Astron. Astrophys. 351, 168–176 (1999)

ASTRONOMY AND ASTROPHYSICS

Oxygen abundances in early B-stars*

S.A. Korotin[1], **S.M. Andrievsky**[1], **and R.E. Luck**[2]

[1] Department of Astronomy, Odessa State University, Shevchenko Park, 270014, Odessa, Ukraine (skyline@eurocom.od.ua; scan@deneb.odessa.ua)

[2] Department of Astronomy, Case Western Reserve University, 10900 Euclid Avenue, Cleveland, OH 44106-7215, USA (luck@fafnir.astr.cwru.edu)

Received 29 April 1999 / Accepted 16 September 1999

Abstract. Kurucz atmospheric models and a modified version of the MULTI code are applied in a NLTE investigation of the O II spectrum. It is shown that previously performed analyses based on the use of lightly line-blanketed Gold models give results that are in variance with those based on the use of the more heavily blanketed Kurucz models.

One result of our calculations is a number of useful relationships between the NLTE oxygen abundance, line equivalent width, and stellar atmospheric parameters.

A NLTE analysis of O II lines in a sample of hot main sequence B stars has been performed. The derived oxygen abundances for the program stars appear to be subsolar. A brief comparison is presented between the oxygen abundance in B stars and other related stellar types.

Key words: atomic processes – line: formation – line: profiles – stars: abundances – stars: atmospheres – stars: early-type

1. Introduction

Oxygen, one of the most abundant elements, is preferentially formed during explosive nucleosynthesis in Type II supernovae. Despite the participation of the oxygen nuclei in the CNO cycle of hydrogen burning in massive stars, the oxygen abundance is not expected to be significantly altered during the standard evolution of the star from the main sequence to red giant region, much less while the star still resides on the main sequence. Thus, surface oxygen abundances in main sequence B stars should reflect the initial oxygen content in the interstellar medium from which the stars are formed. An investigation of oxygen abundance variations among B stars can accordingly much say about the efficiency of Type II supernovae and possible inhomogeneities within the progenitor material of the B stars.

In the present paper we report results from NLTE O II calculations which were performed using a modified version of the MULTI code. The MULTI code has not been used in previously published NLTE determinations of oxygen abundances (e.g. Becker & Butler 1988a). We consider our approach a more realistic one relative to the Becker & Butler analysis as it is based on the use of Kurucz model atmospheres while the Becker & Butler calculations were based upon less line-blanketed models which we feel do not present an adequate description of the atmospheres of early-type stars.

We have also applied our method to derive accurate oxygen abundances in several early B main sequence stars from the solar neighborhood. Some of our program stars were investigated in previous published studies which enables a comparison of independently obtained results.

2. NLTE calculations

Simultaneous solution of the radiative transfer and statistical equilibrium equations have been realized using the MULTI-code (Carlsson, 1986) in the approximation of complete frequency redistribution for all lines. The initial version of this code was modified with the aim to apply it in the analysis of early-type stars. In particular,

1) we have included in the code opacity sources from the ATLAS9 program (Kurucz, 1992). This enables a much more accurate calculation of the continuum opacity and intensity distribution in the UV region which is extremely important in the correct determination of the radiative rates of $b-f$ transitions;

2) we have changed the code to calculate the combined profile of blended lines taking into account stellar rotation and instrumental profiles.

In addition to these modifications, we for the first time have applied to the analysis of O II lines in the spectra of hot stars the well-known blanketed atmosphere models of Kurucz (1992).

2.1. Parameters of the oxygen atom

We employed a model oxygen atom consisting of 141 levels: 3 levels in O I, 132 levels in O II with $L \leq 5$ and $n \leq 8$, 5 levels in O III, and the ground state of O IV. The detailed structure of the multiplets was ignored and each LS multiplet was considered as a single term.

Within the described system of oxygen atom levels we considered the radiative transitions between the first 49 levels of

Send offprint requests to: S.A. Korotin

* Based on spectra collected with the 1.52-m telescope of Haute Provence Observatoire

Table 1. Energy levels included in the oxygen atom model for NLTE calculations.

n	E, cm^{-1}	g_i	$Configuration$	n	$E, cm-1$	g_i	$Configuration$	n	$E, cm-1$	g_i	$Configuration$
1	0.00	4	$2p^3\,^4S^0$	18	229955.00	10	$3p'\,^2D^0$	35	252990.00	6	$3p''\,^2P^0$
2	26820.00	10	$2p^3\,^2D^0$	19	230609.38	2	$3s''\,^2S$	36	253047.00	10	$3d'\,^2D$
3	40468.00	6	$2p^3\,^2P^0$	20	231428.00	28	$3d\,^4F$	37	253790.00	6	$3d'\,^2P$
4	120000.00	12	$2p^4\,^4P^0$	21	232500.00	6	$3p'\,^2P^0$	38	254480.00	28	$4d\,^4F$
5	165990.00	10	$2p^4\,^2D^0$	22	232530.00	12	$3d\,^4P$	39	254900.00	20	$4d\,^4D$
6	185340.00	12	$3s\,^4P$	23	232747.00	20	$3d\,^4D$	40	255140.00	12	$4d\,^4P$
7	189000.00	6	$3s\,^2P$	24	232850.00	14	$3d\,^2F$	41	255220.00	6	$4d\,^2P$
8	195710.40	2	$2p^4\,^2S$	25	233490.00	6	$3d\,^2P$	42	255380.00	14	$4d\,^2F$
9	203942.23	2	$3p\,^2S^0$	26	234425.00	10	$3d\,^2D$	43	255750.00	10	$4f\,^2D^0$
10	206850.00	20	$3p\,^4D^0$	27	238800.00	12	$4s\,^4P$	44	255815.00	20	$4f\,^4D^0$
11	206972.00	10	$3s\,^2D$	28	240420.00	6	$4s\,^2P$	45	255825.00	36	$4f\,^4G^0$
12	208400.00	12	$3p\,^4P^0$	29	245900.00	20	$4p\,^4D^0$	46	255860.00	10	$4d\,^2D$
13	211600.00	10	$3p\,^2D^0$	30	246450.00	12	$4p\,^4P^0$	47	255900.00	18	$4f\,^2G^0$
14	212161.84	4	$3p\,^4S^0$	31	248100.00	10	$4p\,^2D^0$	48	256120.00	28	$4f\,^4F^0$
15	212650.00	6	$2p^4\,2P$	32	248470.00	6	$4p\,^2P^0$	49	256135.00	14	$4f\,^2F^0$
16	214200.00	6	$3p\,^2P^0$	33	251223.00	14	$3d'\,^2F$				$OIII$
17	228735.00	14	$3p'\,^2F^0$	34	252608.00	18	$3d'\,^2G$	50	283240.00	9	$2p^2\,^3P$

