionisation balance for iron. Microturbulent velocities V_t were determined by forcing the abundances determined from individual Fe I lines to be independent of equivalent widths. The abundance analysis was performed using the WIDTH9 code of Kurucz, the Kurucz's (1992) models and the oscillator strengths $\log gf$ from Gurtovenko & Kostyk (1989). The adopted parameters are given in Table 1. The typical accuracy of determination of the model parameters is on average $\Delta_{T_{\rm eff}} \pm 100K$, $\Delta_{\log g} \pm 0.3$ dex and $\Delta_{V_t} \pm 0.3 kms^{-1}$.

Table 2. Comparison of $T_{\rm eff}$ obtained by us with results of other authors.

Star	$T_{\rm eff}$				
	Present work	Tomkin et al. 1992	Pilachovski et al. 1993	Axer et al. 1994	Cavallo et al. 1997
HD 64090	5370	5340	-	5499	-
HD 103912	5000	-	4800	-	4850
HD 175305	5000	-	5190	-	5050
BD+13°13	5000	-	5000	-	-
BD+17°4708	6000	-	-	6100	6100
BD+23°3130	5150	-	5250	5190	5190
BD+23°3912	5750	5630	5600	-	-
BD+66°0268	5250	5250	-	5511	-

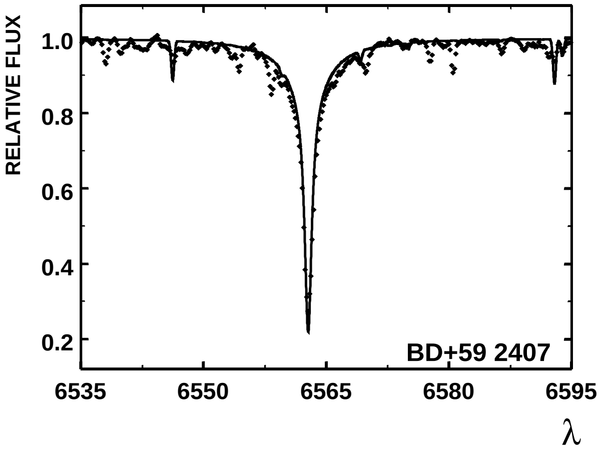

Fig. 3. Comparison between observed H_α profile for the star BD $+59°2407$ and the synthetic profile.

Because of rather low temperature for some program stars (about 5000 K), the formation of molecules (in particular CO) in their atmospheres is expected. Some oxygen atoms can be confined in molecules. This can affect the oxygen line equivalent widths and resulting oxygen abundance. We estimated the cost of oxygen atoms for CO molecule creation. For the model with $T_{\rm eff}$ = 5000 K, $\log g$ = 3.5, [Fe/H] = -1 the influence of the molecular component formation results in the equivalent width of oxygen triplet decreasing of about 4%, corresponding to 0.02 dex in the oxygen abundance. With the temperature increasing, this effect decreases and for $T_{\rm eff}$ = 5250 K the decrease is only 1%. Taking into account that the effect is small, we did not consider it in our calculations.

4. NLTE calculations

Simultaneous solution of the radiative transfer and statistical equilibrium equations has been realized using MULTI-code (Carlsson, 1986) in the approximation of complete frequency redistribution for all the lines. We modified this code. In particular, we have added the opacity sources from the ATLAS9 program (Kurucz, 1992). This enabled us to calculate more precisely a continuum opacity. At the same time, a possibility to take into account an absorption in the great number of spectral lines (especially within the region of the near-UV) allowed us to calculate very accurately an intensity distribution in the region $900 \div 1500$ ÅÅ, that plays a key role in the determination of the radiative rates of $b - f$ transitions. In addition, we changed a code to have the possibility to calculate the combined profile of the blending lines taking into account the star rotation and instrumental profile.

