

## CHEMICAL COMPOSITION OF THE RS CVn-TYPE STAR 33 PISCUM

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**Abstract.** Abundances of 22 chemical elements, including the key elements and isotopes such as  $^{12}\text{C}$ ,  $^{13}\text{C}$ , N and O, are investigated in the spectrum of 33 Psc, a single-lined RS CVn-type binary of low magnetic activity. The high resolution spectra were observed on the Nordic Optical Telescope and analyzed with the MARCS model atmospheres. The following main parameters have been determined:  $T_{\text{eff}} = 4750$  K,  $\log g = 2.8$ ,  $[\text{Fe}/\text{H}] = -0.09$ ,  $[\text{C}/\text{Fe}] = -0.04$ ,  $[\text{N}/\text{Fe}] = 0.23$ ,  $[\text{O}/\text{Fe}] = 0.05$ ,  $\text{C}/\text{N} = 2.14$ ,  $^{12}\text{C}/^{13}\text{C} = 30$ , which show the first-dredge-up mixing signatures and no extra-mixing.

**Key words:** stars: RS CVn binaries, abundances – stars: individual (33 Psc = HD 28))

### 1. INTRODUCTION

This is the third paper in a series dedicated to a detailed study of photospheric abundances in RS CVn stars (Tautvaišienė et al. 2010; Barisevičius et al. 2010, hereafter Papers I and II) with the main aim to get the carbon isotope  $^{12}\text{C}/^{13}\text{C}$  and C/N ratios in these chromospherically active stars. We plan to investigate correlations between the abundance alterations of chemical elements in the atmospheres of these stars and their physical macro parameters, such as the speed of rotation and the magnetic field.

Here we present results of the analysis of a bright K0 IIIb single-line binary 33 Psc (HD 28) of  $V = 4.78$  mag (van Leeuwen 2007). As a binary with an orbital period of  $P = 72.93$  days it was recognized by Harper (1926). The presence of the emission in its H and K lines of Ca II was detected spectroscopically by Young & Konigest (1977). From the analysis of intensity of the Ca II emission in the K line, Glebocki & Stawikowski (1979) concluded that the primary is of  $1.6 M_{\odot}$  and the secondary is of  $0.7 M_{\odot}$ . This evaluation was confirmed by Pourbaix & Boffin (2003) using the *Hipparcos* intermediate astrometric data: the mass of the primary was found to be  $1.7 \pm 0.4 M_{\odot}$  and of the secondary  $0.76 \pm 0.11 M_{\odot}$ . This system has not been resolved by speckle interferometry (Hartkopf et al. 2001).

From narrow-band photometry, Hansen & Kjaergaard (1971) and Gottlieb & Bell (1972) have determined that 33 Psc is slightly metal-deficient ( $[\text{Fe}/\text{H}] \approx -0.2$ ).

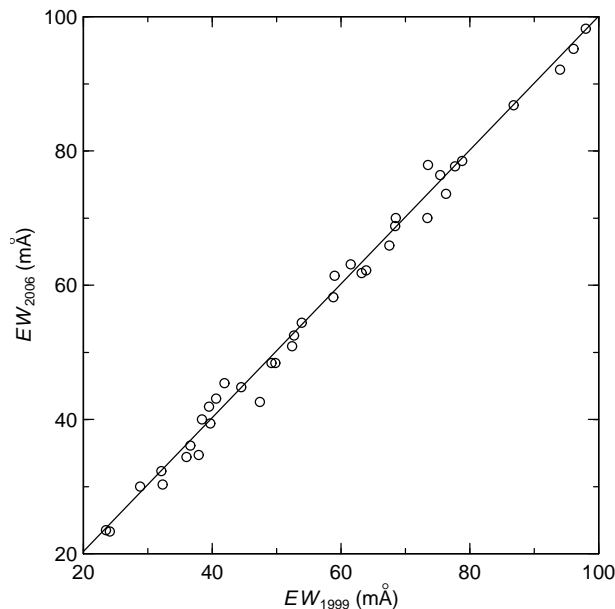
The high-resolution spectroscopic metallicity determinations of 33 Psc are slightly controversial: McWilliam (1990) has obtained  $[\text{Fe}/\text{H}] \approx -0.31$ , while the  $[\text{Fe}/\text{H}]$  values obtained by Randich et al. (1994) and Morel et al. (2004) are solar.