Table 2. Energy levels included in the oxygen atom model for LTE calculations

E, cm^{-1}	g_i	$Conf.$	$E, cm-1$	g_i	$Conf.$	$E, cm-1$	g_i	$Conf.$	$E, cm-1$	g_i	$Conf.$
245037.00	2	$4p\,^2S^0\ OII$	268188.10	18	$5f\,^2G^0$	273596.09	14	$6g\,^2F$	277609.28	18	$4d\,^2G$
245395.36	6	$3s'''\,^6S^0$	268226.51	14	$5g\,^2F$	273596.09	28	$6g\,^4F$	277798.03	2	$8p\,^2S^0$
246291.78	4	$4p\,^4S^0$	268226.51	28	$5g\,^4F$	273602.67	10	$6d\,^2D$	277917.65	12	$8p\,^4P^0$
254981.49	4	$3s\,^4S^0$	268247.36	10	$5d\,^2D$	273607.06	18	$6h\,^2G^0$	278218.34	18	$4f\,^2G^0$
255622.72	2	$3d\,^2S$	268262.72	18	$5g\,^2G$	273607.06	36	$6h\,^4G^0$	278256.74	14	$4f\,^2F^0$
257800.00	12	$5s\,^4P$	268262.72	36	$5g\,^4G$	273621.33	36	$6g\,^4G$	278532.19	2	$4d\,^2S$
258500.00	6	$5s\,^2P$	268281.38	28	$5f\,^4F^0$	273622.42	18	$6g\,^2G$	278813.13	20	$8d\,^4D$
259287.80	10	$4s\,^2D$	268292.35	14	$5f\,^2F^0$	273627.91	28	$6f\,^4F^0$	278950.30	18	$8g\,^2G$
260686.00	2	$5p\,^2S^0$	269236.12	14	$4p\,^2F^0$	273635.59	14	$6f\,^2F^0$	278950.30	28	$8f\,^4F^0$
261050.00	20	$5p\,^4D^0$	269298.67	10	$4p\,^2D^0$	275097.33	2	$7p\,^2S^0$	278950.30	36	$8g\,^4G$
261300.00	12	$5p\,^4P^0$	270106.35	6	$4p\,^2P^0$	275284.98	12	$7p\,^4P^0$	278954.69	14	$8f\,^2F^0$
261750.00	10	$5p\,^2D^0$	270751.63	2	$6p\,^2S^0$	275626.28	4	$7p\,^4S^0$	279591.18	2	$9p\,^2S^0$
262370.00	6	$5p\,^2P^0$	270951.35	20	$6p\,^4D^0$	276564.55	28	$7d\,^4F$	279672.39	12	$9p\,^4P^0$
261621.48	4	$5p\,^4S^0$	271070.97	12	$6p\,^4P^0$	276607.35	14	$7d\,^2F$	280291.32	20	$9d\,^4D$
267504.42	28	$5d\,^4F$	271689.90	4	$6p\,^4S^0$	276652.35	20	$7d\,^4D$	280387.89	18	$9g\,^2G$
265220.00	20	$5d\,^4D$	272057.53	6	$6p\,^2P^0$	276819.15	36	$7f\,^4G^0$	280387.89	28	$9f\,^4F^0$
265470.00	12	$5d\,^4P$	273170.30	28	$6d\,^4F$	276823.54	18	$7f\,^2G^0$	280387.89	36	$9g\,^4G$
267822.66	6	$5d\,^2P$	273310.76	20	$6d\,^4D$	276843.29	18	$7h\,^2G^0$	303513.00	5	$2p^2\,^1D\ OIII$
265580.00	14	$5d\,^2F$	273391.97	14	$6d\,^2F$	276853.17	18	$7g\,^2G$	326425.00	1	$2p^2\,^1S$
268147.50	10	$5f\,^2D^0$	273552.19	20	$6f\,^4D^0$	276853.17	36	$7g\,^4G$	343565.00	5	$2p^3\,^5S^0$
268147.50	20	$5f\,^4D^0$	273570.85	36	$6f\,^4G^0$	276855.36	28	$7f\,^4F^0$	403293.00	15	$2p^3\,^3D^0$
268179.32	36	$5f\,^4G^0$	273576.33	18	$6f\,^2G^0$	276859.75	14	$7f\,^2F^0$	726325.00	6	$2p\,^2P^0\ OIV$

O II and the ground level of O III. These energy levels are given in Table 1. They were selected from the compilation of Hirata & Horaguchi (1994). Transitions between the remaining levels (see Table 2) were not taken into account and those levels were used only in the equations of population conservation.

Only transitions having $\lambda < 100\,000\,$Å were considered. After numerous test calculations, 86 $b-b$ transitions were included in the linearization procedure. These transitions describe quite well the formation of the lines of interest. Another 170 transitions were treated as having fixed radiative rates.

Photoionization cross-sections were mainly taken from the Opacity Project (Yan et al., 1987) keeping account within the calculations of the detailed structure of their frequency dependence, including resonances.

