Astron. Astrophys. 202, 101–108 (1988)

ASTRONOMY AND ASTROPHYSICS

Carbon abundance in β Persei and λ Tauri *

H. Cugier [1] **and J. Hardorp** [2]

[1] Wroclaw Astronomical Observatory, Kopernika 11, PL-51-622 Wroclaw, Poland
[2] Astronomy Program, State University of New York at Stony Brook, New York, NY 11794, USA

Received October 30, 1987; accepted March 10, 1988

Summary. A carbon abundance analysis of two Algol-type stars is performed using IUE archival data released for general use. The primaries of β Per and λ Tau show carbon abundances equal to $\log N(\mathrm{C/H}) = -3.87 \pm 0.20$ and -3.88 ± 0.20, respectively. The results should be compared with the cosmic value of -3.48 given by Allen (1973).

A C-deficiency favours the generally accepted evolutionary status of Algol-type stars. The conversion of C to N by the CNO cycle is expected in stellar interiors and products of this nucleosynthesis may be exposed now in the atmospheres of stars, due to a large-scale transfer of mass between the components. However, the observed carbon abundances in β Per and λ Tau are markedly larger than those expected. A suggestion is made that a large-scale mixing of matter occurs in these stars.

Key words: lines: profile – stars: binaries: close – stars: LTE and non-LTE abundances – UV radiation

1. Introduction

The observed chemical composition of Algol-type stars may be affected by mass transfer between the components and mass loss from the system. An increase in He/H ratio and substantial changes in the relative abundance of C, N, and O elements through the CNO cycle are expected, cf. e.g., Paczyński (1971), Lambert (1982) and De Greve (1986).

According to Iben (1967a, and references therein) the region within which C is being reduced to an equilibrium value with respect to N in massive stars expands outwards with time in greater mass fractions, but becomes essentially fixed after the moment when the central hydrogen content drops by about 15%. The frozen-in C-profile allows us to estimate the carbon depletion as a function of mass of the loser. Carbon depletion of about 2.0 dex, may be expected when a sufficiently large fraction of mass is lost. β Persei is an example of such a system. In order to check this idea, we performed an analysis of UV 1 ($\lambda = 1335$ Å) and UV 11 ($\lambda = 1324$ Å) multiplets of C II, making use of the International Ultraviolet Explorer (IUE) archival data released for general use.

Send offprint requests to: H. Cugier

* Based on observations by International Ultraviolet Explorer collected at the USA National Space Science Data Center

2. Program stars

The program stars include two classical short-period Algol-type binaries, β Persei and λ Tauri, and two comparison stars: 21 Aql and ι Her. β Per (Algol) consists of a well-known close binary system with the period equal to $2\overset{d}{.}8674$ (cf. Table 1, where details are given together with suitable references), and a third component revolving around the barycenter of the triple system with a period equal to 1.862 yr. The largest contribution to the radiation, especially in the UV range, comes from the primary component, a B8 V star. The effective temperature T_{eff} of this star is equal to 13000 ± 1000 K. This value is consistent both with the UV flux distribution (cf. e.g. Eaton, 1975) and with a photometric light-curve solution of Wilson et al. (1972). The observed mass and radius shown in Table 1 give a logarithmic surface gravity equal to $\log g = 4.02 \pm 0.06$, which is exactly the same as that derived by Olson (1975) from the hydrogen line profiles. The rotational velocity is equal to $53 \pm 3\ \mathrm{km\,s^{-1}}$ (cf. Ruciński, 1979). This value corresponds to the synchronous rotation of the primary star with its orbital motion.

The system λ Tauri contains a semidetached binary of the Algol type with the orbital period equal to $3\overset{d}{.}9526$ and a third component, orbiting the Algol pair with a period equal to 33^{d} (cf. Fekel and Tomkin, 1982). The masses and radii of the components of the close binary system are well known (cf. Table 1); they give a surface gravity of the primary component equal to $\log g = 3.68 \pm 0.03$. This value slightly exceeds Olson's (1975) determination of $\log g$ from hydrogen (3.38) and helium (3.42) line profiles. The effective temperature is about 18000 ± 600 K, as derived by Cester et al. (1978) from V and B light curve analysis.

Table 1. The program stars

Star	HD	Sp	P [d]	M [$M_\odot$]	R [$R_\odot$]	Ref.
β Per	19356	B8 V	2.8674	3.7	3.08	(1)
		G8 IV		0.81	3.23	
λ Tau	25204	B3 V	3.9526	7.2	6.4	(2)
		A1 III		1.9	5.3	

References for masses and radii: (1) Tomkin and Lambert (1978), (2) Fekel and Tomkin (1982)

21 Aql is a B7IV type star (Adelman, 1984) with a small rotational velocity, $V \sin i = 19\,\mathrm{km\,s^{-1}}$ (cf. Hoffleit, 1982). We obtained $T_{\rm eff} = 13100$ K and $\log g = 3.8$ from the Strömgren photometric indices, taken from Lindemann and Hauck's (1973) catalogue. For this purpose we used the theoretical grid of m_1 versus c_1 of Relyea and Kurucz (1978), after the observed indices were dereddened by a method for B-type stars, outlined by Crawford (1973). Finally, ι Her, a B3 V star with $T_{\rm eff} \approx 18000$ K, $\log g = 3.7$ and $V \sin i = 11\,\mathrm{km\,s^{-1}}$ has been already analysed in Paper I (Cugier and Hardorp, 1988), where details of the carbon abundance determination are given.