In papers I and II we investigated  $\lambda$  And and 29 Dra which are among most active RS CVn stars. 33 Psc by now has the lowest known magnetic activity among RS CVn stars (Strassmeier et al. 1988). Results of Einstein X-ray observations of 33 Psc were presented by Walter (1985). Its surface flux is  $< 5 \cdot 10^3 \text{ erg cm}^{-2} \text{ s}^{-1}$ , which is about a factor of three lower than the flux from the quiet solar corona, and is two orders of magnitude below the surface fluxes observed in the least-active long-period RS CVn systems. Drake et al. (1989) for 33 Psc have found quite low upper limit of the 6 cm radio flux, implying low activity as well. The ultraviolet chromospheric emission lines are also weak (Basri et al. 1985).

For  $\lambda$  And and 29 Dra the ratios of  $^{12}\text{C}/^{13}\text{C}$  were found to be lower than it is predicted by the first dredge-up theory of the first-ascent giants. Therefore it was interesting to check what are the effects of mixing processes in 33 Psc, which lies on the giant branch almost at the same luminosity but is much less active than  $\lambda$  And and 29 Dra.

## 2. OBSERVATIONS AND THE METHOD OF ANALYSIS

The spectrum of 33 Psc was observed twice – in August of 1999 and September of 2006 on the 2.56 m Nordic Optical Telescope using the SOFIN echelle spectrograph with the optical camera, which provided a spectral resolving power of  $R \approx 80\,000$ , for 26 slightly shifted spectral orders, each of  $\sim 4 \text{ nm}$ , in the spectral region from 500 to 830 nm. Details of spectral reductions and the method of analysis are presented in Paper I.



**Fig. 1.** A comparison of the equivalent widths measured in the 33 Psc spectra observed in 1999 and 2006.

**Table 1.** Equivalent widths of lines,  $EW$ , in the spectrum of 33 Psc.

Element	$\lambda$ (Å)	$EW$ (mÅ)	Element	$\lambda$ (Å)	$EW$ (mÅ)	Element	$\lambda$ (Å)	$EW$ (mÅ)
Si I	5517.55	23.4	Cr I	6274.66	74.0	Fe I	6392.54*	62.3
	5645.60	52.0		6285.16	83.1		6574.21*	93.1
	5793.08	56.0		6292.82	87.1		6581.21*	75.9
	5948.54	91.6		5712.78	49.9		6646.97	43.0
	6131.85	29.5		5783.87	76.6		6786.86*	48.8
7003.57*	51.7	5784.97	63.2	6793.27*	31.3	Ca I	6839.83	78.7
5260.38	66.9	5787.92	81.5	6842.69	60.4		6843.65	79.7
5867.57	53.1	6661.08	27.5	6851.64	33.3		6857.25	45.9
6455.60	94.5	6979.80	73.6	6858.15	71.6		6862.49	51.0
6798.47*	23.7	6980.91	27.0	7461.53*	71.7		7711.72*	43.7
Sc II	5526.81	106.2	Fe I	5395.22	42.3	Fe II	5132.68	33.5
	5667.14	67.5		5406.78	58.9		5264.81	47.0
	6279.75	61.2		5522.45	65.8		6113.33	16.0
	6300.69	22.6		5577.03	21.1		6369.46	23.6
	5648.58	44.7		5579.35	23.8		6456.39	55.2
5662.16	66.6	5607.67*	36.3	6456.39	55.2	Co I	5647.23	60.0
5716.45	33.7	5608.98*	29.4	6117.00	40.8		6117.00	40.8
5739.48*	39.6	5651.48	37.3	6188.98	58.0		6188.98	58.0
5880.27	58.0	5652.33	48.4	6455.00	44.4		6455.00	44.4
5899.30*	95.6	5653.86	57.6	6678.82	42.4		6678.82	42.4
5903.31*	44.7	5679.03	73.8	Ni I	5587.87*	98.1	5587.87*	98.1
5941.76	81.3	5720.90	33.1		5589.37*	45.0	5589.37*	45.0
5953.17	87.7	5732.30	23.9		5593.75*	63.1	5593.75*	63.1
5965.83	83.1	5738.24*	32.2		5643.09	30.3	5643.09	30.3
6064.63*	58.5	5741.86*	52.6		5748.35*	77.7	5748.35*	77.7
6098.66	25.3	5784.67	57.8	5805.22	58.8	5805.22	58.8	
6121.00	27.6	5793.92	56.9	6053.68*	36.3	6053.68*	36.3	
6126.22	83.8	5806.73	72.6	6111.08	54.9	6111.08	54.9	
6220.49*	40.7	5807.79	30.7	6128.98	73.8	6128.98	73.8	
6303.77	52.4	5811.92	27.1	6130.14	37.3	6130.14	37.3	
6599.11*	66.7	5814.82	45.7	6204.60	43.2	6204.60	43.2	
6861.45	41.9	6027.06	86.7	6378.25	51.4	6378.25	51.4	
V I	5604.96*	39.2	6034.04	21.1	6598.60*	41.8	6598.60*	41.8
	5646.11	42.7	6035.35	17.4	6635.13	44.9	6635.13	44.9
	5657.45	52.8	6054.07*	23.5	6767.78	132.3	6767.78	132.3
	5668.37	52.8	6056.01*	86.8	6772.32*	74.9	6772.32*	74.9
	5743.43*	60.2	6098.25	32.1	6842.03	51.6	6842.03	51.6
	6039.74*	69.2	6105.13	24.0	7001.55*	49.1	7001.55*	49.1
	6058.18*	35.2	6120.24	47.4	7062.97	57.9	7062.97	57.9
	6111.65	75.2	6187.99	75.6	7715.59*	78.7	7715.59*	78.7
	6119.53	82.9	6200.32	114.1				
	6135.37	69.8	6226.74*	54.2				
	6224.50*	68.6	6229.23*	75.7				
	6233.19*	62.5	6270.23	92.5				
	6266.30	47.9	6380.75	76.8				