4.1. Parameters of the oxygen atom

We employed the model of oxygen atom consisting of 75 levels: 72 levels of O I, 3 levels of O II and a ground state of O III. A detailed structure of the multiplets was ignored and each LS multiplet was considered as a single term.

Within the described system of the oxygen atom levels, we considered the radiative transitions between the first 23 levels of O I and ground level of O II. A list of energy levels is given in Table 4. They were selected from the compilative catalogue by Hirata & Horaguchi (1994). Transitions between the rest levels were not taken into account and they were used only in the equations of particle number conservation.

Only transitions with $\lambda < 100000$ Å were selected for the analysis. After the numerous test calculations, 46 $b - b$ transitions were included in the linearization procedure. These transitions describe quite well formation of the lines of interest.

Photoionization cross-sections were mainly taken from the Opacity Project (Yan et al., 1987) keeping a detailed structure of their frequency dependence, including resonances. For some important $b - f$ transitions, the cross-section structure is extremely complicated making it difficult to describe it using only simple approximations like $\sim \nu^{-3}$.

Oscillator strengths were selected from the extensive compilative catalogue by Hirata & Horaguchi (1994). Some information was obtained through the Opacity Project. As we ignored a multiple structure of all the levels, the oscillator strengths for each averaged transition were calculated as $f = \frac{\sum g_i f_i}{\sum g_i}$. Results are gathered in Table 5.

After the combined solution of radiative transfer and statistical equilibrium equations, the averaged levels have been split with respect to multiplet structure, then level populations were redistributed proportionally to the statistical weights of the cor-

Table 3. Atomic parameters of the Fe lines including the Fe abundance derived from each line.