3. Observations

The observational material consists of high resolution IUE spectra, obtained from the National Space Science Data Center at the NASA Goddard Space Flight Center. We used IUE programs developed at Stony Brook, which are based on the standard IUE SIPS reduction procedure. IUE images of β Per were already used by Cugier and Molaro (1984) and relevant information about images are shown in their Table 1. For the purpose of the present investigation we selected three images of β Per, SWP 2643, 3794 and 3818, obtained on 13 September 1978, 3 and 6 January 1979, respectively. We used orders 106 to 103 of the SWP camera, which cover the wavelength region from about 1294 to about 1344 Å; cf. Table 2a where details are given. We estimate the accuracy of the observations from the following procedure. First, for a given order of SWP camera, we derived small relative wavelength shifts between images by a cross-correlation method. Next, we constructed the mean spectrum by co-adding three images with the same weight. Table 2a shows the mean square deviations, σ, of the individual images from the mean spectrum. As one can see from this table, $\sigma = 0.04$ to 0.07 in continuum units. The mean spectrum of β Per was then compared with the SWP 21076 image of 21 Aql. The spectrum of 21 Aql was numerically broadened to the rotational velocity of β Per, i.e., $V \sin i = 52.3\,\mathrm{km\,s^{-1}}$. We found $\sigma = 0.05$ to 0.06 with the exception of the order 103 which shows $\sigma = 0.152$, cf. Table 2b. This is caused by the fact that the C II resonance lines located in the order 103 are markedly weaker in β Per than those of 21 Aql. Figures 1a and b show the mean spectrum of β Per and the SWP 21076 image of 21 Aql. As one can see, the agreement between these stars is reasonably good.

In the case of λ Tau, we used two images obtained on 8 and 10 November 1978 at orbital phases $\varphi = 0.93$ (SWP 3266) and $\varphi = 0.56$ (SWP 3297), respectively. These images were used to construct the mean spectrum of λ Tau as described above. We found the mean square deviations, σ, from 0.03 to 0.04, cf. Table 2c. For the comparison star, ι Her, we used the same image (SWP 5720) as in Paper I. The spectrum of ι Her was numerically broadened to $V \sin i = 90\,\mathrm{km\,s^{-1}}$, which shows the best fit to the mean spectrum of λ Tau at the wavelength range from λ 1294 to 1330 Å. The mean square deviations of this pair of spectra are equal to 0.06 to 0.09 (Table 2d). In Figs. 2a and b the wavelength region from λ 1296 to 1343 Å of both stars is displayed. Note that the broadened spectrum of ι Her and the spectrum of λ Tau are quite similar in this wavelength region with the exception of the C II resonance lines at 1335 Å, which are slightly weaker in the case of λ Tau.

The analysed spectra of β Per and λ Tau are not influenced significantly by circumstellar components. In fact, Cugier and Molaro (1984) reported that β Per appears to lack in substantial circumstellar absorptions at certain epochs of observations during which no significant additional components of the resonance lines of C II, Mg II, Al II, Al III, Si IV, etc. were detected. SWP 2643, 3794 and 3818 images used in the present paper are examples of such spectra. UV observations of λ Tau show only minor circumstellar activity of this system (cf. Polidan and Peters, 1980). Additional absorption components are clearly seen in the red wings of the resonance lines of Al III and Si IV at orbital phase $\varphi = 0.93$, but they are not present at $\varphi = 0.56$. The C II resonance lines show similar behaviour but in a much less evident form.

Table 2a. IUE observations of β Per

Image No.	Orbital phase	Order	λ	σ
SWP 2643	0.636	106	1294–1306	0.068
		105	1306–1318	0.072
		104	1318–1331	0.046
		103	1331–1344	0.058
SWP 3794	0.768	106	1294–1306	0.068
		105	1306–1318	0.058
		104	1318–1331	0.042
		103	1331–1344	0.053
SWP 3818	0.493	106	1294–1306	0.058
		105	1306–1318	0.067
		104	1318–1331	0.047
		103	1331–1344	0.062

Table 2b. The mean square deviations of rotationally broadened SWP 21076 image of 21 Aql from the mean spectrum of β Per

Order	λ	σ
106	1294–1306	0.061
105	1306–1318	0.048
104	1318–1331	0.061
103	1331–1344	0.152

Table 2c. IUE observations of λ Tau

Image No.	Orbital phase	Order	λ	σ
SWP 3266	0.93	106	1294–1306	0.033
		105	1306–1318	0.036
SWP 3297	0.56	104	1318–1331	0.033
		103	1331–1344	0.034

Table 2d. The mean square deviations of rotationally broadened SWP 5720 image of ι Her from the mean spectrum of λ Tau

Order	λ	σ
106	1294–1306	0.078
105	1306–1318	0.055
104	1318–1331	0.058
103	1331–1344	0.085