\* The asterisk indicates the averaged equivalent widths from the spectra of 1999 and 2006, while other equivalent widths are only from the spectrum of 1999.

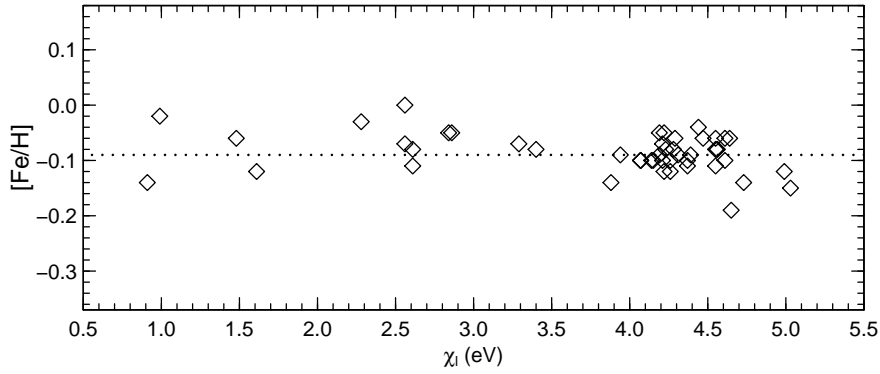
In the spectra we selected 135 atomic lines for the measurement of equivalent widths and 17 lines for the comparison with synthetic spectra. The measured equivalent widths of lines are presented in Table 1, in overlapping regions they show a very good agreement (see Figure 1) and were averaged.

### 2.1. Atmospheric parameters

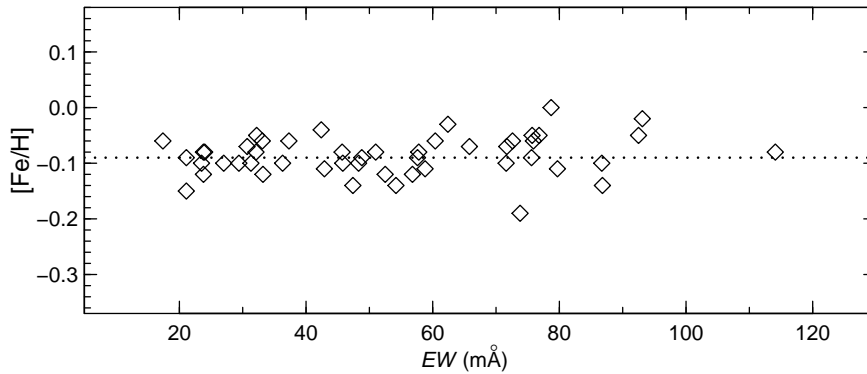
Initially, the effective temperature,  $T_{\text{eff}}$ , for 33 Psc was estimated and averaged from the intrinsic color indices  $(B - V)_0$  and  $(b - y)_0$ , using the calibrations by Alonso et al. (1999). The values of color indices,  $B - V = 1.06$  and  $b - y = 0.627$ , were taken from Reglero et al. (1987) and Hauck & Mermilliod (1998), respectively. A small dereddening correction of  $E_{B-V} = 0.01$ , estimated using the Hakkila et al. (1997) software, was taken into account.

The agreement between the temperatures deduced from the two color indices was quite good, with a difference of 80 K only. No obvious trend of the Fe I abundances with the excitation potential was found (Figure 2).

The surface gravity  $\log g$  was found by adjusting the model gravity to yield the same iron abundance from the Fe I and Fe II lines. The microturbulent velocity  $v_t$  corresponding to a minimal line-to-line Fe I abundance scattering was chosen as the correct value. Consequently,  $[\text{Fe}/\text{H}]$  values do not depend on the equivalent widths of lines (Figure 3).



