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Parameters of the 41 Dra system components

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Abstract. Based on spectral and specle-interferometric observations of the system 41 Dra, model stmosphere parameters of the system components have been derived:
component Aa – $T_{eff}^{\mathrm{Aa}} = 6500°\mathrm{K}$, $\lg g_{\mathrm{Aa}} = 3.99$, $R_{\mathrm{Aa}} = 1.87 R_{\odot}$,
component Ab – $T_{eff}^{\mathrm{Ab}} = 6500°\mathrm{K}$, $\lg g_{\mathrm{Ab}} = 4.11$, $R_{\mathrm{Ab}} = 1.61 R_{\odot}$.

Key words: stars: binaries — binaries: fundamental parameters — binaries: individual: 41Dra

1. Introduction

The problem of the influence the dynamical interaction of the binary system components has on their evolution during the period before one of them fills its Roche lobe is poorly understood. This is caused by the comparatively small variations associated with dynamical interaction in isolated systems. The effects of orbit circularization, synchronization and desynchronization of rotation, conservation and loss of rotation moments are determined by both the fundamental parameters of the components and characteristics of the orbits, and by the structure of the components themselves. A direct conclusion as to the structure of the stars, distributiion of masses along the radius, differential rotation, etc can be drawn on the basis of a detailed analysis of evolutionary alterations of the orbits of the components. It seems probable that the study of binary stars with great orbit eccentricities, in which the dynamical interaction changes depending on the position of the components in orbit, can provide important information about the nature of evolutionary processes that are caused by the multiplicity of a star.

Among the multiple stars 41 Dra is an outstanding representative because of its great eccentricity. The system orbit has eccentricity $e = 0.9754$ which is the greatest of all the known eccentricities (Tokovinin, 1995). The orbit peculiarity has aroused considerable interest in studying this binary system. Besides, 41 Dra is a component of the visual binary ADS 11061 which is the fourth hierarchical system where the components A (41 Dra) and B (40 Dra) are spectral binaries with two systems of lines.

The speckle-interferometry technique is capable of resolving 41 Dra, which makes it possible to refine essentially the parameters of the orbit and system components. The orbital period of the spectral and speckle-interferometric binary 41 Dra is equal to 3.4147 years; the latest periastron transity was observed in 2001.

The masses of the components estimated from observations are strongly dependent on the orbit inclination angle; for $i = 50°$ $M_{\mathrm{Aa}} = 1.26 M_{\odot}$ and $M_{\mathrm{Ab}} = 1.18 M_{\odot}$ have been estimated (Balega et al., 1997a,b) with an accuracy of ±15%. The rifinement of the orbit elements from the latest observations (Tables 1, 2) yields $i = 42\overset{\circ}{.}2$. In this case the masses change substantially: $M_{\mathrm{Aa}} = 2.00 \pm 0.80 M_{\odot}$ and $M_{\mathrm{Ab}} = 1.90 \pm 0.80 M_{\odot}$. The discrepancies are due to the highly uncertain orbit inclination angle ($\pm 9\overset{\circ}{.}9$).

At the moment of periastron transit the separation of the components was but a few radii of the components. Far from the periastron, the effect the components have on each other is insignificant and must grow as the stars are approaching one another. Thus, one might expect effects of structural alterations of the components and of the system as a whole, accessible to observations, to appear as a result of the enhanced interaction between the components (change in the shape of the stars, exchange of moments, reflection effects, matter outflow, etc). In order to reveal these sporadic effects, it is desired to study the system parameters at different stages of orbital motion and at the moment of the periastron transit.