Oscillator strengths were selected from the extensive compilation of Hirata & Horaguchi (1994), from the survey of lines which are formed as transitions from the ground level by Verner et al., (1994) and from CDROM 23 of Kurucz (1994). Some information was also obtained through the Opacity Project. As we ignored the multiplet structure of all levels, the oscil-

Table 3. Linearized transitions

I	J	λ	f	I	J	λ	f	I	J	λ	f	I	J	λ	f
1	4	833.33	4.29E-01	3	11	600.58	4.09E-02	11	18	4349.81	2.90E-01	20	45	4097.71	8.17E-01
1	5	602.44	2.37E-06	3	15	580.78	4.65E-01	11	21	3916.15	1.62E-01	20	47	4085.14	9.04E-02
1	6	539.54	1.22E-01	3	19	525.92	1.18E-02	12	22	4143.04	2.55E-01	20	48	4048.75	6.86E-02
1	22	430.05	3.69E-01	3	25	518.07	2.80E-01	12	23	4106.12	6.44E-01	21	36	4865.53	3.30E-01
1	23	429.65	8.64E-02	3	26	515.57	1.14E-01	12	24	4088.82	3.61E-02	21	37	4695.72	3.77E-01
1	24	429.46	4.25E-03	6	10	4647.7	4.46E-01	13	23	4727.47	5.16E-02	22	43	4305.42	1.78E-01
1	27	418.76	1.52E-02	6	12	4335.29	2.67E-01	13	24	4704.56	6.62E-01	22	44	4293.4	9.56E-01
1	39	392.31	1.74E-02	6	14	3727.24	1.25E-01	13	26	4379.92	1.21E-01	22	45	4291.56	6.42E-02
1	40	391.94	1.65E-01	6	29	1651.25	1.47E-02	14	22	4908.25	7.12E-01	22	48	4237.89	8.18E-02
2	4	1073.19	1.10E-06	6	30	1636.39	6.40E-03	14	23	4856.51	1.53E-01	23	44	4333.79	1.05E-01
2	5	718.54	2.50E-01	7	9	6690.58	7.22E-02	14	27	3752.94	2.36E-01	23	45	4331.91	5.63E-02
2	7	616.59	1.15E-01	7	13	4423.53	4.74E-01	16	25	5182.58	2.80E-01	23	47	4317.87	1.26E-01
2	11	555.08	4.66E-02	7	16	3967.13	3.14E-01	16	26	4942.99	5.97E-01	23	48	4277.23	8.12E-01
2	15	538.12	4.01E-01	7	18	2440.96	5.41E-02	16	28	3812.8	7.02E-02	24	45	4351.33	1.36E-01
2	24	485.36	1.22E-01	7	21	2298.14	3.34E-02	17	33	4445.56	1.46E-01	24	47	4337.17	8.81E-01
2	25	483.86	6.02E-02	9	25	3383.37	8.49E-01	17	34	4187.65	6.77E-01	24	48	4296.16	2.44E-01
2	33	445.62	3.72E-02	9	28	2740.58	2.12E-01	17	36	4112.03	4.41E-02	24	49	4293.4	7.46E-02
2	36	442.03	8.55E-02	10	20	4067.52	7.04E-01	18	33	4700.58	4.69E-01	25	43	4491.1	8.28E-01
2	42	437.52	1.01E-01	10	23	3860.35	1.28E-01	18	36	4329.28	2.10E-01	25	44	4478.02	3.04E-01
3	5	796.67	7.01E-02	10	24	3845.06	7.93E-03	18	37	4194.33	7.83E-02	26	49	4604.88	9.01E-01
3	7	673.25	4.14E-02	10	27	3128.98	1.36E-01	19	35	4466.89	8.82E-01				
3	8	644.15	1.51E-01	11	17	4593.66	3.99E-01	20	43	4110.34	3.21E-02				

lator strength for each averaged transition was calculated as $f = \frac{\sum g_i f_i}{\sum g_i}$. Results are given in Table 3 and Table 4.

After the combined solution of the radiative transfer and statistical equilibrium equations, the average level populations were redistributed proportional to the statistical weights of the corresponding sublevels to regain the detailed multiplet structure, and finally the lines of interest were investigated.

Stark parameters are a very important part of the analysis as their influence on the resulting oxygen abundance as derived from O II lines is rather significant. To calculate the Stark parameters for the considered transitions we used the semiempirical formula provided by Dimitrijević (1997) for the full width at the half maximum (FWHM):

$$W(\text{Å}) = 2.2151 \cdot 10^{-8} \frac{\lambda^2(cm) N(cm^{-3})}{T^{1/2}(K)} \left(0.9 - \frac{1.1}{Z}\right) * \sum_{k=i,j} \left(\frac{3n_k^*}{2Z}\right)^2 \left(2n_k^{*2} - l_k^2 - l_k - 1\right) \quad (1)$$

Here n^* is an effective principal quantum number and l is an angular momentum quantum number. Calculations using this formula were performed for T=20 000 K.

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

$$C_{ik} = 1.55 \cdot 10^{13} \frac{\alpha(\nu_0) \overline{g} N_e e^{-u_0}}{\sqrt{T_e} u_0} \quad (2)$$

where $\alpha(\nu_0)$ is the threshold value of the cross-section, $u_0 = \frac{E_0}{kT_e}$, E_0 is the energy of ionization, and N_e and T_e are the electron density 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:

$$C_{ij} = 5.465 \cdot 10^{-11} N_e \sqrt{T_e} \cdot 14.5 f_{ij} \left(\frac{I_H}{E_0}\right)^2 u_0 e^{-u_0} * \max\left[\overline{g}; 0.276 e^{u_0} E_1(u_0)\right] \quad (3)$$

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

$$C_{ij} = 8.63 \cdot 10^{-6} \frac{N_e e^{-u_0}}{g_i \sqrt{T_e}} \quad (4)$$

3. General results of the calculation

Applying the above prescription we made an attempt to find relationships between the oxygen abundance and oxygen line equivalent width for a range of atmosphere parameters ($T_{\rm eff}$ ranging from 20 000 K to 33 000 K; V_t from 1 km s^{-1} to 8 km s^{-1} and oxygen abundance (O/H) from 8.37 to 8.87). Approximations were found for three different gravity values: 3.50, 3.75 and 4.00. We found that the NLTE oxygen abundance can be expressed by the following formula:

$$(O/H)_{NLTE} = 10^{(a \cdot T_{\rm eff} + b \cdot V_t + c \cdot \log(W))} * 10^{\left(d \cdot T_{\rm eff}^2 + e \cdot T_{\rm eff}^4 + f \cdot T_{\rm eff}^5 + g \cdot (\log(W))^2\right)} \quad (5)$$

Coefficients (for selected O II lines) to be used in this formula are listed in Tables 5–7 for the different $\log\ g$ values. For this fitting formula σ = 0.02 with a maximum deviation of 0.1 dex. We hope that this relationship will be of use in the determination of oxygen abundances in hot main sequence stars.