**Fig. 2.** The  $[\text{Fe I}/\text{H}]$  abundance values versus the lower excitation potential  $\chi_1$ . The mean abundance ( $[\text{Fe I}/\text{H}] = -0.09$  dex) is shown as a dotted line.



**Fig. 3.** The  $[\text{Fe I}/\text{H}]$  abundance values versus the equivalent widths. The mean abundance ( $[\text{Fe I}/\text{H}] = -0.09$  dex) is shown as a dotted line.

## 2.2. Mass determination

The mass of 33 Psc was evaluated from its effective temperature, luminosity and the isochrones from Girardi et al. (2000). The luminosity  $\log(L/L_{\odot}) = 1.39$  was calculated from the *Hipparcos* parallax  $\pi = 25.32$  mas and  $V = 4.61$  mag (van Leeuwen 2007), the bolometric correction calculated according to Alonso et al. (1999), and the above mentioned  $E_{B-V} = 0.01$ . The mass of 33 Psc  $\sim 1.6 M_{\odot}$  was found.

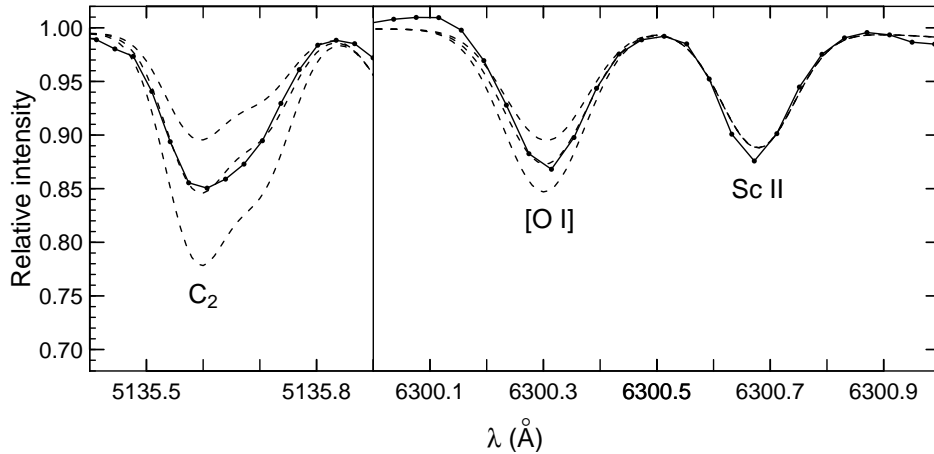
Previous mass determinations for 33 Psc are within  $1.1 M_{\odot}$  (Gottlieb & Bell 1972) and  $3.0 M_{\odot}$  (Barrado y Navascues et al. 1998). The masses  $1.6 M_{\odot}$  obtained by Glebocki & Stawikowski (1979) and  $1.7 M_{\odot}$  by Pourbaix & Boffin (2003) and Morel et al. (2004) are close to our result.

## 2.3. Spectrum syntheses

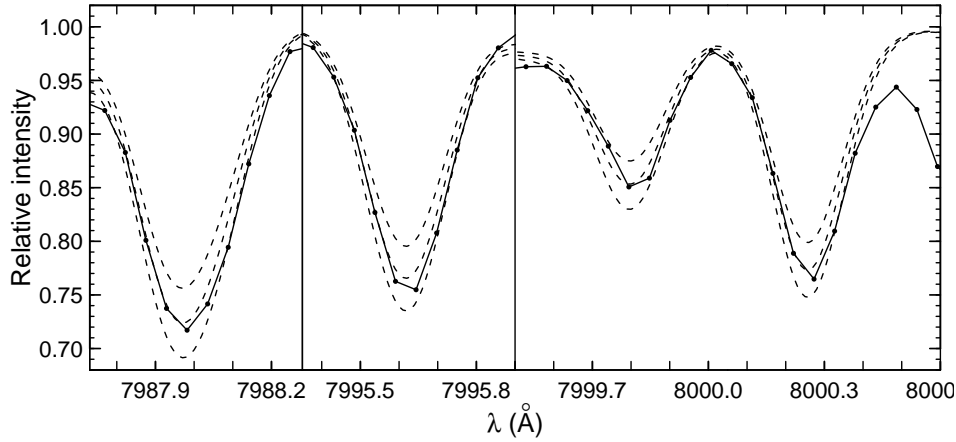
The method of synthetic spectra was used to determine carbon abundance from the  $C_2$  line at 5135.5 Å. The interval 7980–8130 Å, containing strong  $^{12}C^{14}N$  and  $^{13}C^{14}N$  features, was used for the nitrogen abundance and the  $^{12}C/^{13}C$  ratio determinations. The  $^{12}C/^{13}C$  ratio was determined from the (2,0)  $^{13}C^{12}N$  feature at 8004.7 Å. All  $\log gf$  values were calibrated to fit to the solar spectrum by Kurucz (2005) with solar abundances from Grevesse & Sauval (2000).