Parameters of Fe lines			(Fe/H)						
Fe I	Elow(Ev)	lggf	HD 245	HD 64090	HD 65583	HD 103912	HD 157948	HD 175305	HD 219715
6230.74	2.55	-1.25	6.76	5.62	6.90		5.99	5.99	6.67
6232.65	3.65	-1.22	6.71	5.65	6.84	7.07	6.01	6.01	6.27
6240.66	2.22	-3.35	7.07	5.59	7.13	6.72	6.36	6.36	
6246.33	3.60	-.73	6.92	5.85	6.83	7.20	5.96	5.96	6.39
6252.56	2.40	-1.70		5.76	6.77	6.79	6.28	6.28	6.28
6256.36	2.45	-2.25	6.81	5.78	6.89	7.07	6.29	6.29	6.31
6265.14	2.17	-2.56		5.87	6.81	6.69	6.09	6.09	6.48
6270.23	2.85	-2.64	6.70	5.94	6.96	6.85	6.14	6.14	6.57
6301.51	3.65	-.56	6.80	5.57	6.63	6.65	5.70	5.70	6.10
6322.69	2.58	-2.37		5.80	6.82	7.16	6.15	6.15	6.27
6330.83	4.73	-1.29	7.04	5.99	6.92	6.96	5.92	5.92	6.28
6335.34	2.19	-2.23	6.66	5.54	6.87	6.71	6.05	6.05	6.07
6336.83	3.68	-.81		5.77	6.91		5.91	5.91	6.47
6344.15	2.43	-2.92	6.97	5.51	7.16		6.18	6.18	6.46
6355.04	2.84	-2.44		5.88	7.29	7.13	6.23	6.23	6.63
6393.61	2.43	-1.65		5.95	6.98	7.07	6.22	6.22	6.40
6411.65	3.65	-.51		6.06	6.87	6.83	6.00	6.00	6.80
6419.92	4.73	-.33		5.84	6.91	7.16	6.18	6.18	6.67
6421.36	2.27	-2.24	7.08	5.91	6.99		6.43	6.43	6.79
6430.86	2.17	-2.08		5.86	6.73	6.83	6.17	6.17	6.60
Fe II									
6238.39	3.88	-2.84			7.01	7.27	7.23	5.96	6.67
6247.55	3.89	-2.51	7.08	5.87	7.02	7.09	6.83	6.10	6.47
6416.89	3.89	-2.82	6.87	5.92	7.04	6.83	7.20	6.14	6.32
6432.65	2.89	-3.76	6.90		6.96	6.98	7.17	6.11	6.46
6516.08	2.89	-3.43	6.82	5.89	6.89	6.90	6.99	5.94	6.10
Fe I	Elow(Ev)	lggf	BD+13°13	BD+17°4708	BD+23°3130	BD+23°3912	BD+26°4251	BD+59°2407	BD+66°0268
6230.74	2.55	-1.25	7.06	5.78	4.94	6.08	5.82	5.87	5.41
6232.65	3.65	-1.22		5.75		5.90		5.76	
6240.66	2.22	-3.35				6.24			
6246.33	3.60	-.73	6.47	5.75	4.70	5.86	6.14	5.84	5.02
6252.56	2.40	-1.70		5.90	4.99	6.07	5.99	6.00	5.31
6256.36	2.45	-2.25	6.58	6.07	5.32	6.18	6.23	5.86	5.33
6265.14	2.17	-2.56	6.63	6.08		6.19	6.24	5.95	5.54
6270.23	2.85	-2.64	7.22	5.54		6.29			
6301.51	3.65	-.56	6.61	6.00		6.06	5.99	6.17	5.30
6322.69	2.58	-2.37	6.34	6.13	5.22	6.14		6.35	5.43
6330.83	4.73	-1.29				6.56			
6335.34	2.19	-2.23	6.95	5.88	5.01	6.15			
6336.83	3.68	-.81	7.24	5.85	4.86	5.94	5.99	5.82	5.44
6344.15	2.43	-2.92	7.00	5.90	5.28	6.34	6.01	6.20	5.89
6355.04	2.84	-2.44	6.79			6.27	6.15	6.22	5.54
6393.61	2.43	-1.65	6.78	5.81	4.92	6.26	6.32	5.91	5.62
6411.65	3.65	-.51	7.07	5.69	4.72	5.98	6.18	5.73	5.40
6419.92	4.73	-.33	7.15	6.12	4.89	6.27	6.18	6.15	
6421.36	2.27	-2.24	6.46	6.16	5.17	6.28	6.47	6.09	5.55
6430.86	2.17	-2.08	6.36	5.85	5.12	6.03	6.26	6.11	5.48
Fe II									
6238.39	3.88	-2.84	6.86	5.79	5.10	6.27	6.12	6.11	
6247.55	3.89	-2.51	6.64	6.02	5.00	6.19			
6416.89	3.89	-2.82	6.80	5.89		6.34	5.98		
6432.65	2.89	-3.76	6.61	6.06		6.19	6.06	6.11	
6516.08	2.89	-3.43	6.83	6.02	4.97	5.99	5.98		5.43

Table 4. Energy levels included in oxygen atom model for NLTE consideration.

n	E, cm^{-1}	g_i	$Configuration$	n	$E, cm{-}1$	g_i	$Configuration$	n	$E, cm{-}1$	g_i	$Configuration$
			OI	9	96225.05	3.	$4s\,3S^0$	18	102865.60	25.	$4d\,5D^0$
1	0.00	9.	$2p^4\,{}^3P$	10	97420.80	25.	$3d\,5D^0$	19	102908.40	15.	$4d\,3d^0$
2	15867.86	5.	$2p^4\,{}^1D$	11	97488.50	15.	$3d\,3D^0$	20	102968.23	35.	$4f\,5F$
3	33792.58	1.	$2p^4\,{}^1S$	12	99093.00	15.	$4p\,5P$	21	102968.30	21.	$4f\,3F$
4	73768.20	5.	$3s\,5S^0$	13	99681.00	9.	$4p\,3P$	22	103626.00	15.	$5p\,5P$
5	76794.98	3.	$3s\,3S^0$	14	101145.00	15.	$3s'\,3D^0$	23	103870.00	9.	$5p\,3P$
6	86627.00	15.	$3p\,5P$	15	102116.70	5.	$5s\,5S^0$				OII
7	88631.00	9.	$3p\,3P$	16	102412.00	3.	$5s\,3S^0$	24	109837.00	4.	$2p^3\,{}^4S^0$
8	95476.73	5.	$4s\,5S^0$	17	102662.03	5.	$3s'\,1D^0$				

