OPTICAL SPECTROSCOPY OF RU CAM, A PULSATING CARBON STAR

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Abstract. We analysed the high resolution spectra of a RU Cam, classified as W Vir type star. The atmospheric parameters of RU Cam were estimated T_{eff}=5250 K and $\log g$=1.0. The hydrogen deficiency of RU Cam was not confirmed. The iron abundance, [Fe/H]=-0.37, is close to the solar one. Abundances of most other elements are also close to normal. We found considerable excesses of carbon and nitrogen: [C/Fe]=+0.98, [N/Fe]=+0.60. The carbon to oxygen ratio is C/O>1. The carbon isotopic abundance ratio is equal to ^{12}C/^{13}C=4.5. For sodium a moderate overabundance Na/Fe=+0.55 was obtained. For two moments of observations we found close heliocentric velocity values, v_{r}=-21.7 ± 0.8 and -23.1 ± 1.0 km s^{-1}. Both spectra contain a peculiar feature – an emission component of Na I doublet which location agrees with the radial velocity from the bulk of metallic lines. For our two observing moments we found no dependence of radial velocities on the formation depth or on excitation energy for metallic lines.

Key words: stars: atmospheres – stars: carbon – stars: W Vir type – stars: individual: RU Cam

1. INTRODUCTION

RU Cam is a variable star of W Vir type (Harris, 1985) with a photometric period P $\approx 22.0^{\mathrm{d}}$ (Samus et al. 2004). Harris (1985) estimated the star's distances from the Sun and from the galactic plane as d=1.6 and z=0.7 kpc. These distances are based on photometric data and well agree with the value of the star's Hipparcos parallax π=0.59 mas. RU Cam has a rich history of photometric studies. Variability of its radiaton was found a century ago by Ceraski (1907). After that a lot of publications were devoted to studies of its peculiar photometric behavior since the star has variable pulsating magnitude and period. In 1965–1966 its irregular pulsation abruptly decreased in amplitude from 1 mag to about 0.1–0.2 mag (Demers &

Fernie 1967) and later exhibited a highly unstable and modulated light curve (Kollath & Szeidl 1993).

On the contrary to high photometric popularity, RU Cam has not been so popular for spectroscopists. Among the first few was Sanford (1928) who classified RU Cam as a carbon star. In the Catalogue of Carbon Stars by Stephenson (1973) the star has a number CGCS 6891. The estimated spectral types of RU Cam are R0, K0var, C0.1, and C3.2.e. Chemical composition of RU Cam was studied first by Faraggiana & Hack (1967). Based on high resolution spectra and using the curve-of-growth analysis, they concluded that the star's metallicity is close to normal. The carbon excess of the star was found to be not larger than 2–3, the abundances of Ca, Ti, V, Ni, and of rare earths are also sligthly overabundant relative to Fe. Somewhat later Wallerstein (1968) determined also the atmospheric parameters and reached similar conclusions about the metallicity of RU Cam. These results were obtained with photographic observations and with usage of curve-of-growth analysis. In order to use advantages of both modern spectroscopy and analytical possibilities, we undertook a new research of RU Cam spectra.

2. OBSERVATIONS

Our high resolution spectra were taken with the Nasmyth Echelle Spectrometer (Panchuk et al. 1999; Panchuk et al. 2002) of Russian 6 m telescope on Dec., 05 2006 (JD 2454074.6) and on Feb.,07 2007 (JD 2454138.5). The spectrograph was equipped with an image slicer (Panchuk et al. 2003). As a detector a CCD camera with 2052×2052 pixels produced by the Copenhagen University Observatory was used. The spectra for 2006 cover 516–669 nm without caps until 610 nm and the spectra for 2007 cover 452–602 nm without gaps.

The spectra were reduced using the NOAO astronomical data analysis facility IRAF. We describe the reduction procedure in Kipper & Klochkova (2005, 2006).

As measured from the Th-Ar comparison spectra the resolution is $R \approx 42\,800$ with FWHM of comparison lines about $7\,\mathrm{km\,s^{-1}}$.

