Astron. Astrophys. 350, 598–602 (1999)

ASTRONOMY
AND
ASTROPHYSICS

Carbon and nitrogen abundances in early B-stars

I. NLTE calculations for a sample of stars with small $v\ sin\ i$ values*

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Received 28 April 1999 / Accepted 26 August 1999

Abstract. Abundances of carbon and nitrogen in a sample of hot main sequence stars were determined in the NLTE approximation. All calculations were based on Kurucz atmosphere models. Atmospheric parameters for the program stars have been determined using spectroscopic and photometric methods.

In most cases the derived atmospheric abundances appear to be subsolar and probably unaltered by stellar evolution. This is in agreement with the general conclusions on C and N abundances for B main sequence stars reached by other investigators.

Key words: stars: abundances – stars: atmospheres – stars: early-type

1. Introduction

Detailed NLTE calculations have become the tool of choice for the determination of realistic chemical abundances in stars which exhibit marked departures from thermodynamic equilibrium in their atmospheres. In particular, we refer to the hot luminous OB stars in which lines belonging to ionized species are prevalent.

B stars on the main sequence are the progenitors of yellow supergiants, and in particular, classical Cepheids. While evolving off the main sequence, they change the characteristics of their photospheres, and hence, the visual characteristics of their spectra. Therefore, the comparison of abundance analyses of the main sequence B stars and their descendants is complicated by the necessity of analyzing spectral features formed under very different physical conditions. One has to be sure that in both cases the applied methods give reliable results for the elemental abundances, and only then can one be confident that any changes detected in the abundances are real.

This work deals with NLTE calculations for carbon and nitrogen - two elements whose surface abundance is closely related to core nucleosynthetic and dynamical processes which take place during the course of stellar evolution.

There exist a number of problems in the spectroscopy of main sequence B stars that cannot be resolved without accurate NLTE elemental abundance determinations. Among them:

1) Is there evidence of incomplete CNO cycle processed material on the surface of B main sequence stars?
2) If so, does the degree of contamination depend upon rotational velocity?
3) What is the relation between C and N abundances in the progenitor B stars and their descendants - Cepheids and non-variable yellow supergiants?

Some efforts have been made to solve these problems (at least, the first two of them), but here we shall not extensively discuss the work based on fundamentally LTE analyses of carbon-nitrogen abundances in B stars. For example, Gies & Lambert (1992), Cunha & Lambert (1994), Kilian (1992) determined LTE abundances of these elements and attempted to correct for NLTE effects. The method used involves indirect estimates of NLTE corrections based upon corresponding relations between equivalent widths of lines and elemental abundances for different temperature and gravity values calculated with Gold (1984) atmosphere models (Becker & Butler, 1989 and Eber & Butler, 1988). Korotin et al. (1999a b-Paper Iab) performed direct NLTE calculations for lines of C II and N II in the spectrum of γ Peg based on Kurucz (1992) models. They noted a difference in the NLTE corrections obtained from Kurucz models versus the less blanketed Gold models.

2. Observational material

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. A linear array detector (Thompson TH 7832) consisting of the 2048 photodiodes was used. Spectral domains were centered on the wavelengths 4700 Å, 5100 Å and 6500 Å. These spectral regions have been selected in order to

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

Table 1. Program stars and spectra

Star	V	Sp	Region	S/N	Date, 1999
HD886	2.83	B2IV	4595-4800	600	4 Jan
γ *Peg*			4994-5200	700	5 Jan
			6400-6600	450	6 Jan
HD3360	3.66	B2IV	4595-4800	500	4 Jan
ζ *Cas*			4994-5200	650	5 Jan
			6400-6600	400	6 Jan
HD16582	4.07	B2IV	4595-4800	550	4 Jan
δ *Cet*			4994-5200	700	5 Jan
			6400-6600	450	6 Jan
HD22951	4.97	B0.5V	4595-4800	550	4 Jan
40 *Per*			4994-5200	700	5 Jan
			6400-6600	450	6 Jan
HD32249	4.80	B2V	4994-5200	600	7 Jan
ψ *Eri*					
HD35708	4.80	B3V	4595-4800	400	8 Jan
114 *Tau*			4994-5200	150	7 Jan
HD35912	6.41	B2V	4595-4800	400	4 Jan
			4994-5200	600	5 Jan
			6400-6600	250	5 Jan
HD36351	5.46	B1.5V	4595-4800	550	4 Jan
330 *Ori*			4994-5200	600	5 Jan
			6400-6600	400	5 Jan
HD45546	5.00	B2V	4994-5200	500	7 Jan
10 *Mon*					
HD74280	4.30	B3V	4595-4800	550	8 Jan
η *Hya*			4994-5200	170	7 Jan