The oxygen abundance was determined from the forbidden [O I] line at 6300.31 Å with the oscillator strength values for  $^{58}Ni$  and  $^{60}Ni$  from Johansson et al. (2003) and the values  $\log gf = -9.917$  obtained by fitting to the solar spectrum (Kurucz 2005) and  $\log A_{\odot} = 8.83$  taken from Grevesse & Sauval (2000).

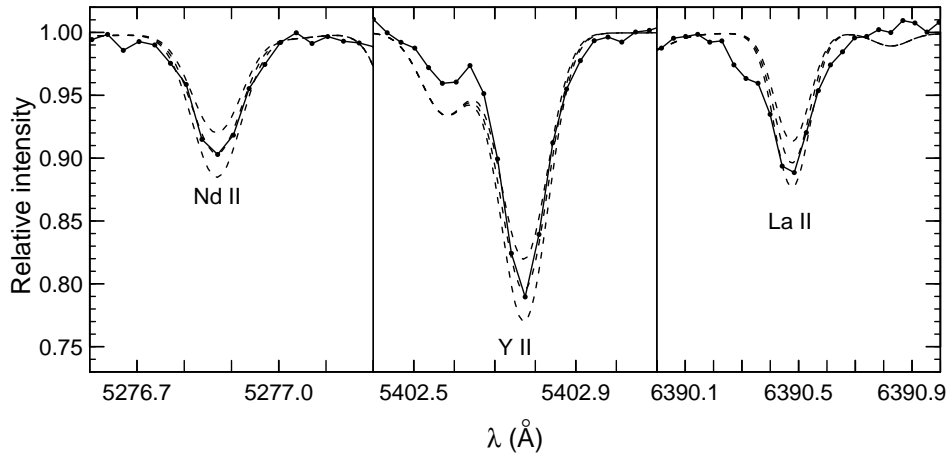
In Figures 4 and 5 we show several examples of synthetic spectra in the vicinity of  $C_2$ , [O I] and  $^{12}C^{14}N$  lines.



**Fig. 4.** Synthetic spectrum fits to the  $C_2$  line at 5135.5 Å and the forbidden [O I] line at 6300.3 Å. The observed spectra are shown as solid lines. The dashed lines are synthetic spectra with  $[C/Fe] = -0.03, 0.13$  and  $0.23$  dex and  $[O/Fe] = 0.03, 0.13$  and  $0.23$  dex.



**Fig. 5.** Synthetic spectrum fits to  $^{12}\text{CN}$  lines. The observed spectrum is shown as a solid line. The dashed lines are synthetic spectra with  $[\text{N}/\text{Fe}] = 0.13, 0.23$  and  $0.33$  dex.



**Fig. 6.** Synthetic spectrum fit to the Nd II line at  $5276.806 \text{ \AA}$ , Y II at  $5402.78 \text{ \AA}$  and La II at  $6390.48 \text{ \AA}$ . The observed spectrum is shown as a solid line. The dashed lines are synthetic spectra with  $[\text{Nd}/\text{Fe}] = 0.11, 0.21$  and  $0.31$  dex,  $[\text{Y}/\text{Fe}] = -0.07, 0.03$  and  $0.13$  dex and  $[\text{La}/\text{Fe}] = -0.07, 0.03$  and  $0.13$  dex for Nd II, Y II and La II lines, respectively.

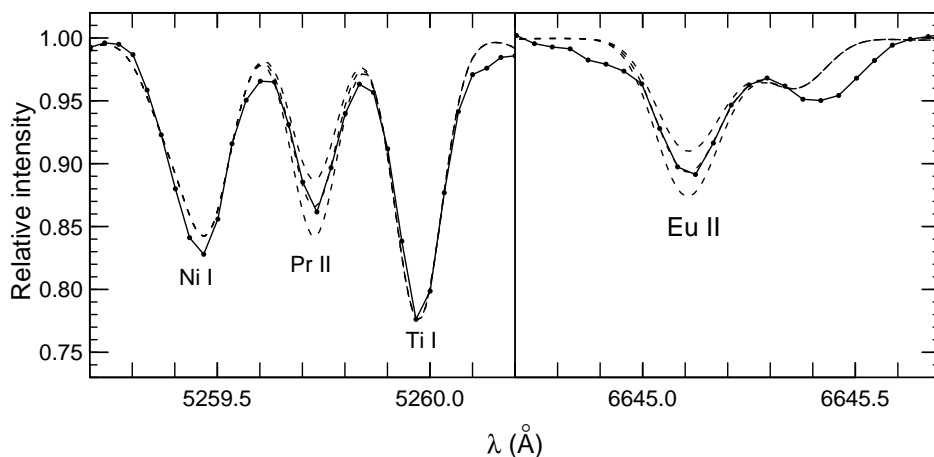
The abundance of Na I was estimated using the line at  $5148.84 \text{ \AA}$  which is slightly blended by the Ni I  $5148.66 \text{ \AA}$  line. These two lines are distinct in the Sun, so we were able to calibrate their  $\log gf$  values using the solar spectrum. So, the sodium abundance value in our study is affected by uncertainty of the nickel abundance determination by the Equivalent Widths method. Fortunately, the line-to-line scatter of  $[\text{Ni}/\text{H}]$  determination from 20 lines of Ni I was as small as 0.06 dex.