3. ANALYSIS and RESULTS

3.1. Atmospheric parameters

We mentioned above that RU Cam has been found to be a Pop. II Cepheid. At the same time it is among the few which are carbon

stars. If we assume that RU Cam is a Pop. II cepheid one could derive from its light period of 22 days T_{eff}=5250 K, $\log g$=1.2, $M_V = -2.4$, and $M/M_{\odot} = 0.6$ (Hall, 2000). These parameters were confirmed by Bergeat et al. (2002), who found for RU Cam T_{eff}=5215 K, M_{bol}=-1.8 and pulsational mass M_{puls}=0.57 $M_{\odot}$. If we adopt $M/M_{\odot}$=0.6 the surface gravity with found M_{bol} and temperature will be $\log g$=1.44.

Kovtyukh et al. (1998) presented the calibrating relations between the spectral line depths and the excitation temperature for F–K supergiants. Using their relations for 15 pairs of lines we found T_{ex}=5227±216 K. According to these data the model (5250/1.5) from Kurucz's grid (Kurucz, 1993) was chosen as a starting model. The independence of abundances on excitation energy of the lines was confirmed for Fe I lines (Fig. 1, right panel). However, the ionization equilibrium of iron was not satisfied and the surface gravity was therefore reduced. As a result the final model (5250/1.0) was adopted. Also the microturbulent velocity using Fe I lines was chosen ξ_{t}=4.3 km s^{-1} (Fig. 1, left panel, illustrates a propriety of such a choise). Afterwards the other elements showed slightly different ξ_{t} giving the error of ξ_{t} about 0.5 km s^{-1}.
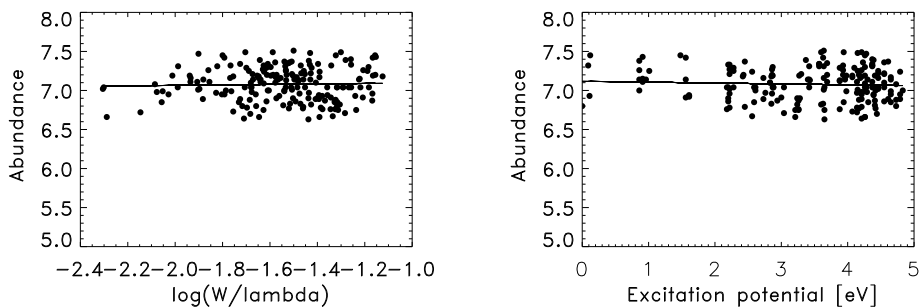
Fig. 1. The dependence of the iron abundance for Fe I lines on W_{λ}/λ (left), and on lower excitation potential (right). The microturbulent velocity is $\xi = 4.3$ km s^{-1}.

3.2. Chemical abundances

The abundances were found using the Kurucz's program WIDTH5. Oscillator strengts were taken from Thevenin (1989, 1990) except of those of C and O, which were taken from Wiese et al. (1996).

Table 1. The chemical composition of RU Cam. For comparison the abundances in V553 Cen (Wallerstein & Gonzalez, 1996) are given in the last column.