observe as many C II and N II lines as possible. The resolving power was about 18000. It should be noted that due to excellent weather conditions and extremely good "seeing" during the observations we were able to reach very high S/N ratios for majority of the spectra. Information concerning the program stars and their spectra is given in Table 1. The S/N ratio is the mean value within the order at the continuum level.

Preliminary reduction of the spectra (i.e. offset correction, flat-fielding, wavelength calibration) was performed using IHAP package installed at Haute Provence Observatoire. Further work upon 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).

3. Atmospheric parameters

Effective temperature and surface gravity values for each star have been estimated from $ubvy\beta$ and Geneva photometry using the calibrations of Castelli (1991) and Kunzli et al. (1997). The necessary colour indices were taken 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 finally adopted values of T_{eff} and $log\ g$ are presented in Table 2.

4. Abundance analysis

4.1. Method

In the investigation of elemental abundances we have employed both LTE and NLTE analyses. For complete information concerning the NLTE calculation for the C II and N II spectrum we refer the reader to Paper Iab, where a detailed description of the applied NLTE code (an updated implementation of Carlsson [1986] MULTI code), atomic models, oscillator strengths, and photoionization and collision cross sections for all considered transitions are given. In principle, the LTE abundances could be also obtained with the MULTI code, but this appears to be a rather time consuming approach so we decided to use Kurucz's well-known WIDTH9 code for the LTE analysis. A test calculation showed that both MULTI and WIDTH9 yield identical LTE abundances.

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

In the present work, we have modified the Stark broadening constants used in the calculations relative to those used in Paper Iab. Their influence on the resulting abundances is quite significant. Therefore, we have paid special attention to this part of the analysis. To calculate the Stark parameters for the considered transitions, we used semiempirical formula provided by Dimitrijević (1997) for the full width at the half maximum (FWHM):

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

Here n^* is an effective principal quantum number and l is an angular momentum quantum number. Calculations using this formula were performed for T=20000 K.

It should be noted that recently obtained experimental data on Stark parameters are in excellent agreement with the predictions of Eq. 1 (see, for example, estimates made by Sarandaev & Salakhov [1995] for the C II lines 6578 Å and 6583 Å and by Milosavljević et al. [1999] for the N II 4630 Å line).

4.2. Abundance analysis and results

The abundance analysis was carried out on the sample of carbon and nitrogen lines listed in Table 3. For the LTE analysis based on equivalent widths only unblended lines were selected. As the NLTE code enables the calculation of a synthetic spectrum, some blends (consisting of close lines of the same element) were also treated in the analysis. NLTE abundances were derived by fitting calculated and observed profiles as well as by using equivalent widths using the method described in Paper Iab. In Fig. 1 we show a comparison of calculated and observed profiles for a sample of lines. While fitting the profiles, projected rotational velocities were estimated (see Table 2).