Table 5. Linearized transitions

I	J	f	λ	I	J	f	λ	I	J	f	λ	I	J	f	λ
1	2	3.54E-11	6300.0	2	4	7.78E-10	1727.1	6	8	1.65E-01	11296.7	9	23	2.18E-02	13076.9
1	4	9.00E-07	1355.6	2	5	4.58E-07	1641.3	6	10	9.27E-01	9262.0	10	20	9.52E-01	18021.4
1	5	4.88E-02	1302.2	2	14	1.63E-05	1172.6	6	15	1.61E-02	6454.1	10	21	1.96E-02	18021.2
1	9	9.20E-03	1039.2	2	17	1.10E-01	1152.2	6	18	7.07E-02	6156.5	11	20	3.00E-02	18244.1
1	10	1.90E-03	1026.5	3	5	1.41E-09	2324.7	7	9	1.87E-01	13164.6	11	21	9.53E-01	18243.9
1	11	2.03E-02	1025.8	3	14	5.13E-06	1484.7	7	11	9.68E-01	11286.8	12	15	3.00E-01	33063.0
1	14	5.13E-02	988.7	4	6	9.64E-01	7774.6	7	14	1.53E-03	7988.9	12	18	1.13E+00	26499.7
1	16	3.30E-03	976.4	4	12	3.26E-03	3947.6	7	16	1.67E-02	7254.4	13	16	3.21E-01	36606.7
1	17	1.13E-05	974.1	4	22	3.02E-04	3348.2	7	19	4.74E-02	7002.1	15	22	1.89E+00	66237.8
1	18	2.68E-04	972.1	5	7	1.07E+00	8446.5	8	12	1.46E+00	27645.2	16	23	1.94E+00	68568.2
1	19	1.48E-02	971.7	5	13	5.60E-03	4368.3	8	22	1.67E-02	12267.7				
2	3	1.15E-09	5577.3	5	23	7.23E-04	3692.4	9	13	1.51E+00	28927.6				

Table 6. Equivalent widths and final O abundances

Star	Equivalent width (mÅ)				LTE		NLTE				
	6300	7771	7774	7775	(O/H)	σ	(O/H)	σ	Δ_{NLTE}	[O/H]	[O/Fe]
HD245	-	65	51	49	8.80	0.04	8.69	0.03	-0.11	-0.21	0.45
HD64090	-	15	11	6	7.90	0.05	7.83	0.04	-0.07	-1.07	0.69
HD65583	-	39	28	21	8.66	0.04	8.66	0.04	0.00	-0.24	0.40
HD103912	-	52	44	37	9.01	0.02	8.89	0.03	-0.12	-0.01	0.60
HD157948	8	40	32	-	8.67	0.06	8.64	0.01	-0.03	-0.26	0.29
HD175305	-	22	18	15	8.08	0.05	7.97	0.06	-0.11	-0.93	0.51
HD219715	24	44	36	-	8.64	0.01	8.43	0.01	-0.21	-0.47	0.63
BD+13°13	-	-	37	-	8.66		8.58		-0.08	-0.32	0.43
BD+17°4708	-	-	33	-	8.01		7.95		-0.06	-0.95	0.70
BD+23°3130	-	8	6	4	7.15	0.01	7.05	0.01	-0.10	-1.85	0.66
BD+23°3912	4	50	35	23	8.24	0.09	8.15	0.05	-0.09	-0.75	0.64
BD+26°4251	-	62	52	42	8.37	0.01	8.20	0.01	-0.17	-0.70	0.72
BD+59°2407	-	32	26	18	8.09	0.01	7.98	0.01	-0.11	-0.92	0.65
BD+66°0268	-	12	9	-	8.01		8.00		-0.01	-0.90	1.20
SUN	5	77	68	56	9.07	0.04	8.90	0.02	-0.17	0.00	0.00

responding sublevels and finally the lines of the interest were studied.