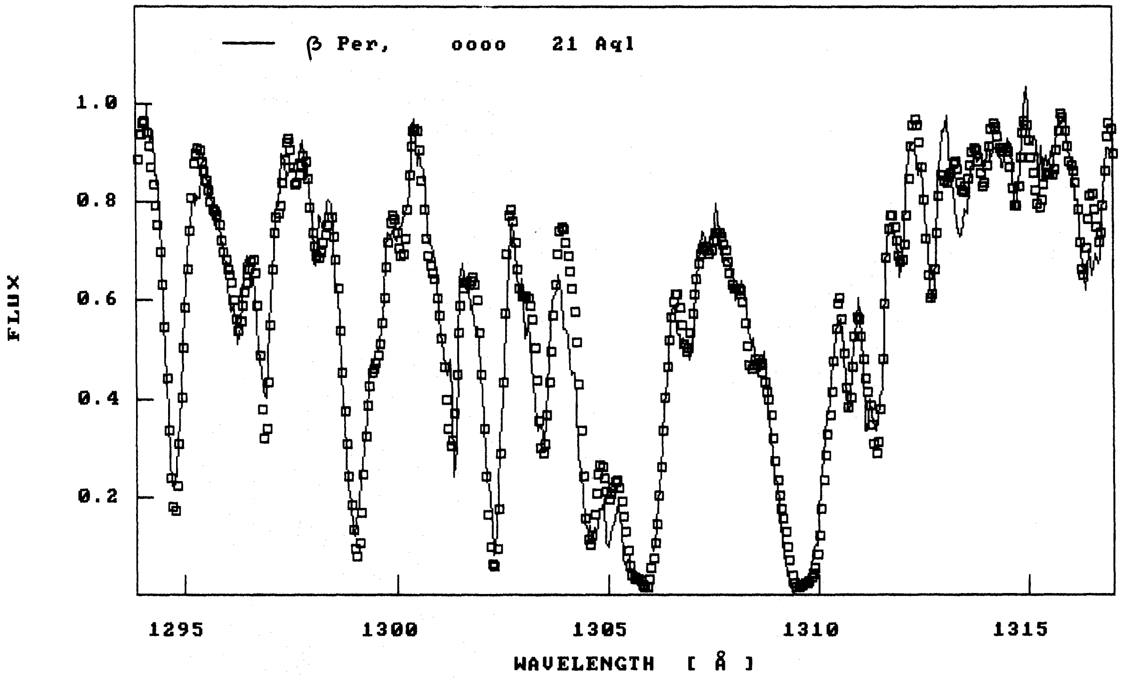

Fig. 1a. IUE observations of β Per (———) in the wavelength region from 1294 to 1317 Å in comparison with those of 21 Aql (□ □ □). The observed spectrum of 21 Aql was broadened to the rotational velocity of 52.3 km s^{-1}

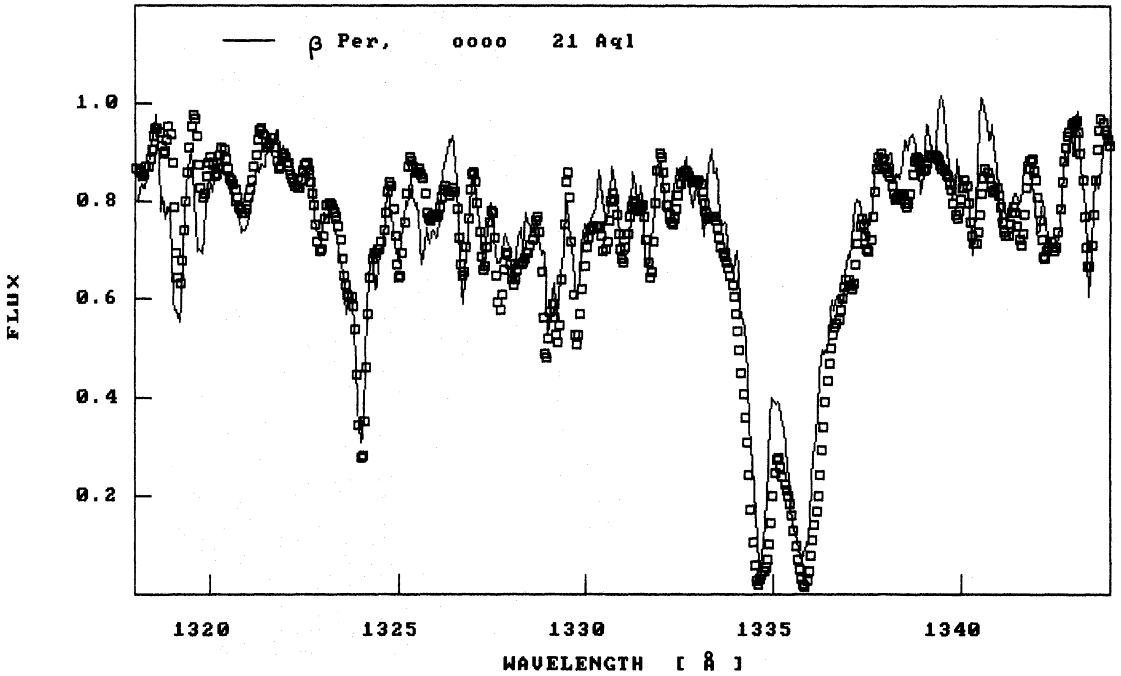

Fig. 1b. The same as Fig. 1a but for the wavelength region 1318 to 1343 Å. The C II multiplets are located at 1324 and 1335 Å

4. Carbon abundance analysis

The method of analysis we use is essentially the same as that described in Paper I. Both, LTE synthetic spectra and non-LTE line profiles of the C II resonance multiplet (λ1334.53, 1335.66 and 1335.71 Å) were computed. We adopted the f_{ij} – and A_{ij} – values of the C II lines given by Nussbaumer and Storey (1981). The damping mechanism is mainly due to the natural one and the Stark effect (taken from Sahal-Brechot and Serge, 1971). For the blend contribution of other elements, we assumed solar abundances (taken from Kurucz, 1979) and the gf values of Kurucz and Peytremann (1975) and Kurucz (1981). In the non-LTE calculations, we took into account a partial redistribution effect on the emergent line profiles, which leads to slightly weaker wings of the