Table 2. Atmosphere parameters

	T_{eff}		log g		Adopted		LTE	NLTE	
Star,HD	$ubvy\beta$	Geneva	$ubvy\beta$	Geneva	T_{eff}	log g	$V_t,\ km\ s^{-1}$	$V_t,\ km\ s^{-1}$	$v\ sin\ i,\ km\ s^{-1}$
886	21430	21730	3.70	3.80	21600	3.75	5.2	3.3	8±2
3360	21040	21170	3.64	3.80	21100	3.70	4.5	4.1	25±3
16582	21400	21860	3.50	4.00	21600	3.75	4.9	3.0	15±3
22951	26040	26730	3.87	3.90	26400	3.90	1.0	1.0	30±5
32249	18980	18050	3.90	4.07	18500	4.00	3.0	2.0	48±8
35708	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	21670	21450	3.93	4.20	21600	4.10	4.2	2.0	24±5
45546	19350	18790	3.84	4.10	19100	4.00	3.0	2.0	85±10
74280	18670	18190	3.72	3.97	18400	3.85	3.0	2.0	120±15

Abundances were calculated after the microturbulent velocity determination. The microturbulent velocity was determined by applying the usual condition that there should be no dependence between the calculated abundances from individual carbon or nitrogen lines and their equivalent width. Note, that there exists a difference between V_t values determined under the LTE and NLTE approaches. As has often been found, the NLTE approach requires smaller values of the microturbulence parameter. This procedure has not been employed for all the stars. If a sufficient number of lines were not available, then V_t= 3 $km\ s^{-1}$ (LTE case) or V_t= 2 $km\ s^{-1}$ (NLTE case) was adopted. Average values for the carbon and nitrogen abundances are given in Table 4.

Let us compare the results on carbon and nitrogen abundances in HD 886 ($\gamma\ Peg$) obtained in the present study with those given in our previous work (Paper Iab). The previous result for carbon was $[C/H] = -0.25$, while present study yields $[C/H] = -0.44$. A similar comparison for nitrogen gives $[N/H] = -0.32$ and $[N/H] = -0.42$ respectively. The dominant reasons for the differences are differing stellar parameters, Stark broadening, and equivalent widths. In previous study we used the atmospheric parameters for HD 886 given by Gies & Lambert (1992), i.e., T_{eff}=22600 K and $log\ g$=4.0, while in present work we have used updated photometric calibrations for the temperature and gravity determination. As a result we obtained: T_{eff}=21600 K and $log\ g$=3.75. These latter atmospheric parameters we consider as being the more accurate. Stark broadening parameters greatly influence the derived abundances and in this study we recalculated the Stark broadening parameters using Dimitrijević's updated formula which makes the present results more reliable. Finally, note that the previous study of $\gamma\ Peg$ was based on a single CCD spectrum. A comparison of the equivalent widths of carbon and nitrogen lines measured in that spectrum with those measured in spectra from the present analysis (as well as with the data of other authors, e.g. Gies & Lambert, 1992) shows that equivalent widths of some lines measured in Paper Iab were slightly overestimated (most probably due to an instrumental effect). Nevertheless, the detected abundance differences are not very pronounced, and indicate that the uncertainty in the abundances is at about the 0.1 dex or less level. Qualitatively, Paper Iab gives the same result as the present more reliable study.

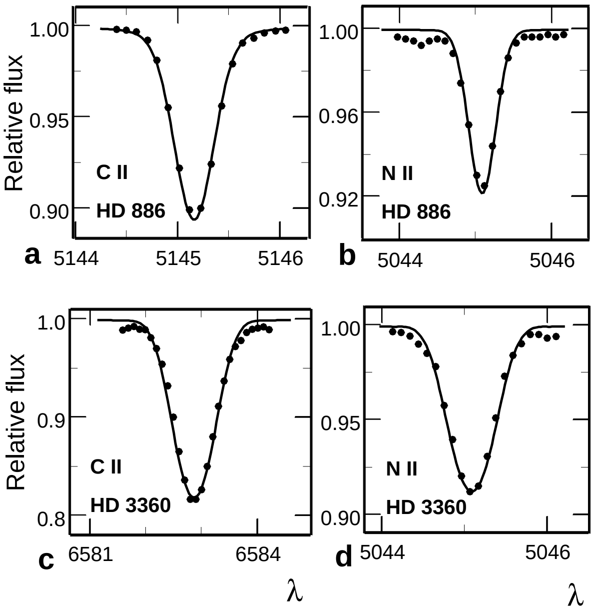

Fig. 1a–d. Calculated (NLTE) and observed spectrum profiles for a sample of lines. Synthetic spectrum – solid line, observed – dots.