El.	$\log\varepsilon$ Sun[1]	$\log\varepsilon$ RU Cam	[El/Fe] RU Cam	Remarks	[El/Fe] V553 Cen
C	8.39	8.97 ± 0.35	0.98	8[2]C I, C_2 bands	0.88
N	7.78	8.00 ± 0.30	0.60	CN bands	1.15
O	8.66	8.45 ± 0.50	0.16	1 O I, 2 [O I]	0.40
Na	6.17	6.35 ± 0.17	0.55	5 Na I	0.43
Mg	7.53	7.25 ± 0.10	0.09	6 Mg I	0.06
Si	7.51	7.34 ± 0.21	0.20	16 Si I	0.17
Ca	6.31	5.94 ± 0.31	0.00	24 Ca I	0.20
Sc	3.05	2.71 ± 0.21	0.03	15 Sc II	0.14
Ti	4.90	4.58 ± 0.25	0.05	37 Ti I, 25 Ti II	0.05
V	4.00	3.82 ± 0.23	0.19	24 V I, 7 V II	-0.20
Cr	5.64	5.26 ± 0.32	-0.01	34 Cr I, 16 Cr II	-0.18
Fe	7.45	7.08 ± 0.22		191 Fe I,27 Fe II	
Co	4.92	4.79 ± 0.28	0.24	8 Co I	0.10
Ni	6.23	5.84 ± 0.26	-0.02	52 Ni I	-0.24
Cu	4.21	4.08 ± 0.06	0.24	2 Cu I	
Zn	4.60	4.02	-0.21	1 Zn I	
Y	2.21	1.95 ± 0.18	0.11	7 Y II	-0.22
Zr	2.59	2.27 ± 0.30	0.05	2 Zr I, 2 Zr II	
Ba	2.17	1.72 ± 0.08	-0.08	4 Ba II	0.19
La	1.13	0.79 ± 0.22	0.03	4 La II	-0.04
Ce	1.58	1.03 ± 0.33	-0.18	9 Ce II	-0.09
Pr	0.71	0.33 ± 0.07	-0.01	3 Pr II	
Nd	1.45	1.12 ± 0.16	0.04	14 Nd II	
Sm	1.01	0.82	0.18	1 Sm II	

[1] Asplund et al. (2005), relative to $\log\varepsilon(\mathrm{H})$,

[2] Number of used lines.

As follows from Table 1, the abundances determined for most chemical elements are close to the chemical composition of the Sun (Asplund et al., 2005). Metallicity of RU Cam is slightly decreased with [Fe/H]=-0.37. The result is consistent with the normal values of ratios [El/Fe] for a set of iron-group elements: Sc, Ti, V, Cr, Ni. We note that the metals with the high condensation temperature (Ca and Sc) also have the solar relative abundances: [Ca/Fe]=0.00 and [Sc/Fe]=0.03. This points on ineffectiveness of selective depletion processes by dust formation. That agrees with nondetection of dusty

IR–source associated with RU Cam.

At the same time we obtained the considerably modified content of CNO–triad: [C/Fe]= +0.98, [N/Fe]=+0.60 and the carbon to oxygen ratio C/O> 1. Overabundances of carbon and nitrogen mean that matter which had been mixed into outer atmospheric layers had been processed through He–burning. This points to an advanced evolutionary stage of RU Cam. The obtained abundances indicate that the matter in RU Cam suffered helium burning followed by CN cycling and mixing to the surface of the star. The carbon abundance found from the atomic carbon lines was confirmed by synthesizing the C_2 Swan bands $\log A(C) = 9.00 \pm 0.05$ and the nitrogen abundance was determined from the CN red system bands $\log A(N) = 8.00 \pm 0.30$. The Bell's (1976) line-list was used for spectrum synthesis. The carbon isotopic abundance ratio $^{12}C/^{13}C$=4.5±0.5 was determined using the C_2 Swan system (1,0) bands at 473.7 and 474.4 nm and (0,1) bands at 562.55 and 563.50 nm. At these wavelengths Bell's list does not give good wavelength match and therefore the list compiled by Alexander (1991) was used. Earlier determinations of the carbon isotopic ratio for RU Cam were by Climenhaga (1960), who found $^{12}C/^{13}C$=5.7 and Fraggania & Hack (1967) $^{12}C/^{13}C$=9.

In addition to CNO –excess, we obtained a moderate sodium overabundance, [Na/Fe]=+0.55 which could be expalined by activity of Ne–Na cycle. One could suspect that this Na-excess could be overestimated due to the non-LTE effects in the atmosphere of cool supergiant. But, according to Takeda et al. (2003), for the used lines the non-LTE effects are practically insignificant being less than -0.10 dex. For Na I D lines, however, these effects are very large amounting to –1.0 dex in the most worse cases. This is one of the reasons why Na I D lines are not suitable for abundance determinations. For the illustration these lines were synthesized taking into account the hyperfine structure of the lines (McWilliam et al. 1995). In Fig. 3 the results are plotted. The used abundance is by 0.9 dex larger than found from weaker lines.