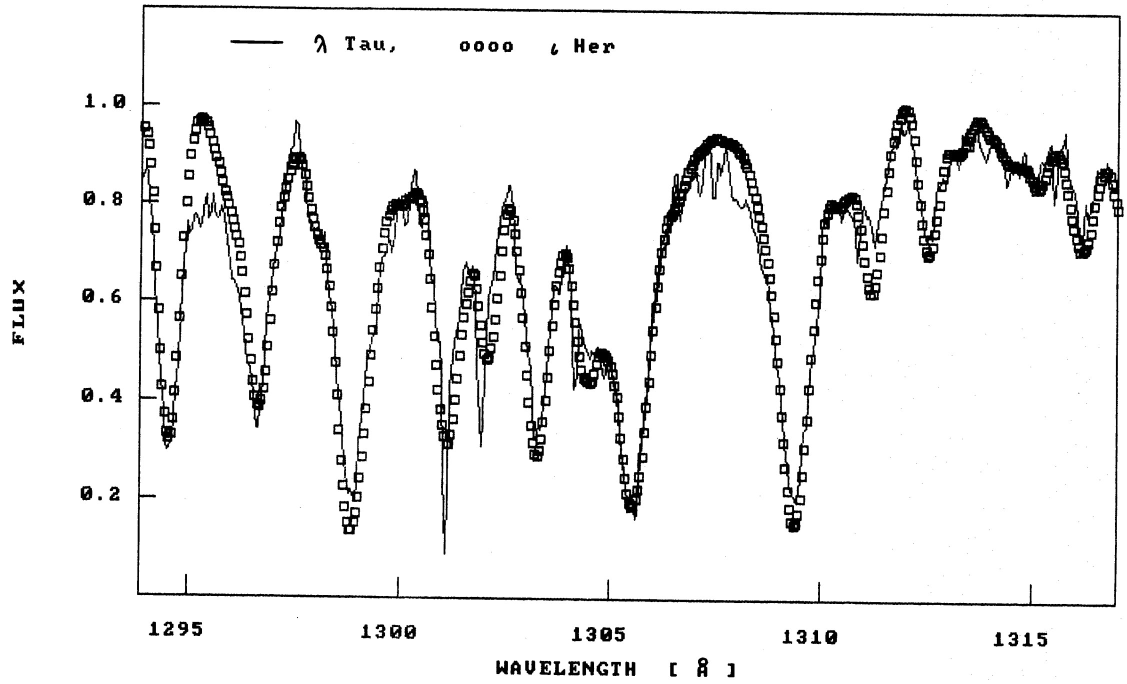

Fig. 2a. IUE observations of λ Tau (———) in the wavelength region from 1294 to 1317 Å in comparison with those of ι Her (□ □ □). The observed spectrum of ι Her was broadened to the rotational velocity of 90 km s^{-1}

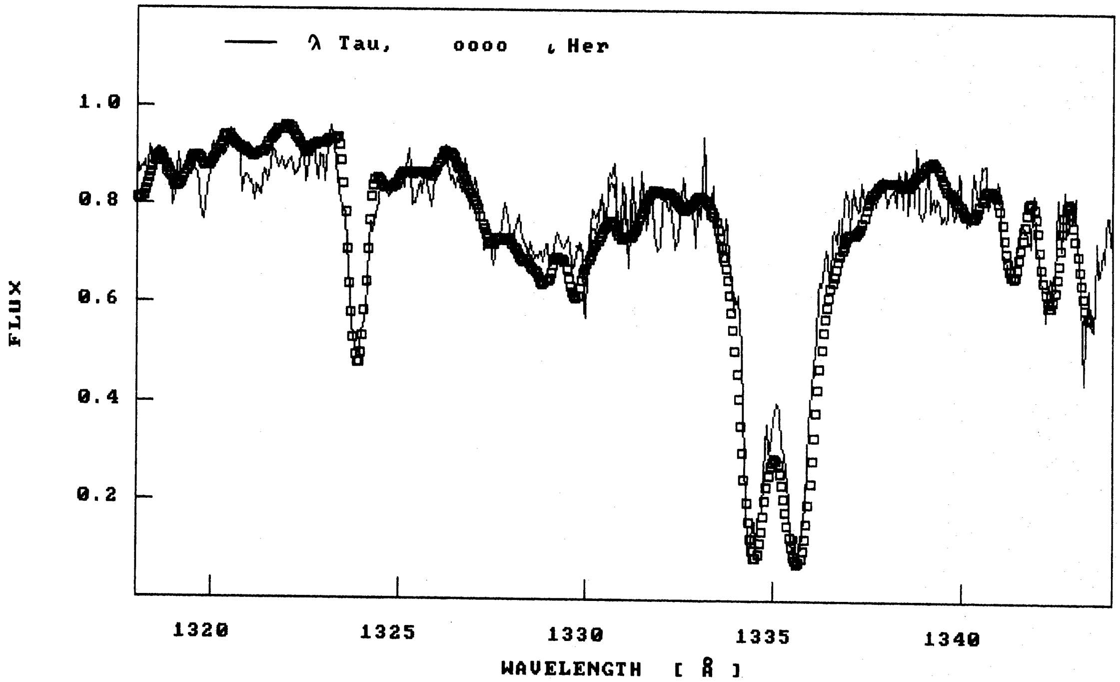

Fig. 2b. The same as Fig. 2a but for the wavelength region 1318 to 1343 Å. The C II multiplets are located at 1324 and 1335 Å

C II resonance lines than does complete redistribution, cf. Paper I. For a comparison with the observations, the computed spectra were then broadened for a given rotational velocity and convolved with the instrumental profile. We assumed the gaussian shape for the instrumental profile with FWHM as in Boggess et al. (1978).

In the present paper, we also examined the C II multiplet at λ1324 Å. The wavelengths of the individual components were taken from Moore (1970). We used the oscillator strength of this multiplet from Nussbaumer and Storey (1981) to calculate f_{ij} – values of the individual lines according to their intensity ratios given by Moore (1970). To assess the sensitivity of this multiplet to the parameters entering the calculations, we analysed the total equivalent widths, W_λ, of these lines at the wavelength range from 1323.10 to 1324.80 Å for several models. The LTE line profiles are