5. Discussion

While inspecting Table 4 one feature draws attention: all of the investigated stars possess an apparent carbon deficiency. Nitrogen shows either an under- or over- abundance with respect to the solar value. This hints that 1) the program stars represent the different initial abundances of carbon and nitrogen and 2) some of them show probably the signs of CN-processed material at the surface. Let us discuss the implications further.

Incomplete CNO cycling leads to transformation of some part of the carbon nuclei into nitrogen nuclei without a significant alteration in the number of oxygen nuclei. Upon being brought to the surface and mixed with the photospheric gas (provided a mixing mechanism is present) the CN-processed material alters the initial atmospheric chemical composition -

Table 3. Equivalent widths of selected lines and their parameters

			Star, HD									
Lambda	$log gf$	Γ_{st}	886	3360	16582	22951	32249	35708	35912	36351	45546	74280
C II												
5032.07	-0.16	3.5E-04	31	45						26		
5122.08	-0.53	2.1E-04						27			36	
5122.27	-0.38	2.1E-04										
5122.27	-1.68	2.1E-04										
5132.94	-0.24	2.2E-04				33	37	47			54	
5133.28	-0.21	2.2E-04										
5137.26	-0.94	2.2E-04		9				5	5	5		
5139.17	-0.74	2.2E-04		12				9	8	8		
5143.49	-0.25	2.2E-04	28	26	28	18	19	22	17	28	34	
5145.17	0.16	2.2E-04	51	48	48	37	26	38	32	42	59	
5151.08	-0.21	2.2E-04	31	36	26	18	16	26	19	24	28	30
6578.05	-0.05	4.5E-06	178	212	171	90			165	166		
6582.87	-0.34	4.5E-06	147	162	137	64			131	118		
N II												
4601.48	-0.39	4.8E-06	36	57	62	38		51	19	34		33
4607.15	-0.48	4.8E-06	31	53	54	27		39	19	30		
4613.87	-0.61	4.8E-06	28	50	51	24		36	15	28		
4621.39	-0.48	4.8E-06	34	49	50	22		42	22	29		
4630.54	0.09	4.8E-06	57	86	94	59		70	31	57		52
4643.08	-0.39	4.8E-06	36	61	60	21		50	18	36		
4779.72	-0.58	3.7E-06		21	21			20				
4788.14	-0.39	3.7E-06	14	28	27	14		24	6	13		
4803.28	-0.14	3.7E-06		36	34			29				
4994.37	-0.05	4.2E-06		43				28				
5001.13	0.26	3.6E-06				84	37	86	38	80	53	
5001.48	0.43	3.6E-06										
5002.70	-1.09	4.6E-06	10	24				20				
5005.15	0.59	3.6E-06	47	64	74	48	21	58	25	52	27	37
5007.33	0.17	4.2E-06	24	40	47	26	10	32		33		
5010.62	-0.61	4.6E-06	23	39	47	27		31	13	23		
5025.65	-0.47	3.6E-06	10	20	21			17	4	10	7	
5045.09	-0.39	4.6E-06	34	58	59	33	24	45	14	32	28	

carbon becomes deficient, while nitrogen becomes proportionately overabundant. To express the resulting nitrogen abundance one can use the following formula:

$$10^{(N/H)^{fin}} = 10^{(N/H)^{init}} + 10^{(C/H)^{init}} - 10^{(C/H)^{fin}} = 10^{(N/H)^{init}} + 10^{(C/H)^{init}} \left(1 - \frac{1}{10^{\Delta}}\right) \quad (2)$$

where

$$\Delta = (C/H)^{init} - (C/H)^{fin} \quad (3)$$

In Fig. 2 we show several dependencies representing $(N/H)^{fin}$ as a function of the $(C/H)^{fin}$ value for different sets of the initial carbon and nitrogen abundances scaled by a factor of 0.2 dex starting from the solar composition (i.e., 8.55/7.97). Of course, the initial C and N abundances cannot with absolute confidence be proportionally scaled to the solar abundances of these elements, but the figure does indicate the overall behavior of the final nitrogen abundance.