Collisional ionization was described using Seaton's formula (Seaton, 1962):

$$C_{ik} = 1.55 \cdot 10^{13} \frac{\alpha(\nu_0)\overline{g} N_e e^{-u_0}}{\sqrt{T_e} u_0} \tag{1}$$

were $\alpha(\nu_0)$ - threshold value of the cross-section, $u_0 = \frac{E_0}{kT_e}$, E_0 - energy of ionization, N_e and T_e - electron concentration and temperature respectively. For the Gaunt factor we adopted a value of 0.3. For all allowed $b-b$ transitions we used the Van Regemorter (1962) formula:

$$\begin{aligned} C_{ij} &= 5.465 \cdot 10^{-11} N_e \sqrt{T_e} \cdot 14.5 f_{ij} \left(\frac{I_H}{E_0}\right)^2 u_0 e^{-u_0} * \\ &\quad \max\left[\overline{g}; 0.276 e^{u_0} E_1\left(u_0\right)\right] \end{aligned} \tag{2}$$

where I_H -hydrogen ionization potential, $E_1\left(u_0\right)$ - first-order integral exponential function. Collisional rates for the forbidden transitions were calculated by using the semiempirical formula (Allen, 1973), with a collisional force of = 1:

$$C_{ij} = 8.63 \cdot 10^{-6} \frac{N_e e^{-u_0}}{g_i \sqrt{T_e}} \tag{3}$$

Inelastic collisions with hydrogen play a significant role in the atmospheres of cool stars. We took into account this effect with the help of formulas offered Steenbock & Holweger (1984), with a correction factor of 1/3. For all the transitions we also took into account such broadening parameters of lines as radiative damping, Stark effect, van der Waals damping and microturbulent velocity. For temperatures, considered by us, the influence of Stark effect is small. Van der Waals damping was evaluated with the help of Unsöld's (1955) formula. Special attention was given to a selection of oscillator strengths for considered oxygen triplet. For the 7772, 7774 and 7775 Å O I lines, we adopted $\log gf$ = + 0.333, +0.186, and -0.035 respectively (Wiese et al.1966). These values agree with theoretical oscillator strengths. Biemont et al. (1991) find $\log gf$ = + 0.35, +0.21, and -0.02 from their configuration interaction code. For the 6300 Å [O I] line we adopted $\log gf$ =-9.75 (Lambert 1978). To check the adopted oscillator strengths, the determination of the oxygen content in the solar atmosphere was performed using 7774 triplet and the forbidden line 6300 Å. The Solar Flux Atlas of Kurucz et al. (1984) and Kurucz's model of the solar atmosphere (1992) were used. To take into account the chromospheric growth of temperature, this model was completed by a model of the solar chromosphere from work of Maltby et al. (1986). Nevertheless, the influence of a chromosphere on the equivalent width of considered lines was insignificant (less than 2%). Estimates obtained of the oxygen content (O/H)=8.90 agree well with the determination by Anders & Grevesse (1989) and Biemont et al. (1991) who derived (O/H)=8.93 and 8.86 respectively.