Abundances of all heavy metals (Y, Zr, Ba, La, Ce, Pr, Nd, Sm) are not enhanced. Their relative contents are close to the solar ones. As a whole, the chemical composition of RU Cam is not coincident with the chemical abundances pattern typical for W Vir type stars in globular clusters. Atmospheres of these evolved stars are metal-poor and enriched by helium, carbon, and heavy metals of *s*–process (Gonzalez & Wallerstein, 1994). We have to note also that the chemical abundance pattern of RU Cam differs from the chemical composition of W Vir itself – the archetype of population II cepheids. According to Barker et

al. (1971) W Vir is a metal-poor star, its metallicity [Fe/H]=−1.1, its content of heavy metals is essentially decreased relative to metallicity: [Met/Fe]=−2.2.

Lloyd Evans (1983) selected a small group (7 stars) of pulsating stars having a carbon excess and called them carbon cepheids. These stars show strong absorbtion bands of C_2, CH, CN and the absence of any enhancement of the heavy metals produced in s–process. RU Cam was listed among these objects. Two of this group members V553 Cen and RT TrA were studied by Wallerstein & Gonzalez (1996) and Wallerstein et al. (2000). In order to compare the results we present in the last column of Table 1 the chemical abundances of V553 Cen obtained by these authors. The results for RT TrA are very close to that of V553 Cen. The comparison shows almost coinciding abundance pattern. The carbon isotopic abundance ratio for V553 Cen and RT TrA $^{12}C/^{13}C$=4.0–5.0 is also close to that of RU Cam. Both these stars have been associated with shorter period subclass of Pop. II cepheids BL Her. They are somewhat hotter and less luminous than RU Cam. At the moment no evolutionary sequences could predict their chemical composition.

3.3. Hydrogen deficiency

Bergeat et al. (2002) when deriving the parameters of RU Cam added a HdC label to it. However we found that the Hα and Hβ lines are quite normal for early K spectral type. We compare the profiles of the Hα and Hβ lines in RU Cam with those in Arcturus (K1.5III) spectrum (Fig. 2). On our request RU Cam was observed by K. Annuk on June, 06 2007 with the Tartu Observatory 60" telescope with resolution $R \approx 2500$ near the CH G-band near 430 nm. Comparison of this spectrum with the synthesized CH band spectrum gave satisfactory fit. For synthesizing we used the Bell's linelist, model (5250/1.0) and normal H content. We therefore judge that RU Cam is not hydrogen deficient. A similar result was obtained by Faraggiana & Hack (1967).

4. RADIAL VELOCITIES

In the following we call the spectra obtained on Dec., 05 2006 for shortness as SpI, and the ones obtained on Feb., 07 2007 as SpII. The corrections due to the solar motion we adopted for SpI is $+9.37\,\mathrm{km\,s^{-1}}$ and for SpII $-12.64\,\mathrm{km\,s^{-1}}$. To improve the accuracy we selected only weakly blended lines. For SpI we measured 158 lines and for SpII – 150 lines. All results concerning radial velocities
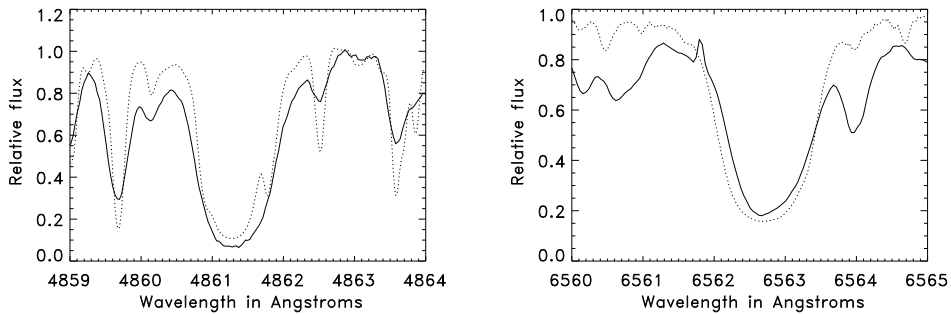
Fig. 2. The comparison of the Hβ and Hα lines in the spectra of RU Cam (solid line) and Arcturus.