2. Observations

The orbit of the system 41 Dra and the moments of periastron transit were determined in a series of observations (Tokovinin, 1995; Balega et al., 1997a,b). Around the periastron transit in 2001, spectral and speckle-interferometric observations of the system were carried out at the Special Astrophysical Observatory. The data of the spectral observations made as the system was approaching the periastron are col-

Table 1: *Measurements of the system 41 Dra*

Date	Telescope	Spectrogr.	Number	Sp.range	R	S/N
10.11.2000	BTA		o01	4263-4425	15000	200
			o04	4748-4909	15000	400
			o05	4454-4616	15000	400
		MSS	o08	4454-4616	15000	200
13.11.2000	BTA		o01	4450-4616	15000	250
			o04	4550-4860	15000	350
			o05	4450-4616	15000	250
14.11.2000	Zeiss(1-m)	CEGS	Z3818	4120-9159	100000	200
			Z3819	4120-9159	100000	200
11.12.2000	BTA	NES	L01	4862-5720	40000	250
12.12.2000	BTA	MSS	O11	4451-4614	15000	250
12.01.2001	BTA		o0203	3993-4155	15000	150
			o0405	4262-4425	15000	150
			o0809	4774-4938	15000	400
07.02.2001	BTA	NES	L09	4686-5541	40000	250
08.02.2001	BTA		L14	4686-5541	40000	250

Table 2: *Luminosity difference between the components of 41 Dra*

λ, Å	Δm	Error	Date
5000	$0^{\mathrm{m}}.40$	$\pm 0^{\mathrm{m}}.04$	2001.2713
5450	$0^{\mathrm{m}}.48$	$\pm 0^{\mathrm{m}}.03$	1998.7769
6000	$0^{\mathrm{m}}.46$	$\pm 0^{\mathrm{m}}.05$	2001.2713
6500	$0^{\mathrm{m}}.38$	$\pm 0^{\mathrm{m}}.05$	1994.7129
7000	$0^{\mathrm{m}}.44$	$\pm 0^{\mathrm{m}}.10$	2001.2713
8500	$0^{\mathrm{m}}.41$	$\pm 0^{\mathrm{m}}.14$	2001.2713
12390	$0^{\mathrm{m}}.47$	$\pm 0^{\mathrm{m}}.20$	2000.7800
12390	$0^{\mathrm{m}}.55$	$\pm 0^{\mathrm{m}}.20$	2001.1920
16480	$0^{\mathrm{m}}.46$	$\pm 0^{\mathrm{m}}.20$	2000.7800
21910	$0^{\mathrm{m}}.47$	$\pm 0^{\mathrm{m}}.10$	1996.2667

lected in Table 1.

The processing of spectra was performed with the aid of the systems Dech20 (Galazutdinov, 1994) and MIDAS. Table 2 presents the speckle-interferometry data.

3. Parameters and model atmospheres of 41 Dra components

The average spectral class of the two 41 Dra components has been estimated to be from k2V (Turon et al., 1992) to F7V (Tokovinin, 1995; Balega et al., 1997a). The latter spectral class value is more trustworthy and yields an effective temperature close to $T_{eff} = 6200 - 6500$°K for 41 Dra (Straizis, 1982; Kopylov, 1958). The effective temperature value found from the colour indices ($\mathrm{B-V} = 0.50$, $\mathrm{U-B} = -0.01$) lies within the same limits, $T_{eff} = 6500$°K (Kopylov, 1985). The 41 Dra components have but little difference in their characteristic features, which makes it difficult to distinguish between the received radiations from the components and to determine the parameters of each of them. The estimates of the correlation profile width of the radial velocity measuring device (Tokovinin, 1995) lead to a luminosity difference between the components of the system $\Delta\mathrm{V} = 0^{\mathrm{m}}.83$ and to colour indices $(\mathrm{B-V})_{\mathrm{Aa}} = 0^{\mathrm{m}}.46$ and $(\mathrm{B-V})_{\mathrm{Ab}} = 0^{\mathrm{m}}.59$. These data suggest that the second component, having also a smaller mass, must be cooler than the first one. At the same time, the difference in brightness estimated directly from speckle-interferometric observations at different wavelengths (Balega et al., 1997a,b) with an accuracy of $0^{\mathrm{m}}.05$ yields an essentially smaller difference of the components (see Table 2).