As one can see from Fig. 2, three stars of our sample likely possess CN-processed material in their atmospheres, while the rest have carbon and nitrogen abundances which are close to the presumed initial values. It is interesting to note that from the whole sample only two stars: HD 45546 and HD 74280 have an initial CN-abundance which could be considered as solar-like.

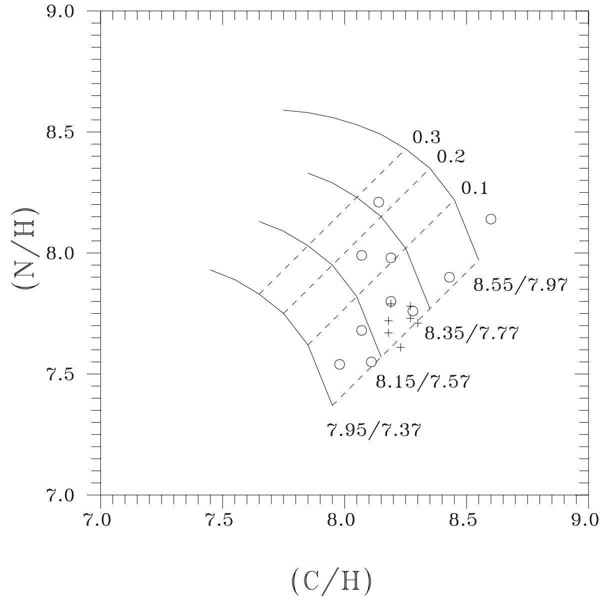

Fig. 2. Resulting nitrogen abundance as a function of carbon content. Solid lines are dependencies obtained by decreasing the carbon abundance from initial value with a step of Δ=0.1 dex (indicated near dashed lines). The initial values of carbon and nitrogen abundances for different cases are indicated near the solid lines. Stars of Ori OB1 association (crosses) have been added to our sample

Table 4. Abundances of carbon and nitrogen

Star,HD	LTE				NLTE			
	(C/H)	σ	(N/H)	σ	(C/H)	σ	(N/H)	σ
886	8.24	0.03	7.65	0.05	8.11	0.04	7.55	0.08
3360	8.30	0.14	8.11	0.07	8.19	0.08	7.98	0.11
16582	8.19	0.04	8.08	0.05	8.07	0.04	7.99	0.06
22951	8.05	0.16	7.64	0.11	7.98	0.04	7.54	0.11
32249	8.25	0.12	7.95	0.29	8.19	0.10	7.80	0.18
35708	8.21	0.08	8.30	0.08	8.14	0.07	8.21	0.11
35912	8.27	0.04	7.79	0.12	8.28	0.07	7.76	0.10
36351	8.16	0.10	7.75	0.05	8.07	0.06	7.68	0.07
45546	8.56	0.08	8.10	0.26	8.43	0.10	7.90	0.12
74280	8.61		8.19	0.09	8.60		8.14	0.07

(Note that the result for HD 74280 is not quite reliable as only one carbon and three nitrogen lines were used).

Carbon appears to be deficient in main-sequence B stars. This circumstance indicates that the rather high initial abundance inherent to Sun is likely not representative of main-sequence B stars.

As a particular example, in Fig. 2 we added to our sample of stars those belonging to Ori OB1 association which were analysed by Kilian (1992). Ori OB1 stars are compactly clustered on the figure (as should be expected for the stars that were simultaneously born from rather homogeneous gas) and their position also clearly indicates the common carbon deficiency.

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 help with organizing the observations. He also gratefully acknowledges the Ministère l'Enseignement Superieur et de la Recherche (France) for the opportunity to perform part of this study at the Paris-Meudon Observatoire. The authors are thankful to Dr. M.S. Dimitrijević for providing useful information about Stark parameters.

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