5. Oxygen abundances

Oxygen abundance in program stars was determined both in NLTE and LTE approximations. The latter was based on the Kurucz's WIDTH9 code with the same atomic line parameters as for NLTE calculations. Table 6 shows our results for (O/H) in LTE and (O/H), [O/H], [O/Fe] in NLTE approximation and corresponding NLTE corrections. Note that the mean value of NLTE correction is 0.1 dex and individual corrections do not exceed 0.2 dex, which agrees well with the results derived by Takeda (1994) for metal-poor stars. Unfortunately, only for a few stars HD 157948, HD 219715 and BD $+23°3912$ the equivalent widths of [O I] at 6300 Å were measured and oxygen abundance log A(O)=8.65; 8.40 and 8.16 respectively was found. In the case of these stars, the O abundances derived from O I triplet lines and the forbidden line show no significant difference between the O I (7774) and O I (6300) abundances. The typical accuracy of the derived oxygen abundances is ~ 0.15 dex.

Table 7. Recalculated Fe and O abundances from paper of Cavallo et al., (1997)

Star	[Fe/H]	(O/H)	σ	[O/H]	[O/Fe]
HD44007	-1.67	7.83	0.06	-1.07	0.60
HD45282	-1.69	8.08	0.08	-0.82	0.87
HD76932	-0.97	8.44	0.01	-0.46	0.51
HD87140	-1.76	7.80	0.06	-1.10	0.66
HD94028	-1.59	7.91	0.03	-0.99	0.60
HD97916	-0.61	8.57	0.06	-0.33	0.28
HD103912	-0.71	8.54	0.06	-0.36	0.35
HD108317	-2.21	7.23	0.10	-1.67	0.54
HD111721	-1.59	8.59	0.04	-0.31	1.28
HD122563	-2.71	7.15	0.25	-1.75	0.96
HD128279	-2.21	7.47	0.18	-1.43	0.78
HD163810	-1.27	7.82	0.05	-1.08	0.19
HD166161	-1.30	8.49	0.01	-0.41	0.89
HD171496	-0.40	8.25	0.00	-0.65	-0.25
HD175305	-1.45	7.88	0.04	-1.02	0.43
HD189558	-1.22	8.12	0.01	-0.78	0.44
HD190287	-1.33	7.94	0.03	-0.96	0.37
HD201889	-0.79	8.47	0.01	-0.43	0.36
BD$-14°$ 5890	-2.31	7.87	0.10	-1.03	1.28
BD$-18°$ 5550	-3.03	7.06		-1.84	1.19
BD$+17°$ 4708	-1.63	8.02	0.02	-0.88	0.75
BD$+23°$ 3130	-2.73	7.29		-1.61	1.12
BD$+37°$ 1458	-1.99	7.65	0.07	-1.25	0.74
BD$+42°$ 3187	-1.61	7.56	0.08	-1.34	0.27

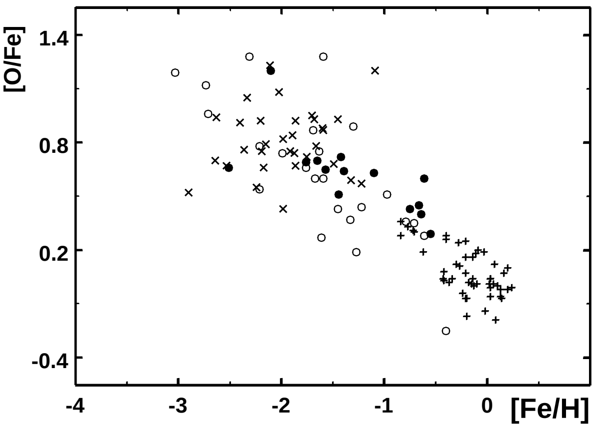

Fig. 4. [O/Fe] as a function of [Fe/H]. The filled circles represent the data from this work. The recalculated data from Cavallo et al. (1997) are presented by open circles, data from Tomkin et al. (1992) - x symbols, and + symbols represent the data from King & Boesgaard (1995).