Table 4. Fixed transitions

I	J	λ	f	I	J	λ	f	I	J	λ	f	I	J	λ	f
1	8	510.96	9.08E-07	9	23	3471.65	1.55E-03	22	32	6273.53	6.90E-04	31	33	32020.55	3.13E-04
1	15	470.26	1.74E-06	9	26	3280.54	5.36E-03	22	47	4278.99	2.05E-03	31	34	22182.78	6.92E-06
1	20	432.10	1.60E-05	9	27	2868.80	1.70E-04	22	49	4236.39	1.63E-02	31	38	15673.99	1.02E-03
1	25	428.28	2.40E-04	9	39	1962.41	5.00E-05	23	29	7602.83	2.98E-02	31	39	14705.88	1.13E-03
1	26	426.58	2.93E-04	9	41	1950.16	5.08E-03	23	31	6513.38	1.93E-02	31	40	14204.54	7.22E-04
1	36	395.18	1.37E-05	9	46	1926.12	2.29E-05	23	32	6360.11	1.25E-04	31	41	14044.95	1.37E-03
1	37	394.03	1.46E-05	10	22	3894.08	4.87E-03	23	43	4347.26	1.41E-02	31	42	13736.26	9.14E-01
1	41	391.82	1.08E-04	10	38	2099.52	1.30E-03	23	49	4275.70	3.90E-02	31	46	12886.59	1.71E-01
1	46	390.84	1.55E-04	10	39	2081.17	3.91E-04	24	29	7662.83	8.25E-03	32	33	36323.99	4.19E-06
2	8	592.10	8.11E-06	10	40	2070.82	1.50E-03	24	31	6557.37	1.36E-01	32	36	21848.38	2.58E-06
2	20	488.74	4.81E-04	11	12	70028.51	1.00E-06	24	32	6402.05	1.71E-04	32	37	18797.00	1.91E-05
2	22	486.12	1.65E-03	11	13	21607.63	3.54E-03	24	43	4366.81	2.45E-03	32	39	15552.08	2.21E-03
2	23	485.61	2.71E-02	11	16	13835.11	3.13E-03	24	44	4354.45	2.52E-02	32	40	14992.48	6.68E-04
2	26	481.68	2.58E-02	11	35	2173.06	8.28E-04	25	29	8058.02	9.30E-04	32	41	14814.81	2.80E-01
2	28	468.17	9.26E-03	12	25	3985.65	1.19E-03	25	31	6844.63	3.77E-02	32	42	14471.76	3.65E-03
2	34	442.89	1.20E-04	12	27	3289.47	1.12E-01	25	32	6675.57	1.61E-01	32	46	13531.78	8.43E-01
2	37	440.59	1.49E-03	12	28	3123.05	3.95E-05	25	45	4477.28	9.81E-02	33	43	22089.68	2.14E-06
2	38	439.25	6.61E-05	12	39	2150.54	3.31E-04	25	48	4418.91	4.58E-02	33	44	21777.02	4.85E-05
2	39	438.44	6.49E-05	12	40	2139.50	5.52E-05	25	49	4415.99	1.35E-02	33	45	21729.70	2.90E-04
2	40	437.98	3.81E-05	13	25	4568.30	1.66E-03	26	29	8714.60	8.50E-05	33	47	21381.20	1.02E-03
2	41	437.83	7.90E-04	13	27	3676.47	2.10E-05	26	31	7312.62	3.82E-03	33	48	20420.63	1.45E-05
2	46	436.61	5.11E-03	13	28	3469.81	1.29E-01	26	43	4689.33	1.15E-01	33	49	20358.27	1.84E-04
3	20	523.67	2.85E-05	13	41	2292.53	2.34E-04	26	44	4675.08	4.46E-02	34	45	31084.97	3.12E-06
3	22	520.67	2.86E-04	13	42	2284.15	9.57E-03	26	45	4672.90	1.23E-02	34	47	30376.68	5.82E-06
3	23	520.08	5.70E-05	13	46	2259.38	9.72E-04	26	47	4656.58	1.55E-02	34	49	28352.71	5.82E-07
3	24	519.80	2.41E-04	14	24	4833.68	4.99E-03	26	48	4609.36	8.68E-02	36	48	32541.36	3.63E-06
3	28	500.12	4.33E-02	14	39	2339.83	6.52E-04	27	29	14084.51	6.91E-01	36	49	32383.30	2.69E-06
3	36	470.41	3.65E-02	14	40	2326.76	1.32E-02	27	31	10752.69	1.82E-04	37	43	51020.32	3.87E-05
3	37	468.78	5.87E-03	16	39	2457.00	1.65E-05	27	32	10341.27	1.11E-04	37	44	49382.73	3.03E-05
3	39	466.35	1.46E-04	16	41	2437.84	5.71E-03	28	29	18248.16	1.94E-04	37	45	49140.07	1.00E-05
3	40	465.83	3.95E-05	16	46	2400.38	4.42E-03	28	31	13020.82	7.11E-01	37	48	42918.24	2.15E-06
3	41	465.65	4.43E-03	18	28	9555.67	2.70E-03	28	32	12422.36	3.29E-01	37	49	42643.73	5.65E-06
3	42	465.31	1.96E-04	18	42	3933.14	1.35E-05	28	35	7955.45	2.40E-04	38	43	78740.20	6.50E-06
3	46	464.27	5.57E-02	20	29	6909.90	1.50E-01	29	33	18786.40	2.30E-06	38	44	74906.62	3.21E-04
6	9	5375.70	3.65E-05	20	31	5998.08	2.13E-04	29	34	14907.56	7.27E-06	38	45	74349.73	1.36E-01
6	13	3808.07	8.33E-05	20	32	5867.86	2.66E-05	29	38	11655.01	6.59E-01	38	47	70422.25	8.72E-03
6	16	3465.00	1.53E-04	20	44	4100.55	2.09E-03	29	39	11111.11	1.84E-01	38	48	60975.32	1.36E-02
7	12	5154.64	1.91E-04	20	49	4047.44	5.42E-03	29	40	10822.50	5.87E-01	38	49	60422.71	3.94E-04
7	14	4317.45	3.46E-04	21	28	12626.27	2.63E-03	29	41	10729.61	8.10E-04	39	48	81967.05	1.05E-01
7	31	1692.05	3.40E-04	21	41	4401.41	8.86E-05	29	42	10548.52	1.69E-03	39	48	81967.05	1.74E-02
7	32	1681.52	1.78E-04	21	46	4280.82	3.51E-05	29	46	10040.15	2.69E-04	39	49	80971.55	6.04E-03
7	35	1562.74	3.45E-03	22	29	7479.43	1.58E-02	30	39	11834.31	9.33E-01				
9	22	3498.00	5.60E-03	22	31	6422.61	1.14E-03	30	40	11507.47	3.68E-01				

4. Comparison with previous studies

For illustration, in Figs. 1–4 we present individual dependencies between a) line equivalent width and effective temperature for a selection of O II lines which were investigated by Becker & Butler 1988b calculated with (O/H)=8.88 and $\log g = 4.0$ and b) equivalent width and relative oxygen abundance ($V_t = 5\,\mathrm{km\,s^{-1}}$, $\log g$ =4.0 and $T_{\rm eff}$=30 000 K).