are presented in Table 2. The average radial velocity obtained from metallic lines for SpI was $v_r = -21.7 \pm 0.8\,\mathrm{km\,s^{-1}}$ and $v_r = -23.1 \pm 1.0\,\mathrm{km\,s^{-1}}$ for SpII. The errors indicated are the weighted by the number of lines standard deviations of measurements for different metals. Coincidence of our two v_r values is explained by similar phase of our observations since the observing moments are separated by approximately 64 days what is close to 3P.

Our v_r values agree very well with the earlier published data. Wallerstein & Crampton (1967) found after RU Cam has ceased its light variations $v_r = -22.9 \pm 2.2\,\mathrm{km\,s^{-1}}$. Much earlier Sanford had (1928) found the velocity variation $v_r \approx -3 \div -37$ and the systemic velocity $-23.9\,\mathrm{km\,s^{-1}}$. Later Barnes et al. (1988) confirmed this interval of v_r variability.

If the radial velocity is completely caused by Galactic rotation at the distance of 1.7 kpc in direction of RU Cam it would be $-14\,\mathrm{km/s}$. Our measured velocity is reached at the distance of 2.7 kpc. This is also the upper limit posed by Wallerstein (1968). If the distance is so large the star's bolometric magnitude would be $M_b = -3.9$. This means that $\log g$ should be lowered 0.5 dex, which is not impossible considering our errors. This luminosity is already higher than the carbon stars formation limit by third dredgeup on TP-AGB. But this is not certainly true for V553 Cen and RT TrA. It is doubtful if the shorter and longer period carbon cepheids have different origins and exactly the same chemistry.

The Na I D lines in the RU Cam spectra have composite profiles. First, they show a two-components structure (Fig. 3). We propose that there are emission components close to the core of both D–lines. As follows from Table 2, location of Na I–emission to v_r practically

coincides with the average v_r value from numerous metallic lines. Secondly, the red wings of Na I profiles are slightly sharper than the blue ones. Earlier Faraggiana & Hack (1967) detected emission core in the H and K lines of Ca II. These authors believed that emissions are of chromospheric origin. Indeed, due to the star's location at fairly high galactic latitude, $l=+29^o$, its interstellar extinction does not exceed 0.01^m (Wamsteker, 1966). This means that we see Na I lines without interstellar components. This suggestion is confirmed by the comparison of the observed and theoretical spectra near the Na I doublet (Fig. 3). It is natural to suggest for a pulsating star that emission components of D–lines Na I indicate the presence of a shock wave in the stars atmosphere. But permanency of both intensity and location of emissions is doubtful in the framework of this proposal. In accordance with Faraggiana & Hack (1967), we are apt to think that a gaseous envelope reveals itself in the Na I emissions.
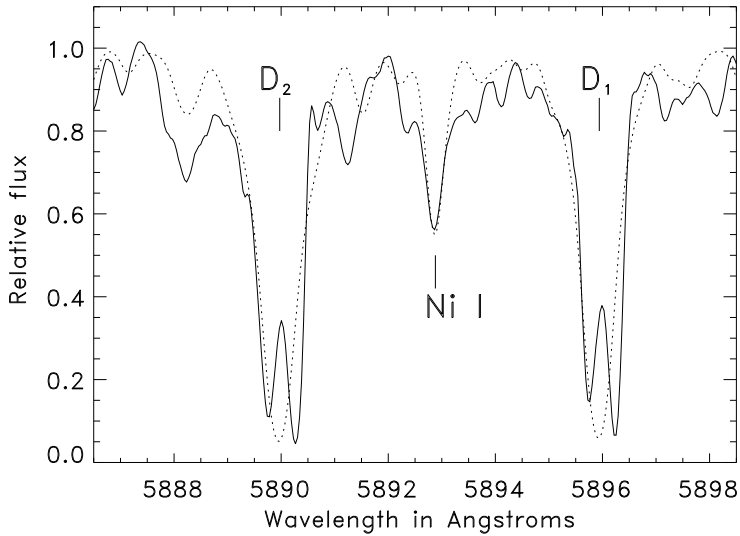
Fig. 3. The region of RU Cam spectrum near the Na I doublet (solid line) and LTE synthetic spectrum with the model (5250/1.0) and the sodium abundance $\log A(\mathrm{Na}) = 7.25$. The hyperfine splitting of Na I lines is taken into account.