For the evaluation of Zr I abundance the lines at  $5385.13 \text{ \AA}$ ,  $6127.48 \text{ \AA}$  and  $6134.57 \text{ \AA}$  were used. Evaluation of the Y II abundance was based on the  $5402.78 \text{ \AA}$

line, La II on the 6390.48 Å line, Ce II on the 5274.22 Å and 6043.38 Å lines and Nd II on the 5276.86 Å line. The synthetic spectrum fits to the Nd II line at 5276.806 Å, Y II at 5402.78 Å and La II at 6390.48 Å are displayed in Figure 6.

The abundance of *r*-process element praseodymium was based on the Pr II line at 5259.72 Å and of europium on the Eu II line at 6645.10 Å (Figure 7). The hyperfine structure of Eu II was taken into account when calculating the synthetic spectrum. The wavelength, excitation energy and total  $\log gf = 0.12$  were taken from Lawler et al. (2001), the isotopic meteoritic fractions of  $^{151}\text{Eu}$ , 47.77%, and  $^{153}\text{Eu}$ , 52.23%, and isotopic shifts were taken from Biehl (1976).

Due to slow rotation spectral lines of 33 Psc are broadened very little. We used  $v \sin i = 1.9 \text{ km s}^{-1}$  from Batten et al. (1989), which fits well the profiles of spectral lines of 33 Psc.



**Fig. 7.** Synthetic spectrum fit to the Eu II line at 6645.10 Å. The observed spectrum is shown as a solid line. The dashed lines are synthetic spectra with  $[\text{Eu}/\text{Fe}] = 0.02$ , 0.12 and 0.22 dex.

#### 2.4. Estimation of uncertainties

The sources of uncertainty were described in detail in Paper I. The sensitivity of the abundance estimates to changes in the atmospheric parameters for the assumed errors ( $\pm 100 \text{ K}$  for  $T_{\text{eff}}$ ,  $\pm 0.3 \text{ dex}$  for  $\log g$  and  $\pm 0.3 \text{ km s}^{-1}$  for  $v_t$ ) is illustrated in Table 2. It is seen that possible parameter errors do not affect the abundances seriously; the element-to-iron ratios, which we use in our discussion, are even less sensitive.

The scatter of the deduced line abundances  $\sigma$ , presented in Table 3, gives an estimate of the uncertainty due to the random errors, e.g., in the continuum placement and the line parameters (the mean value of  $\sigma$  is 0.06 dex). Thus, the uncertainties in the derived abundances originating from the random errors are close to this value.

Since the abundances of C, N and O are bound together by the molecular equilibrium, we have also investigated how the error in one of them typically affects the abundance determination of others.

$$\Delta[\text{O}/\text{H}] = 0.10 \text{ causes } \Delta[\text{C}/\text{H}] = 0.04 \text{ and } \Delta[\text{N}/\text{H}] = 0.05; \Delta[\text{C}/\text{H}] = 0.10$$

causes  $\Delta[\text{N}/\text{H}] = -0.12$  and  $\Delta[\text{O}/\text{H}] = 0.02$ .  $\Delta[\text{N}/\text{H}] = 0.10$  has no effect on both carbon and oxygen abundances.

**Table 2.** Sensitivity of the abundances to changes of the atmospheric parameters. The table entries show the effects on the logarithmic abundance relative to hydrogen,  $\Delta[\text{El}/\text{H}]$ .