Note that in the figures we have reproduced only the Becker & Butler (1988b) NLTE results. As one can see from these figures our NLTE equivalent widths are systematically stronger than those derived by Becker & Butler. To be sure that this is not caused by the difference in adopted oscillator strengths, we compared our values with those used by the above mentioned authors (see Table 2 from their work). Having compared the oscillator strenghts we found that there is no significant differences between our and Becker & Butler's values (the difference does not exceed 10%).

For the majority of the investigated lines Becker & Butler obtained NLTE equivalent widths which are practically the same as those derived by us in the LTE approximation. The Becker & Butler (1988a, 1988b) calculations were performed using the grid of Gold (1984) models which only take into ac-

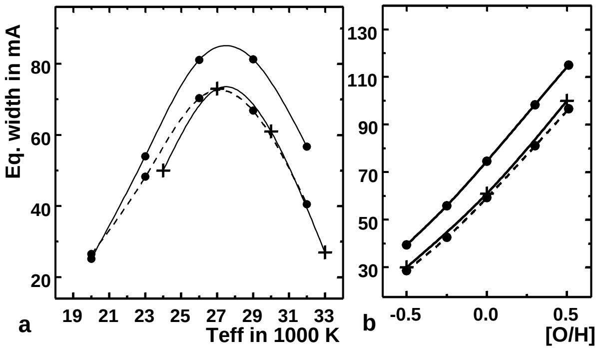

Fig. 1a and b. Equivalent width of 4078.84 Å line versus T_{eff} **a** and [O/H] **b** for NLTE (solid line) and LTE (dashed line). Our results are indicated by filled circles and those of Becker & Butler (1988b) by crosses.

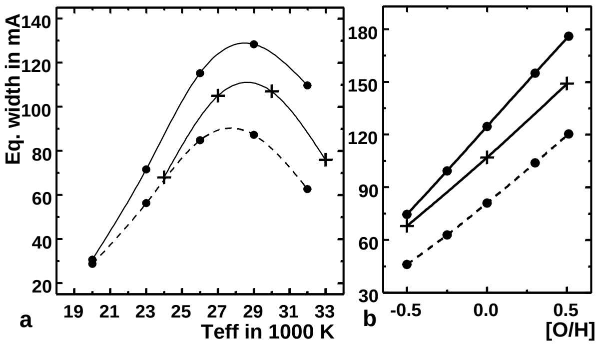

Fig. 2a and b. Same as Fig. 1, but for 4185.45 Å.

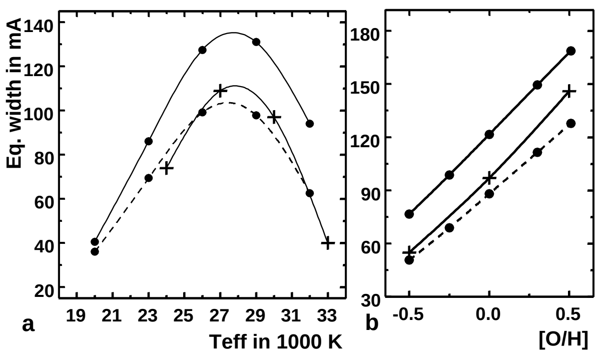

Fig. 3a and b. Same as Fig. 1, but for 4638.86 Å.

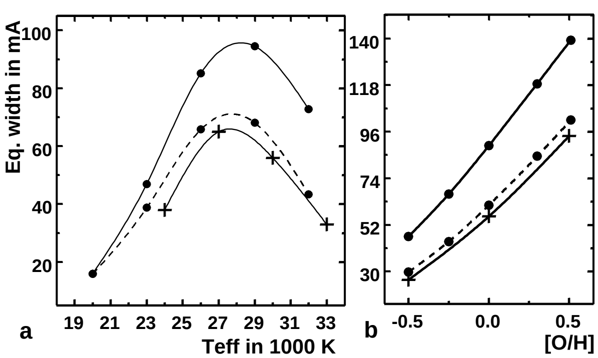

Fig. 4a and b. Same as Fig. 1, but for 4906.83 Å.

count the blanketing from the 104 strongest lines present in the spectra of B stars. In our study, the more heavily blanketed Kurucz models were used. We believe that the main source of the disparity between these NLTE results originates in the grids of atmospheric models used in the respective analyses. In fact, it was first noted by Cunha & Lambert (1994) that in NLTE determinations of elemental abundances in hot stars that the more heavily blanketed models should produce a more realistic result. Later, Korotin et al. (1999) discussed this problem having presented direct NLTE calculations of the nitrogen abundance in γ Peg based on Kurucz models.

5. Application to observations

5.1. Spectroscopic observations

Several B main sequence stars having small projected rotational velocities were selected for analysis. Observations were made with the AURELIE spectrograph (1200 lines mm^{-1} grating) on the 1.52-m telescope of Haute Provence Observatoire (France) during January 1999. The detector was a linear array (Thompson TH 7832) of 2048 photodiodes.

The spectral domain was centered on the wavelength 4700 Å. This spectral region was selected in order to observe as many O II lines as possible in a single integration. The resolving power was about 18 000.

It should be noted that due to excellent weather conditions and extremely good "seeing" during the observations we were able to reach a very high S/N ratio for the majority of the spectra.

Information concerning the program stars and their spectra is given in Table 8. The quoted S/N ratio is the mean value within the order at the continuum level.