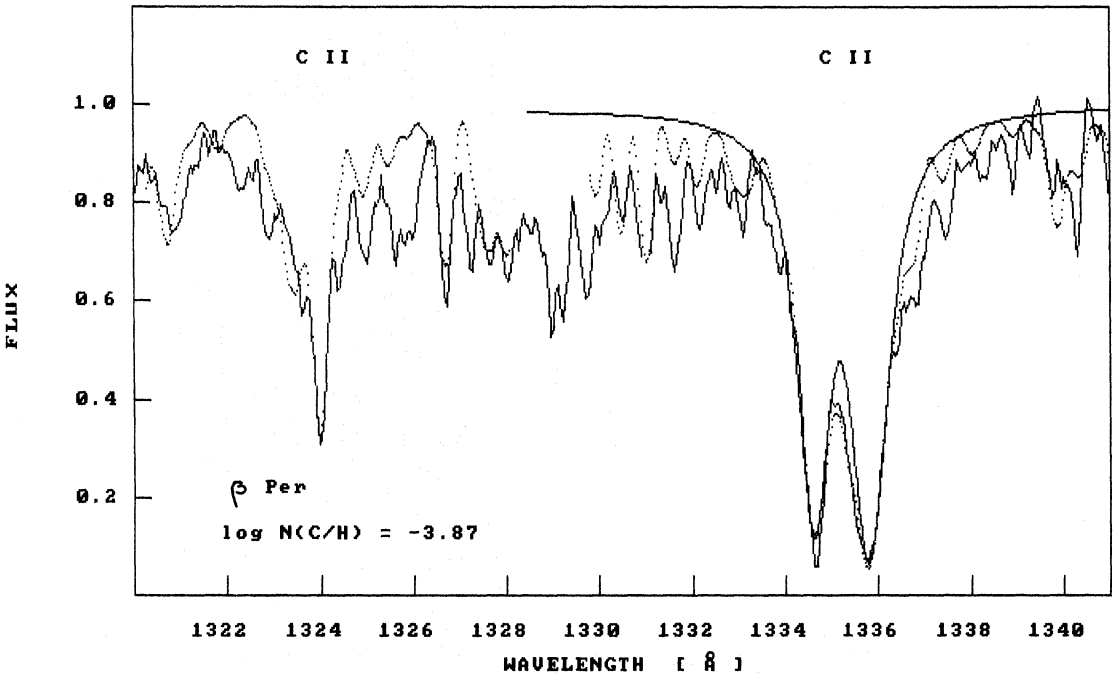

Fig. 3. Comparison of the calculated spectra with IUE observations of β Per. LTE synthetic spectra are shown as the dotted curves. Non-LTE line profiles of the C II 1335 resonance multiplet are indicated by means of the solid line

rather insensitive to T_{eff}, $\log g$ and microturbulent velocity, ξ: an increase of T_{eff} from 13000 K to 14000 K gives +4.5% in W_λ, which corresponds to $\Delta \log N(\text{C/H}) = +0.097$ dex.; a decrease of $\log g$ from 4.0 to 3.5 gives +5.7% in W_λ ($\Delta \log N(C/H) = +0.122$ dex.); an increase of ξ from 2 km s^{-1} to 4 km s^{-1} causes an effect of about +5.3% in W_λ.

LTE synthetic spectra near λ1324 Å were calculated as mentioned above in the case of the C II resonance lines. Unfortunately, an atomic model of carbon used in the non-LTE calculations presented in Paper I does not include the upper level ($2p^3\,{}^2D^0$) of the C II multiplet at 1324 Å. The lower level ($2s2p^2\,{}^2D$) of this line transition does not deviate markedly from LTE populations at the atmospheric layers where these lines originate (cf. Paper I). Therefore, the LTE calculations seem to be adequate for an analysis of the C II lines at 1324 Å. As we will see in Sects. 4.1–4.3, the good agreement between LTE line profiles and IUE observations supports this conclusion.

4.1. *β Per*

The calculated spectra are shown in Fig. 3 in comparison with the mean spectrum of β Per. We obtained $\log N(\text{C/H}) = -3.98 \pm 0.15$ from the C II resonance lines at 1335 Å under the LTE assumption, whereas non-LTE calculations gave -3.87 ± 0.20. The accuracy of the carbon abundance determination was estimated by taking into account uncertainties in the following data: $\Delta T_{\text{eff}} = \pm 1000$ K, $\Delta \log g = \pm 0.25$, $\Delta\xi = \pm 2$ km s^{-1}, the error in damping constants of the Stark broadening equal to 30% and the error in the continuum level equal to 5%. Kurucz's (1979) model atmosphere with $T_{\text{eff}} = 13000$ K and $\log g = 4.0$ was used in the LTE case, whereas Borsenberger and Gros (1978) model with the same parameters was adopted in the non-LTE calculations. As one can see from Fig. 3, the C II lines at 1324 Å calculated with $\log N(\text{C/H}) = -3.87$ are also in good agreement with the observations. However, these line profiles are not very sensitive to the abundance of carbon: an increase of $\log N(\text{C/H})$ by 0.30 dex. gives +14% in W_λ. The accuracy of the carbon abundance determination from the C II lines at 1324 Å (±0.36 dex.) is therefore markedly affected by an error in the continuum level. For instance, an increase of the continuum level by 5% causes an increase in $\log N(\text{C/H})$ by about 0.3 dex. The lack of a complete list of spectral lines is the major source of the discrepancy between the synthetic and observed spectra (cf. also Paper I).

4.2. *λ Tau*

The observed C II lines at 1324 and 1335 Å of λ Tau (mean spectrum, cf. Sect. 3) are shown in Fig. 4 together with calculated spectra. Kurucz's (1979) model atmosphere with $T_{\text{eff}} = 18000$ K and $\log g = 3.5$ was used in the LTE calculations, whereas Mihalas (1972) model with $T_{\text{eff}} = 17500$ K and $\log g = 3.0$ was used in the non-LTE case. From the C II resonance lines we obtained $\log N(\text{C/H}) = -4.09 \pm 0.15$ (LTE) and -3.92 ± 0.20 (non-LTE). Similar calculations were performed using Mihalas' (1972) model atmosphere of $T_{\text{eff}} = 17500$ K and $\log g = 4.0$. The final non-LTE carbon abundance determination shown in Table 3 was interpolated to $\log g = 3.38$ of λ Tau. The LTE synthetic spectrum near 1324 Å, shown in Fig. 4, was calculated with Kurucz's (1979) model atmosphere of $T_{\text{eff}} = 18000$ K, $\log g = 3.5$ and $\log N(\text{C/H}) = -3.88$.