Ion	$\Delta T_{\text{eff}}$ +100 K	$\Delta \log g$ +0.3	$\Delta v_t$ +0.3 km s <sup>-1</sup>	Ion	$\Delta T_{\text{eff}}$ +100 K	$\Delta \log g$ +0.3	$\Delta v_t$ +0.3 km s <sup>-1</sup>
C(C <sub>2</sub> )	0.02	0.11	0.00	Fe II	-0.09	0.17	-0.06
N(CN)	0.05	0.13	0.00	Co I	0.05	0.06	-0.08
O([O I])	0.00	0.13	0.00	Ni I	0.01	0.06	-0.10
Na I	0.08	-0.01	0.00	Y II	0.00	0.11	-0.03
Si I	-0.04	0.06	-0.04	Zr I	0.20	-0.04	-0.01
Ca I	-0.09	-0.01	-0.08	La II	0.01	0.13	-0.01
Sc II	-0.02	0.12	-0.09	Ce II	0.00	0.08	0.00
Ti I	0.12	0.01	-0.08	Pr II	0.01	0.13	-0.01
V I	0.15	0.01	-0.10	Nd II	0.01	0.13	-0.01
Cr I	0.08	-0.01	-0.08	Eu II	-0.01	0.13	0.00
Fe I	0.04	0.04	-0.08				
C/N	-0.23	-0.10	0.10	<sup>12</sup> C/ <sup>13</sup> C	-2	1	-2

**Table 3.** Element abundances relative to hydrogen,  $[\text{El}/\text{H}]$ .  $\sigma$  is a standard deviation in the mean value due to the line-to-line scatter within the species.  $N$  is the number of lines used for the abundance determination.

Ion	$N$	$[\text{El}/\text{H}]$	$\sigma$	Ion	$N$	$[\text{El}/\text{H}]$	$\sigma$
C(C <sub>2</sub> )	1	-0.13	-	Fe II	6	-0.08	0.06
N(CN)*	4	0.14	0.02	Co I	5	0.05	0.07
O([O I])	1	0.04	-	Ni I*	20	0.00	0.06
Na I	1	-0.01	-	Y II	1	-0.06	-
Si I*	6	0.04	0.06	Zr I	3	-0.21	0.08
Ca I*	4	-0.02	0.07	La II*	1	-0.06	-
Sc II	4	0.13	0.08	Ce II	2	-0.12	0.07
Ti I*	18	-0.01	0.06	Pr II	1	-0.02	-
V I*	16	0.07	0.07	Nd II	1	0.12	-
Cr I	7	0.01	0.05	Eu II	1	0.03	-
Fe I*	49	-0.09	0.04				

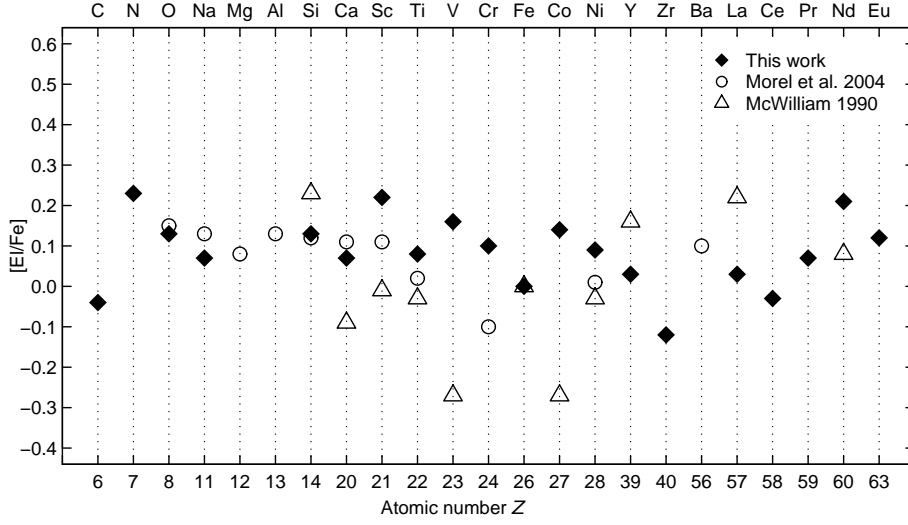
\* The asterisk indicates the elements, whose abundances were calculated from the 1999 and 2006 spectra, while the others were calculated only from the 1999 spectrum.