Table 2. Radial velocities of RU Cam for two observing dates derived from various spectral features. For metallic lines the number of measured lines is indicated in parentheses.

Date	v_{r} [km s^{-1}]				
	Metals	Hα	Hβ	D$_2$(em)	D$_1$(em)
Dec., 05 2006	$-21.7 \pm 0.8(158)$	-20.6		-19.3	-18.1
Feb., 07 2007	$-23.1 \pm 1.0(150)$		-19.4	-19.4	-18.7

Faraggiana & Hack (1967) found an evidence of v_r stratification: spectral lines of different excitation give different v_r. Having numerous accurate v_r values, we check whether the radial velocities depend on excitation energy or the formation depth of the lines. For this aim we used Fe I, Fe II, Ti I and Ti II lines. As a result, for two moments of observations we found no dependence on formation depth as defined in Kurucz's program WIDTH5 or on excitation energy for these lines. As is evident in Fig. 2 the Hα profile is asymmetrical and if the blue wing is mirrored, then $v_{\mathrm{r}}=-24.9$ km s^{-1}. If the full line is fitted $v_{\mathrm{r}}=-20.6$ km s^{-1}. This asymmetry could well be caused by the emission in red wing. The Hβ line is more or less symmetrical and $v_{\mathrm{r}}=-19.4$ km s^{-1}. The metal lines are more blueshifted than the hydrogen lines, but taking into account the accuracy of v_{r} measurements, we may conclude that the position of both H I lines is consistent with the value of v_{r} derived from numerous metallic lines.

5. CONCLUSIONS

Based on the high resolution spectra of a carbon star RU Cam, we obtained its atmospheric parameters $T_{\mathrm{eff}}=5250$ K, $\log g=1.0$, $\xi_{\mathrm{t}} = 4.3 \pm 0.5$ km s^{-1}, and detailed chemical composition. As a result, the hydrogen deficiency of RU Cam was not confirmed. The iron abundance, [Fe/H]$=-0.37$, is close to the solar one. The abundances of most other elements are also close to normal. We obtained considerably altered abundances of carbon and nitrogen: [C/Fe]$=+0.98$, [N/Fe]$=+0.60$. The carbon to oxygen ratio is C/O> 1. The sodium overabundance, Na/Fe$=+0.55$, is real since the non-LTE effects for the studied Na I lines are small. As a whole the chemical composition of RU Cam is not coincident with the chemical abundances pattern typical for W Vir type stars.

The heliocentric velocity values $v_{\mathrm{r}}= -21.8 \pm 1.8$ and -23.2 km s^{-1} taken for 2 close photometric phases are coincident within the error box.

Both spectra of RU Cam contain a peculiar feature – an emission

component of NaI doublet whose location agrees with the radial velocity from the bulk of metallic lines.

As a whole, taking into account the position above galactic plane, the close to the solar metallicity of RU Cam, details of chemical composition and value of its systemic velocity $v_r = -24$ $^{-1}$, we may conclude that this far evolved star belongs to thick disc population of Galaxy.

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