4.3. *Comparison stars*

As mentioned in Sect. 2, the C II resonance lines at 1335 Å of ι Her were already analysed in Paper I. We found $\log N(\text{C/H}) = -3.65 \pm 0.15$ and -3.54 ± 0.20 under the assumption of LTE and non-LTE, respectively. The C II lines at 1324 Å of ι Her are shown in Fig. 5, where the LTE synthetic spectrum

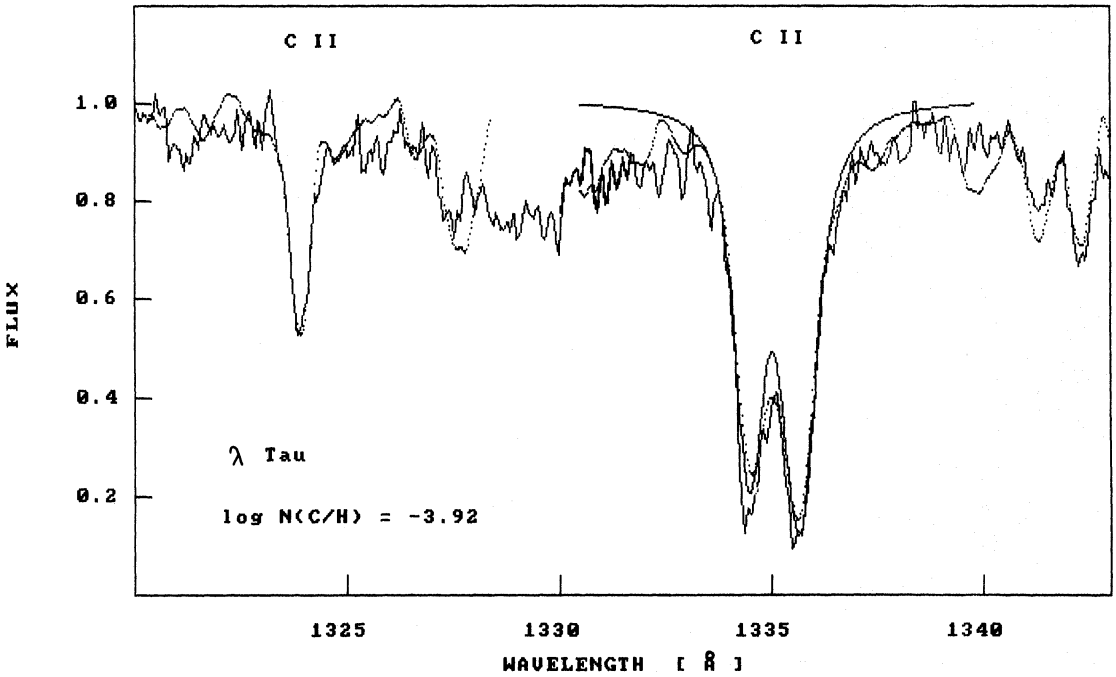

Fig. 4. Comparison of the calculated spectra with IUE observation of λ Tau. LTE synthetic spectra are shown as the dotted curves. Non-LTE line profiles of the C II 1335 resonance multiplet are indicated by means of the solid line

Table 3. The derived carbon abundance

Star	$T_{\rm eff}$	Log g	Log N(C/H)	
			LTE	Non-LTE
β Per	13000 K	4.02	-3.98 ± 0.15	-3.87 ± 0.20
λ Tau	18000 K	3.38	-4.09 ± 0.15	-3.88 ± 0.20
21 Aql	13100 K	3.80	-3.55 ± 0.15	-3.43 ± 0.20

calculated with $\log N(\rm C/H) = -3.54$ is compared with observations. For this purpose Kurucz's (1979) model atmosphere with $T_{\rm eff} = 18000$ K and $\log g = 3.5$ was used.

From the C II resonance lines of 21 Aql, we obtained $\log N(\rm C/H) = -3.55$ in the LTE case and -3.43 in the non-LTE case. We selected Kurucz's (1979) atmospheric model with $T_{\rm eff} = 13000$ K and $\log g = 4.0$ for the LTE analysis, whereas Borsenberger and Gros (1978) model was used in the non-LTE case. The C II multiplets at 1324 and 1335 Å of 21 Aql are shown in Fig. 6.

5. Results and discussion

In the present study, we have analysed the C II lines at 1335 and 1324 Å of two Algol-type stars, β Per and λ Tau, making use of the IUE images obtained in the high resolution mode. Our final carbon abundance determinations are shown in Table 3. The results may be compared with those of 21 Aql and ι Her or with a cosmic value $\log N(\rm C/H) = -3.48$ given by Allen (1973). This comparison indicates that both β Per and λ Tau are carbon depleted by about -0.40 ± 0.20 dex. Figures 1b and 2b show that the C II lines of β Per and λ Tau are indeed slightly weaker than those of 21 Aql and ι Her used as the comparison stars.

The observed slight under-abundances of carbon in β Per and λ Tau can be compared with theoretical predictions. As mentioned in Sect. 1, the region within which C is being reduced to an equilibrium value with respect to N expands outwards with time to greater mass fractions, however, it becomes essentially fixed at the moment when the central hydrogen content has dropped by about 15%, i.e., after 6 10^7 yr for a 3 $M_\odot$ star, cf. Iben (1965). This is caused by the envelope expansion and temperature decrease in the region above the convective core. Qualitatively, the same behaviour was found for all models of the main-sequence stars of 2.25 to 9 $M_\odot$ (cf. Iben 1966, 1967b). The very rapid fixation of the C-profile at almost constant mass fractions of the stars allows us to estimate the carbon abundance under the assumption of a simple loss of outer layers by the originally more massive stars. The present masses of the investigated Algols are well known (cf. Sect. 2) and $M_2^0 = (M_1 + M_2)/2$ corresponds to the minimum initial mass of the losers. This indicates that layers with $M_r < M_2/M_2^0$ are exposed now at the surface of the mass-losing components. We found $M_r < 0.36$ and 0.42 for β Per and λ Tau, respectively. Taking into account the above discussed C-profiles as a function of M_r, we obtained depletion of carbon by about 2.0 and about 1.1 dex. for β Per and λ Tau, respectively, much more than the observed 0.40 ± 0.20 dex. An increase of the initial mass does not remove this discrepancy for β Per. In the case of λ Tau, we would obtain an even larger discrepancy between the predicted and observed abundance of carbon if the initial mass was increased.