### 3. RESULTS AND DISCUSSION

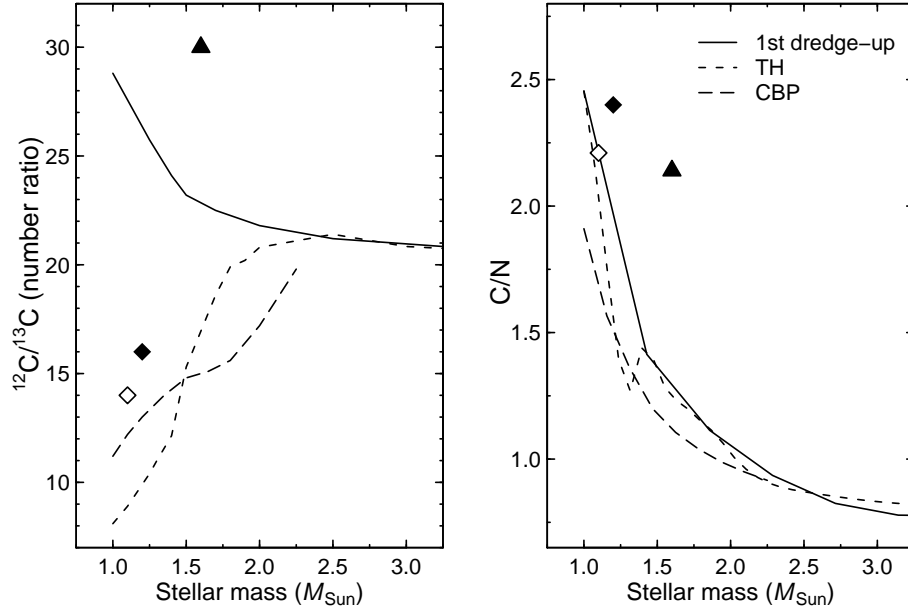
The following atmospheric parameters are obtained for 33 Psc:  $T_{\text{eff}} = 4750$  K,  $\log g = 2.8$ ,  $v_t = 1.1$  km s<sup>-1</sup>,  $[\text{Fe}/\text{H}] = -0.09$ ,  $[\text{C}/\text{Fe}] = -0.04$ ,  $[\text{N}/\text{Fe}] = 0.23$ ,  $[\text{O}/\text{Fe}] = 0.13$ , as well as the ratios  $\text{C}/\text{N} = 2.14$  and  $^{12}\text{C}/^{13}\text{C} = 30$ . The element abundances  $[\text{A}/\text{H}]$  and the  $\sigma$  values (the line-to-line scatter) are listed in Table 3.

In Figure 8 the obtained values of  $[\text{El}/\text{Fe}]$  for 33 Psc are compared with the results of other authors. Although McWilliam (1990) has used a high-resolution spectrum, his values of  $[\text{El}/\text{Fe}]$  are rather scattered, probably due to small number of lines measured. The recent results of Morel et al. (2004) are in good agreement with ours. The element to iron ratios in 33 Psc are close to solar.





**Fig. 8.** Element abundances for 33 Psc, as determined in this work (filled diamonds), by Morel et al. (2004, circles) and by McWilliam (1990, triangles).



**Fig. 9.** Comparisons of C/N and  $^{12}\text{C}/^{13}\text{C}$  ratios in 33 Psc (filled triangles),  $\lambda$  And (open diamonds, Paper I) and 29 Dra (filled diamonds, Paper II) with the theoretical predictions explained in the text.

The evolutionary sequences in the luminosity vs. effective temperature diagram by Girardi et al. (2000) show that 33 Psc with its luminosity  $\log(L/L_{\odot}) = 1.39$  is a first ascent giant lying slightly below the red giant sequence bump at  $\log(L/L_{\odot}) = 1.6$  (Charbonnel & Lagarde 2010). According to the mentioned model of mixing,

carbon and nitrogen abundances in 33 Psc should be altered only by the first dredge-up. Our results confirm this prediction. In Figure 9 we compare C/N and  $^{12}\text{C}/^{13}\text{C}$  ratios of 33 Psc with the theoretical models including extra-mixing. The model, called ‘cool bottom processing’ (CBP), was proposed by Boothroyd & Sackmann (1999) and the model, called ‘thermohaline mixing’ (TH), was proposed by Charbonnel & Lagarde (2010). The position of 33 Psc in Figure 9 indicates that its ratios of carbon isotopes and C/N have not been altered by extra mixing.

Two more active RS CVn stars  $\lambda$  And and 29 Dra, investigated by now in our program, gave a hint that extra-mixing processes may start acting in these low-mass chromospherically active fast rotating stars slightly earlier than at the bump of the red giant sequence in non-active stars. The star 33 Psc with negligible activity seems to be normal in this respect.

The abundance of lithium is also very sensitive to mixing. During the first dredge-up, for a star of the mass of 33 Psc, the Li abundance drops to approximately  $\log A(\text{Li}) = 1.44$  (Charbonnel & Lagarde 2010). However, the available determinations of Li abundance in 33 Psc show lower abundances: Brown et al. (1989) found  $\log A(\text{Li}) = 0.8$ , Pallavicini et al. (1992) and Randich et al. (1994) found  $\log A(\text{Li}) \leq 0.1$ , and Barrado y Navascues et al. (1998) found  $\log A(\text{Li}) = 0.41$ . These values are lower than predicted by the first dredge-up model, while the carbon and nitrogen abundances are in agreement with it. Thus, the lowered lithium abundance should be related to other mechanisms.

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