Preliminary reduction of the spectral material (i.e. offset correction, flat-fielding, wavelength calibration) was done using the IHAP package installed at Haute Provence Observatoire. Further work with the spectra (continuum placement, equivalent width measurement, fragment extraction from the whole spectrum, etc) has been performed with the IBM/PC compatible package DECH20 (Galazutdinov, 1992).

Equivalent widths of oxygen lines selected for analysis are presented in Table 9.

5.2. Atmospheric parameters

Effective temperature and surface gravity values for each star have been estimated from $ubvy\beta$ and Geneva photometry using the calibrations by Castelli (1991) and Kunzli et al. (1997). The necessary colour indices were selected from the Catalogue of Geneva Photometric System (Rufener F., 1988) and the Catalogue of $uvby\beta$ Data (Hauck & Mermilliod, 1998). Results of the individual determinations together with the final adopted values of T_{eff} and $log\ g$ are presented in Table 10.

We have several stars in common with Gies & Lambert (1992). Comparison of our effective temperature and gravity determinations with those of Gies & Lambert shows that our values are 1 000–2 000 K and 0.2–0.3 dex lower than those of Gies & Lambert. At the same time, our estimates occupy an in-

Table 5. Coefficients for $\log g = 4.0$

λ	a	b	c	d	e	f	g
4595.96	1.5124159E-04	-2.0471793E-03	1.1170454E-02	-6.9585345E-09	5.6306715E-18	-8.3406351E-23	2.5195905E-02
4609.43	1.5550496E-04	-1.9760641E-03	3.7945134E-02	-7.2792605E-09	6.0706978E-18	-9.1441341E-23	1.7967415E-02
4610.20	1.5342524E-04	-6.4951778E-04	5.4851509E-02	-7.0222524E-09	5.8144563E-18	-8.7656958E-23	5.2823667E-03
4638.85	1.5098142E-04	-2.9185301E-03	5.3815554E-03	-6.9548807E-09	5.6546257E-18	-8.3610841E-23	3.0510199E-02
4641.81	1.5556961E-04	-4.2725404E-03	-2.0024990E-02	-7.3153636E-09	6.1042202E-18	-9.1532692E-23	4.1677337E-02
4649.14	1.5747199E-04	-5.1880087E-03	-2.8205318E-02	-7.5325189E-09	6.4400702E-18	-9.7818988E-23	4.6517209E-02
4650.84	1.5099143E-04	-2.9357199E-03	4.9863263E-03	-6.9583613E-09	5.6634497E-18	-8.3799094E-23	3.0643451E-02
4661.63	1.5228854E-04	-3.3137111E-03	-3.1963094E-03	-7.0562897E-09	5.7812318E-18	-8.5851170E-23	3.4133706E-02
4673.74	1.4803582E-04	-1.2051937E-03	4.4609172E-02	-6.7489229E-09	5.5337076E-18	-8.2534395E-23	1.1919067E-02
4676.24	1.5139794E-04	-3.0697621E-03	1.7360954E-03	-6.9924989E-09	5.7116551E-18	-8.4694643E-23	3.1920778E-02
4701.18	1.5169998E-04	-8.2484372E-04	5.0335866E-02	-6.9317828E-09	5.7352080E-18	-8.7010008E-23	7.8638346E-03
4701.71	1.5261058E-04	-2.6835721E-04	5.2427504E-02	-6.8918749E-09	5.7108517E-18	-8.7095172E-23	3.1452259E-03
4703.16	1.5283858E-04	-1.1437849E-03	4.8370093E-02	-7.0431963E-09	5.8077093E-18	-8.7432427E-23	1.0043059E-02
4705.35	1.5583200E-04	-2.9512437E-03	1.3518314E-02	-7.3146649E-09	6.0608582E-18	-9.0682382E-23	2.8147661E-02

Table 6. Coefficients for $\log g = 3.75$

λ	a	b	c	d	e	f	g
4595.96	1.5818248E-04	-2.3497411E-03	8.3003630E-03	-7.5308156E-09	6.4044870E-18	-9.6876532E-23	2.8641347E-02
4609.43	1.6206867E-04	-2.1993521E-03	4.0001418E-02	-7.8348275E-09	6.8434770E-18	-1.0496580E-22	1.9773060E-02
4610.20	1.6145329E-04	-7.1977819E-04	5.8161035E-02	-7.6947409E-09	6.8336005E-18	-1.0659798E-22	4.9297307E-03
4638.85	1.5762685E-04	-3.4791378E-03	9.8773155E-03	-7.5576263E-09	6.5305826E-18	-9.9256489E-23	3.3043315E-02
4641.81	1.6260848E-04	-4.8742939E-03	-2.1495756E-02	-7.9535248E-09	7.0787165E-18	-1.0952849E-22	4.5668031E-02
4649.14	1.6528388E-04	-5.7827268E-03	-3.8418733E-02	-8.2057405E-09	7.4888534E-18	-1.1759610E-22	5.2269174E-02
4650.84	1.5768924E-04	-3.4996126E-03	9.3298543E-03	-7.5656412E-09	6.5476069E-18	-9.9616927E-23	3.3237900E-02
4661.63	1.5916635E-04	-3.8998935E-03	-7.5546154E-04	-7.6788990E-09	6.6992830E-18	-1.0243329E-22	3.7288605E-02
4673.74	1.5317344E-04	-1.4847151E-03	5.3207010E-02	-7.2146370E-09	6.2153895E-18	-9.4618969E-23	1.1129314E-02
4676.24	1.5825738E-04	-3.6460966E-03	5.1309199E-03	-7.6127789E-09	6.6202295E-18	-1.0103721E-22	3.4819245E-02
4701.18	1.6217063E-04	-9.9795688E-04	5.5854237E-02	-7.8090002E-09	7.0897737E-18	-1.1299280E-22	7.8873099E-03
4701.71	1.6582553E-04	-3.1353119E-04	5.5320693E-02	-7.9823693E-09	7.4359338E-18	-1.2066954E-22	2.3231178E-03
4703.16	1.5868826E-04	-1.3369163E-03	5.0029739E-02	-7.5227508E-09	6.4489943E-18	-9.8501747E-23	1.1559815E-02
4705.35	1.6194701E-04	-3.2342595E-03	1.0843579E-02	-7.8196774E-09	6.7273954E-18	-1.0192404E-22	3.1383322E-02