The data of Table 2 show that the luminosity difference of the components at all wavelengths is the same within the measurement errors and is, on the average, $\Delta\mathrm{m} = 0^{\mathrm{m}}.426 \pm 0^{\mathrm{m}}.028$. The absence of significant variations of Δm with wavelength points out that the effective temperature of the surfaces of the components must be nearly the same.

Speckle-interferometric, spectral and astrometric observations allow the distance of 41 Dra to be reliably measured as equal to 43.5 ± 5.6 pc (Balega et al., 1997a), which yields for the luminosities of the components $L_{\mathrm{a}} = 5.60 \pm 2.10 L_\odot$ and $L_{\mathrm{b}} = 3.94 \pm 2.10 L_\odot$. The values of the luminosity and of the effective temperature which, in a first approximation, can be considered to be the same for both components, $T_{eff} = 6500$°K, permit the radii to be estimated:

$$\lg(R/R_\odot) = 0.5\lg(L/L_\odot) - 2\lg(T/T_\odot),$$

which yields $R_{\mathrm{Aa}} = 1.9 R_\odot$ and $R_{\mathrm{Ab}} = 1.6 R_\odot$.

Given the masses of the components and the radii, obtain the gravity acceleration at the surfaces of the stars:

$$\lg g = \lg(M/M_{\odot}) - 2\lg(R/R_{\odot}) + 4.43, \lg g_{\mathrm{Aa}} = 3.48, \lg g_{\mathrm{Ab}} = 4.11,$$

which, in conjunction with the effective temperatures, makes it possible to construct model atmospheres of the components.

The model atmospheres of the 41 Dra components were calculated by interpolation from T_{eff} and $\lg g$ using the grid of the Kurucz (1994) blanketed models for the solar chemical composition. Then, employing the programme Sam1 modified for the programme KONTUR (Leushin, Topilskaya, 1985), the energy distribution in the continuous spectrum H_{λ}^{a} and H_{λ}^{b} was computed. The theoretical distribution was compared with the observed distribution available in the catalogue of Kharitonov et al. (1988) (catalogue III/202 of Strasbourg Centre of Astronomical Data).

The distribution is presented in the catalogue in energy units at the boundary of the Earth's atmosphere. The energy flux from 41 Dra is created by the net luminosity of the components Aa and Ab located at a distance d from the Earth. So, we can write

$$E_{\lambda} \cdot d^2 = H_{\lambda}^{a} \cdot R_{\mathrm{Aa}}^2 + H_{\lambda}^{b} \cdot R_{\mathrm{Ab}}^2,$$

from which

$$E_{\lambda} = (R_{\mathrm{Aa}}^2/d)^2 (H_{\lambda}^{a} + H_{\lambda}^{b} \cdot (R_{\mathrm{Ab}}/R_{\mathrm{Aa}})^2),$$

where H_{λ}^{a} and H_{λ}^{b} are fluxes from a unit surface of the corresponding components. Using those expressions and the values of the theoretical fluxes, we computed a few variants of illuminations created by the components of 41 Dra at the boundary of the Earth's atmosphere. The observed radiation is in good agreement with that computed by the formula for E_{λ} for the components with the parameters $T_{eff}^{\mathrm{Aa}} = 6500°\mathrm{K}$, $T_{eff}^{\mathrm{Ab}} = 6500°\mathrm{K}$, $\lg g_{\mathrm{Aa}} = 3.48$, $\lg g_{\mathrm{Ab}} = 4.11$, $R_{\mathrm{Aa}} = 1.9R_{\odot}$ and $R_{\mathrm{Ab}} = 1.6R_{\odot}$ and $d = 43.5$ pc (Fig. 1). At the same time, a flatter slope of the observed Pashen and Balmer continua, as compared to the theoretical, requires lower temperatures of the components. However, the Balmer discontinuity value in the observed distribution is characteristic of temperatures higher than 6500°.