As mentioned above, we used the C profile found by Iben for massive stars. Recently, Cugier and De Greve (1987) verified this theoretical prediction using a stellar evolution program with more up-to-date physics. The results confirm the rapid fixation of the

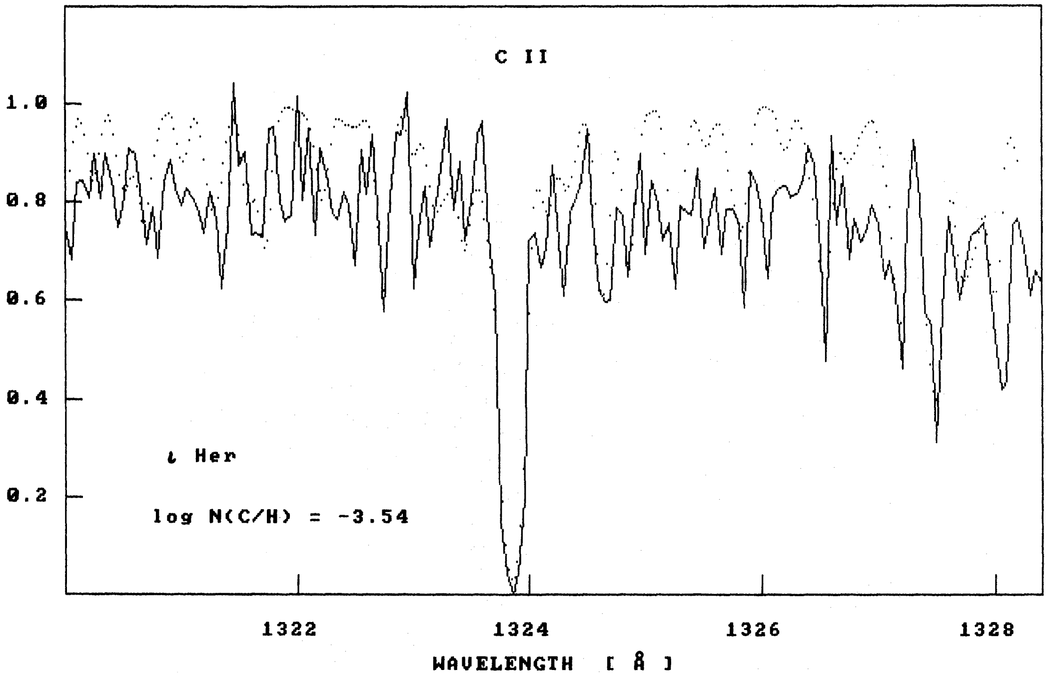

Fig. 5. Comparison of the calculated LTE synthetic spectrum (dots) near the C II 1324 multiplet with IUE observations of ι Her (solid line)

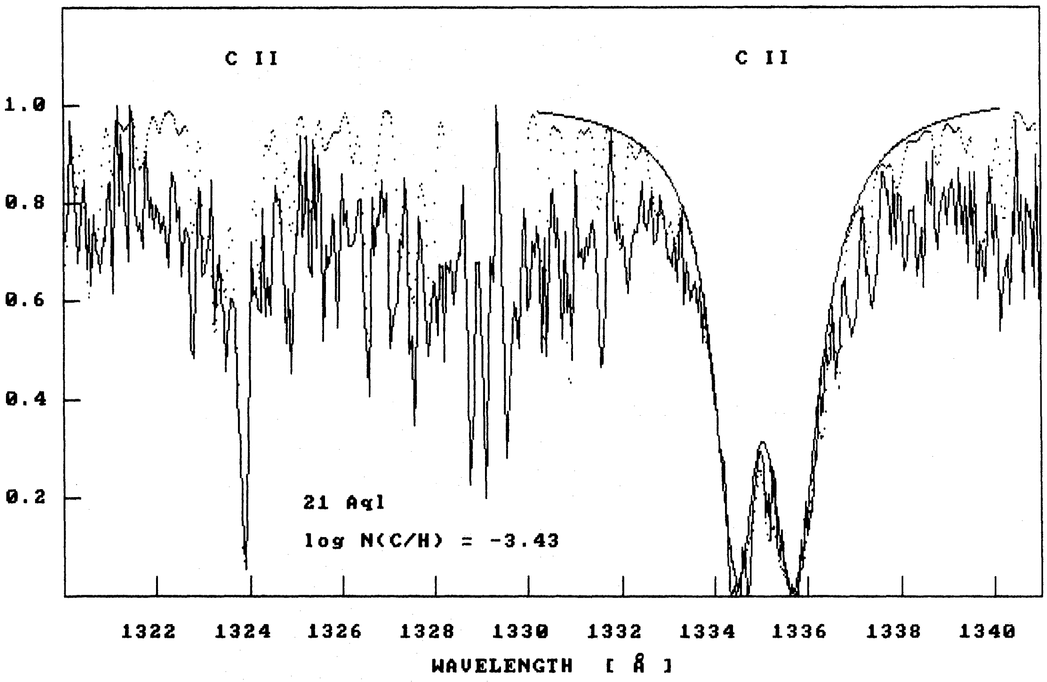

Fig. 6. Comparison of the calculated spectra with IUE observations of 21 Aql. LTE synthetic spectra are shown as the dotted curves. Non-LTE line profiles of the C II 1335 resonance multiplet are indicated by means of the solid line

C-profile at almost constant mass fractions in stars with masses corresponding to β Per and λ Tau.

Mixing in the outer convective zone may change to some degree the original C and N distributions of the mass-losing star when $T_{\rm eff}$ of this star has dropped below 7300 ± 500 K, which corresponds to spectral type F0 and $M = 1.5\,M_{\odot}$, cf. e.g. Clayton (1968). We estimated the mass fraction, $\Delta M_{\rm con}$, contained in the outer convective zone from Clayton's (1968) Fig. 6–11. The result is that $\Delta M_{\rm con}/M$ increases from about 0.01 to about 0.10 when $T_{\rm eff}$ drops from 6000 K to 5000 K. Detailed model calculations of the evolution of binary systems with mass exchange between components published by Ziolkowski (1970) indicate that this is a good approximation. Therefore, we conclude that convective mixing is unlikely to change markedly the original distribution of C and N in the mass-losing component of β Per. In the case of λ Tau, the mass losing component (an A III star) is too hot for a deep outer convective zone. The observed carbon depletion of Algols may therefore eequire another explanation.