Table 7. Coefficients for $\log g = 3.5$

λ	a	b	c	d	e	f	g
4595.96	1.6079796E-04	-2.5305435E-03	1.6841984E-02	-7.8929755E-09	7.1144087E-18	-1.1062902E-22	2.6620385E-02
4609.43	1.6496742E-04	-2.4034305E-03	4.1862426E-02	-8.1890307E-09	7.5067666E-18	-1.1731028E-22	1.9926116E-02
4610.20	1.5921632E-04	-8.2052104E-04	5.8927117E-02	-7.5960925E-09	6.7073715E-18	-1.0275765E-22	5.6171124E-03
4638.85	1.5795731E-04	-3.7836232E-03	1.7160895E-02	-7.7252475E-09	6.8833710E-18	-1.0536840E-22	3.2206704E-02
4641.81	1.6505913E-04	-5.4637484E-03	-2.3209422E-02	-8.2717780E-09	7.6452575E-18	-1.1975818E-22	4.8391266E-02
4649.14	1.6932802E-04	-6.5899926E-03	-4.8219516E-02	-8.6316391E-09	8.2155537E-18	-1.3102738E-22	5.7763210E-02
4650.84	1.5803201E-04	-3.8061369E-03	1.6705296E-02	-7.7353770E-09	6.9057767E-18	-1.0585360E-22	3.2390344E-02
4661.63	1.6001377E-04	-4.2796142E-03	4.9433570E-03	-7.8876596E-09	7.1146639E-18	-1.0977545E-22	3.7236508E-02
4673.74	1.5195166E-04	-1.5761129E-03	5.4466399E-02	-7.2096549E-09	6.2760012E-18	-9.5001266E-23	1.1237115E-02
4676.24	1.5871367E-04	-3.9762727E-03	1.2465191E-02	-7.7945504E-09	7.0006491E-18	-1.0774082E-22	3.4108289E-02
4701.18	1.6058249E-04	-1.0406804E-03	6.3991701E-02	-7.8080825E-09	7.2441869E-18	-1.1638921E-22	4.6312505E-03
4701.71	1.6119949E-04	-3.1750974E-04	5.5109248E-02	-7.6997140E-09	7.1124958E-18	-1.1455931E-22	2.2297030E-03
4703.16	1.6130156E-04	-1.4516562E-03	5.4553511E-02	-7.8557148E-09	7.1009259E-18	-1.1113663E-22	1.0287603E-02
4705.35	1.6823938E-04	-3.5500940E-03	8.2575492E-03	-8.4236977E-09	7.7444909E-18	-1.2102193E-22	3.3036626E-02

Table 8. Program stars and spectra

Star,HD	V	Sp	Region	S/N	Date, 1999
886	2.83	B2IV	4595-4800	600	4 Jan
3360	3.66	B2IV	4595-4800	500	4 Jan
16582	4.07	B2IV	4595-4800	550	4 Jan
22951	4.97	B0.5V	4595-4800	550	4 Jan
35708	4.80	B3V	4595-4800	400	8 Jan
35912	6.41	B2V	4595-4800	400	4 Jan
36351	5.46	B1.5V	4595-4800	550	4 Jan
41753	4.42	B3V	4595-4800	300	4 Jan
74280	4.30	B3V	4595-4800	550	8 Jan

termediate position between the results of Gies & Lambert and Barnett & McKeyth (1988) for HD 3360 and HD 16582. Note also that we are in good agreement with the Cunha & Lambert (1994) determination of atmospheric parameters for HD 35912 and HD 36391. We consider our choice of the adopted atmospheric parameters, based on the use of updated photometric calibrations, to be rather reliable.

We have performed an investigation of the influence of possible errors in the atmospheric parameters on the resulting NLTE oxygen abundance. Adopting as the uncertainty in the temperature and gravity $\pm$ 500 K and $\pm$ 0.2 dex respectively, we find for the atmosphere model with $T_{\rm eff}$ = 20 000 K and $\log\ g$ = 4.0 that the maximum error in the derived oxygen abundance is approximately 0.15 dex. More precisely; varying the effective temperature within the above mentioned range we find an abundance uncertainty of about $\pm$ 0.10 dex. The same uncertainty results from varying $\log\ g$ within the prescribed range. For an uncertainty in the microturbulent velocity of ± 1 km s^{-1} we find an uncertainty in the abundance of $\pm$ 0.05 dex.

5.3. Results of the calculations

The oxygen abundance of the program stars was determined both in NLTE and LTE approximation. The latter was based on an application of Kurucz's WIDTH9 code with the same atomic line parameters as for the NLTE calculations. Results are given in Table 11. Note that in all the cases NLTE abundances appear to be lower than the LTE ones with the difference ranging up to 0.3 dex. In Fig. 5 we show a comparison of calculated and observed profiles for HD 886 and HD 3360.

6. Discussion

The most important result reported in the previous sections is the following: our NLTE consideration of O II lines shows that larger equivalent widths are computed when the calculations are based on the more heavily line-blanketed Kurucz model atmospheres than when the NLTE calculations are based on the lightly blanketed Gold (1984) models. For example, from Figs. 1 - 4 one can see that for the same equivalent width the NLTE calculations of Becker & Butler (1988a, 1988b) give an overestimated oxygen abundance. The difference in some cases can achieve 0.3 dex or greater. A similar conclusion was reached

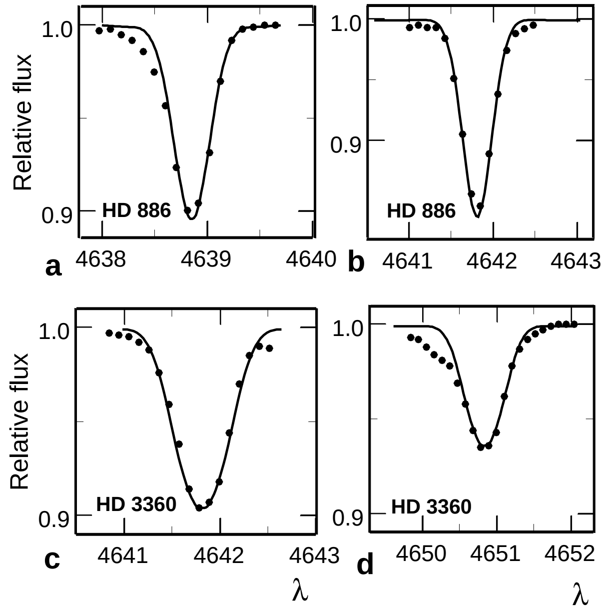

Fig. 5a–d. Calculated (NLTE) and observed line profiles for some lines. Synthetic spectrum – solid line, observed – dots.

by Cunha & Lambert (1994) in their study of CNO abundances in hot main sequence stars.