6. Discussion

The averaged value [O/Fe] for all investigated stars is 0.61 ± 0.21, and that for stars with metallicity $-3 < [Fe/H] < -1$ is 0.71 ± 0.19. Fig. 4 shows our results and results of other authors who derived O abundances from O I triplet (Tomkin et al., 1992; Cavallo et al., 1997) and from [O I] 6300 line (King & Boesgaard 1995). Data for iron and oxygen triplets (in the NLTE assumption) from paper of Cavallo et al., 1997 were recomputed by us with the same atomic line parameters as for pro-

Table 8. [Fe/H], (O/H), [O/Fe] published values vs. this study.

	Boesgaard et al. (1999)						This study		
Star	King $T_{\rm eff}$ scale			Carney (1983) $T_{\rm eff}$ scale					
	[Fe/H]	(O/H)	[O/Fe]	[Fe/H]	(O/H)	[O/Fe]	[Fe/H]	(O/H)	[O/Fe]
HD 64090	-1.67	7.83	0.57	-1.77	7.82	0.66	-1.76	7.90	0.69
BD +23 3912	-1.41	8.22	0.70	-1.53	8.13	0.73	-1.39	8.24	0.66
BD +17 4708	-1.73	7.98	0.78	-1.81	7.96	0.84	-1.65	7.94	0.69

gram stars. The atmosphere models for this calculations were interpolated from the grid of Kurucz's models (1992) according to the adopted stellar parameters by Cavallo et al. (1997). The results are given in Table 7. Our averaged value [O/Fe] for $-3 < [Fe/H] < -1$ is slightly smaller than that found by Tomkin et al. (1992) from the O I triplet lines (their value is 0.8 ± 0.2) and it is close to the averaged reanalyzed [O/Fe] value of Cavallo et al. (1997), which is 0.68 ± 0.36. The O abundances determined by us do not show the trend with atmospheric parameters such as $T_{\rm eff}$ and $\log g$, but, as one can see from Fig. 4, the trend of the oxygen abundance increasing with iron abundance decreasing exists. The relation between [O/Fe] and [Fe/H] is linear: $[O/Fe] = -0.370 * [Fe/H] + 0.047$. The slope agrees with that of Israelian et al. (1998) and Boesgaard et al. (1999), they found -0.31 and -0.35 respectively. Boesgaard et al. (1999) determined O abundances from OH lines and from OI triplet with the published equivalent widths from six sources (including the papers of Tomkin et al. (1992), and Cavallo et al. (1997)). We compared our results with those of Boesgaard et al. (1999) for three common stars HD 64090, BD$+17°4708$ and BD$+23°3912$ (see Table 8). We found a good agreement between the results obtained in this work and those reported in paper of Boesgaard et al. (1999).

7. Conclusions

We determined stellar parameters and O abundances for 14 metal-deficient stars from the spectra obtained with echelle - spectrometer of 6- m telescope of Special Astrophysical Observatory of the Russian Academy of Sciences. For NLTE calculations we have specified the oxygen atom model. The O abundance analysis was carried out using both LTE and NLTE assumptions. The averaged value [O/Fe] is 0.61 ± 0.21, and that for stars with metallicity $-3 < [Fe/H] < -1$ is 0.71 ± 0.19. The trend of oxygen abundance increasing with the iron abundance decreasing was revealed. The relation between [O/Fe] and [Fe/H] is linear: $[O/Fe] = -0.370 \times [Fe/H] + 0.047$. Our data are compared with the results of other authors. We recomputed the data from paper of Cavallo et al. (1997) in the NLTE assumption to perform the comparison correctly. The evidence of the trend and larger $[O/Fe] \sim 0.9$ dex at metallicity $-2.5 \div -3.0$ are in agreement with papers by Israelian et al. (1998), Cavallo et al. (1997), Boesgaard et al. (1999) and Nissen (1999), but these results are in contradiction with traditional galactic evolution models which suggest that the enrichment of interstellar medium by α -elements (including oxygen) at early stages of the Galaxy evolution is about 0.3 dex.

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