In Paper I (cf. also Hardorp et al., 1986), we analysed the C II lines at 1335 Å of A0 V to B3 V stars. We found that the main sequence stars with low rotational velocities and not classified as chemically peculiar objects (Vega, π Cet, τ Her and ι Her) show essentially the cosmic abundance of carbon, whereas some stars with high rotational velocity show large depletion of carbon. The smallest carbon abundances we found for ψ^2 Aqr (B5 V, $V \sin i = 280\,\mathrm{km\,s^{-1}}$) and α Leo (B7 V, $V \sin i = 260\,\mathrm{km\,s^{-1}}$), viz., $\log N(\mathrm{C/H}) = -4.9 \pm 0.2$ and -4.32 ± 0.20, respectively. An interpretation of this effect as caused by mixing due to meridional circulations suggested in Paper I refers to the same CN part of the CNO tri-cycle of nucleosynthesis as in the case of Algols analysed in this paper. In both cases, we did not obtain a satisfactory explanation of all our observations using the standard models of 2.25 to 9 $M_\odot$ stars. Less efficient conversion of C to N above the convective core of massive stars would be in better agreement with the observed carbon abundances in both the Algol-type binaries and the main-sequence B-type stars with high rotational velocities discussed in Paper I.

Finally, there is a possibility that a large scale mixing of matter occurs in the primaries of β Per and λ Tau. In fact, mixing due to thermohaline convection was already suggested by Kippenhahn et al. (1980) in the case when an inversion of the mean molecular weight develops in mass accreting stars receiving helium-rich matter from the companion (cf. also Cugier and De Greve, 1987).

References

Adelman, S.J.: 1984, *Monthly Notices Roy. Astron. Soc.* **206**, 637

Allen, C.W.: 1973, *Astrophysical Quantities*, 3rd edn., The Athlone Press, London

Boggess et al.: 1978, *Nature* **275**, 7

Borsenberger, J., Gros, M.: 1978, *Astron. Astrophys. Suppl. Ser.* **31**, 291

Cester, B., Fedel, B., Giuricin, G., Mardirossian, F., Mezzetti, M.: 1978, *Astron. Astrophys.* **62**, 291

Clayton, D.D.: 1968, *Principles of Stellar Evolution and Nucleosynthesis*, McGraw-Hill, New York

Crawford, D.L.: 1973, in *Problems of Calibration of Absolute Magnitudes and Temperatures of Stars*, eds. B. Hauck, B.E. Westerlund, Reidel, Dordrecht, p. 93

Cugier, H., De Grève, J.P.: 1987, in *Atmospheric Diagnostics of Stellar Evolution: Chemical Peculiarity, Mass Loss, and Explosion*, ed. K. Nomoto, Springer, Berlin, Heidelberg, New York (in press)

Cugier, H., Molaro, P.: 1984, *Astron. Astrophys.* **140**, 105

Cugier, H., Hardorp, J.: 1988, *Astron. Astrophys.* **197**, 163 (Paper I)

De Grève, J.P.: 1986, *Space Sci. Rev.* **43**, 139

Eaton, J.A.: 1975, *Publ. Astron. Soc. Pacific* **87**, 745

Fekel, F.C., Tomkin, J.: 1982, *Astrophys. J.* **263**, 289

Griem, H.R.: 1974, *Spectral Line Broadening by Plasmas*, Academic Press, New York

Hardorp, J., Cugier, H., Koratkar, A., Scott, J.: 1986, in *Proc. New Insights in Astrophysics – 8 Year of UV Astronomy with IUE*, London, UK

Hoffleit, D.: 1982, *The Bright Star Catalogue*, 4th edn., Yale University Observ., New Haven, Connecticut, USA

Iben, I., Jr.: 1965, *Astrophys. J.* **142**, 1447

Iben, I., Jr.: 1966, *Astrophys. J.* **143**, 505

Iben, I., Jr.: 1967a, *Ann. Rev. Astron. Astrophys.* **5**, 571

Iben, I., Jr.: 1967b, *Astrophys. J.* **147**, 650

Kippenhahn, R., Ruschenplatt, G., Thomas, H.C.: 1980, *Astron. Astrophys.* **91**, 175

Kurucz, R.L.: 1979, *Astrophys. J. Suppl.* **40**, 1

Kurucz, R.L.: 1981, *Smithson. Astrophys. Obs. Spec. Rep. No.* 390

Kurucz, R.L., Peytremann, E.: 1975, *Smithson. Astrophys. Obs. Spec. Rep. No.* 362

Lambert, D.L.: 1982, in *Advances in Ultraviolet Astronomy*, eds. Y. Kondo, J.L. Mead, R.D. Chapman, (NASA Conf. Pub. 2238), p. 114

Lindemann, E., Hauck, B.: 1973, *Astron. Astrophys. Suppl.* **11**, 119

Mihalas, D.: 1972, NCAR Tech. Note, Boulder, NCAR-TN/STR-76

Moore, C.E.: 1970, *Selected Tables of Atomic Spectra*, NSRDS-NBS 3, Sect. 3

Nussbaumer, H., Storey, P.J.: 1981, *Astron. Astrophys.* **96**, 91

Olson, E.C.: 1975, *Astrophys. J. Suppl.* **29**, 43

Paczyński, B.: 1971, *Ann. Rev. Astron. Astrophys.* **9**, 183

Pathasarathy, M., Lambert, D.L., Tomkin, J.: 1983, *Monthly Notices Roy. Astron. Soc.* **203**, 1063

Polidan, R.S., Peters, G.J.: 1980, *IAU Symp.* **88**, 293

Relyea, L.J., Kurucz, R.L.: 1978, *Astrophys. J. Suppl.* **37**, 45

Ruciński, S.M.: 1979, *Acta Astron.* **29**, 339

Sahal-Brechot, S., Serge, E.R.: 1971, *Astron. Astrophys.* **13**, 161

Tomkin, J., Lambert, D.L.: 1978, *Astrophys. J. Letters* **222,** L119

Wilson, R.E., De Luccia, M., Johnston, K., Mango, S.A.: 1972, *Astrophys. J.* **177**, 191

Ziółkowski, J.: 1970, *Acta Astron.* **20**, 213