As an application of our updated NLTE code together with Kurucz models, a sample of hot B stars has been analyzed. Oxygen appears to be deficient in all of the investigated B stars when their abundance is compared to the solar value. This conclusion is supported by several independent studies. For example, Gies & Lambert (1992) found for a sample of main sequence B stars a mean oxygen abundance [O/H]=-0.25. Kilian (1992) for unevolved B stars of the galactic field determined a mean [O/H] value of ≈ -0.4 and for B stars of the Ori OB1 association [O/H] ≈ -0.3. Cunha & Lambert (1994) found that for B stars of the Orion association [O/H] = -0.26. Thus, one can see that an oxygen deficiency seems endemic among B stars. It is of great importance, therefore, to compare B star oxygen results with oxygen abundances from other stellar groups. Nissen & Edvardsson (1992) have performed an LTE analysis of the forbidden oxygen line at 6300 Å for F and G dwarfs. One can conclude from that paper that F/G dwarfs of solar metallicity possess an [O/H] ratio of ≈ -0.05. It is interesting to note that the direct mean [O/H] value for the total Nissen & Edvardsson sample of dwarfs is -0.17 ± 0.22.

Cunha (1996) reports oxygen abundances for spectral type F-G stars in Ori OB1 and gives a comparison of the results with those of Cunha & Lambert (1994) for B stars from the same association (see above). It should be noted that the oxygen triplet at 7774 Å was analysed in the later Cunha work. A rather high oxygen abundance (O/H) = 8.98 (i.e., [O/H] = +0.11) was found for the sample of F-G stars, while the B stars demonstrate an apparent deficiency of oxygen. More recently, Cunha et al. (1998) derived oxygen abundances for a sample of pre-main sequence F and G stars in the Orion association and compared their results with those obtained for the sample of B stars. They

Table 9. Equivalent widths of selected oxygen lines

			Star, HD								
Lambda	$loggf$	Γ_{st}	886	3360	16582	22951	35708	35912	36351	41753	74280
4595.96	-0.95	7.9E-06	42	34	43	78	27	17	39		
4596.18	0.20	7.9E-06									
4609.43	0.71	8.1E-06	31	23	28	49	17		28		
4610.20	-0.17	8.1E-06		6	10				8		
4638.85	-0.35	3.6E-06	50	48	49	73	38	24	49	10	13
4641.81	0.05	3.6E-06	69	63	69	103	47	31	63	16	
4649.14	0.33	4.0E-06	84	77	86	131	59	38	80	9	
4650.84	-0.35	3.6E-06	47	44	45		34	21	58		
4661.63	-0.24	3.6E-06	49	44	51	73	33	18	48		
4673.74	-1.05	3.6E-06	17	15	16	32	14	7	18		
4676.24	-0.32	3.6E-06	42	40	42	66	27	16	44		
4701.18	0.10	1.9E-05	9			22					
4703.16	0.27	1.6E-05		12		28	11		16		
4705.35	0.58	4.0E-06	37	36	38	66	27	15	40		

Table 10. Atmosphere parameters

Star		$T_{\rm eff}$		log g		Adopted		LTE	NLTE	
HD	Name	$ubvy\beta$	Geneva	$ubvy\beta$	Geneva	$T_{\rm eff}$	log g	V_t, km s^{-1}	V_t, km s^{-1}	$v\ sin\ i$, km s^{-1}
886	$\gamma\ Peg$	21430	21730	3.70	3.80	21600	3.75	5.2	3.3	8±2
3360	$\zeta\ Cas$	21040	21170	3.64	3.80	21100	3.70	4.5	4.1	25±3
16582	$\delta\ Cet$	21400	21860	3.50	4.00	21600	3.75	4.9	3.0	15±3
22951	$40\ Per$	26040	26730	3.87	3.90	26400	3.90	1.0	1.0	30±5
35708	$114\ Tau$	21020	19910	3.89	4.36	20500	4.10	2.5	2.0	25±2
35912		19350	18630	4.04	4.22	19000	4.10	8.0	4.0	22±4
36351	$330\ Ori$	21670	21450	3.93	4.20	21600	4.10	4.2	2.0	24±5
41753	$\nu\ Ori$	16940	16400	3.71	4.10	16700	3.90	16.0	15.0	40±8
74280	$\eta\ Hya$	18670	18190	3.72	3.97	18400	3.85	3.0	2.0	120±15

Table 11. Oxygen abundances in program stars

Star, HD	(O/H) LTE	σ	(O/H) NLTE	σ
886	8.58	0.06	8.45	0.09
3360	8.63	0.08	8.40	0.09
16582	8.62	0.07	8.47	0.08
22951	8.62	0.18	8.28	0.10
35708	8.85	0.13	8.73	0.11
35912	8.68	0.13	8.67	0.12
36351	8.72	0.07	8.69	0.12
41753	8.64	0.08	8.62	0.07
74280	8.55		8.50	

found that the mean oxygen abundance of the F and G stars is slightly higher than that of the B stars.

A mild oxygen deficiency [O/H] ≈ -0.3 has been also detected in the intermediate-mass supergiants (Luck & Lambert, 1985) and supergiants (Luck, 1994) which are regarded as descendants of B stars. In further work we plan to perform a NLTE investigation of the oxygen abundance in a sample of F-G supergiants and then turn to a more detailed comparison of the oxygen abundances in massive B stars and their progeny.

Acknowledgements. SMA would like to express his sincere gratitude to the director (Dr. J.-P. Sivan) and the staff of the Observatoire de Haute Provence for the provision and support of the observations. Special thanks to F. Huppert (OHP) and Dr. F. Spite (Paris-Meudon Observatoire) for the help with organizing the observations. He also gratefully acknowledges the Ministère de l'Enseignement Superieur et de la Recherche (France) for the opportunity to perform part of this study in Paris-Meudon Observatoire. The authors thank Dr. M.S. Dimitrijević for providing useful information about Stark parameters and to an anonymous referee for useful comments and suggestions.

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