An attempt has been made to attain the best fit of the observed and theoretical energy distribution. We have computed several versions of net distributions produced by the two components with the parameters presented in Table 3, provided that the luminosity of the first and second components conserved: $L_{\mathrm{a}} = 5.60L_{\odot}$ and $L_{\mathrm{b}} = 3.94L_{\odot}$.

In Fig. 2 is shown a comparison of the observed and theoretical distributions for the components: Aa – $T_{eff}^{\mathrm{Aa}} = 6000°\mathrm{K}$, $\lg g_{\mathrm{Aa}} = 3.84$, $R_{\mathrm{Aa}} = 2.21R_{\odot}$, Ab – $T_{eff}^{\mathrm{Ab}} = 6000°\mathrm{K}$, $\lg g_{\mathrm{Ab}} = 3.97$, $R_{\mathrm{Ab}} = 1.84R_{\odot}$, here the fit is even better than for the higher temperature; however, both the Balmer jump and the profiles and hydrogen line intensities observed in the 41 Dra spectrum cannot be described by models with $T_{eff} < 6500°\mathrm{K}$.

The observed luminosity of the system can be represented well enough by the total theoretical luminosity of the components, if the following parameters are taken:
component Aa – $T_{eff}^{\mathrm{Aa}} = 6500°\mathrm{K}$, $\lg g_{\mathrm{Aa}} = 3.99 \div 4.19$, $R_{\mathrm{Aa}} = 1.87R_{\odot}$, $M_{\mathrm{Aa}} = 1.26 \div 2.00M_{\odot}$,
component Ab – $T_{eff}^{\mathrm{Ab}} = 6500°\mathrm{K}$, $\lg g_{\mathrm{Ab}} = 4.08 \div 4.11$, $R_{\mathrm{Ab}} = 1.57R_{\odot}$, $M_{\mathrm{Ab}} = 1.18 \div 1.90M_{\odot}$, with a system distance of 43.5 pc.

The correctness of the choice of parameters is confirmed also by speckle-interferometric measurements of the difference in luminosity of the components at different wavelengths. Table 4 presents the observed values of $\Delta \lg E_{\lambda} = \lg(E_{\lambda}^{\mathrm{a}}/E_{\lambda}^{\mathrm{b}})$ and the theoretical values of $\lg(E_{\lambda}^{\mathrm{a}}/E_{\lambda}^{\mathrm{b}})$ computed for the model atmospheres of the components at different wavelengths. The temperatures (equal for a and b) and the algorithms of acceleration of gravity (different for a and b) are indicated in brackets.

The temperatures and $\lg g$ of the components for the radii and masses from Table 3 are indicated in brackets in Table 4 for the theoretical models. Since the accuracy of differential speckle-interferometric measurements is considerably higher than that of the absolute flux measurements burdened, in addition, with inaccuracies of reduction for the atmosphere, it can be assumed that the second version of the theoretical calculations represent adequately enough the parameters of 41 Dra components. However, it should be noted that the precision of observations is insufficient to opt unambiguously for a model since the data over all the versions are consistent with observations within the errors.

At the same time we have to take account of the circumstance that the system 41 Dra may possess a number of peculiarities related to the peculiary elongated orbit. It is possible that there exists interstellar matter in the system which can transform the short-wave radiation into the long-wave radiation and lead to changes in the slope of the Balmer and Pashen continuum spectra. The Balmer jump in the observed spectrum is at a variance with the low temperature. The temperature from the jump must be higher than 6500° K. The value of the Balmer discontinuity is possibly related to the abrupt rise of interstellar matter absorption in the system for the radiation with $\lambda < 3647$ Å.

4. Hydrogen lines

Hydrogen lines are one of the most sensitive indicators of parameters of a normal star. The equivalent

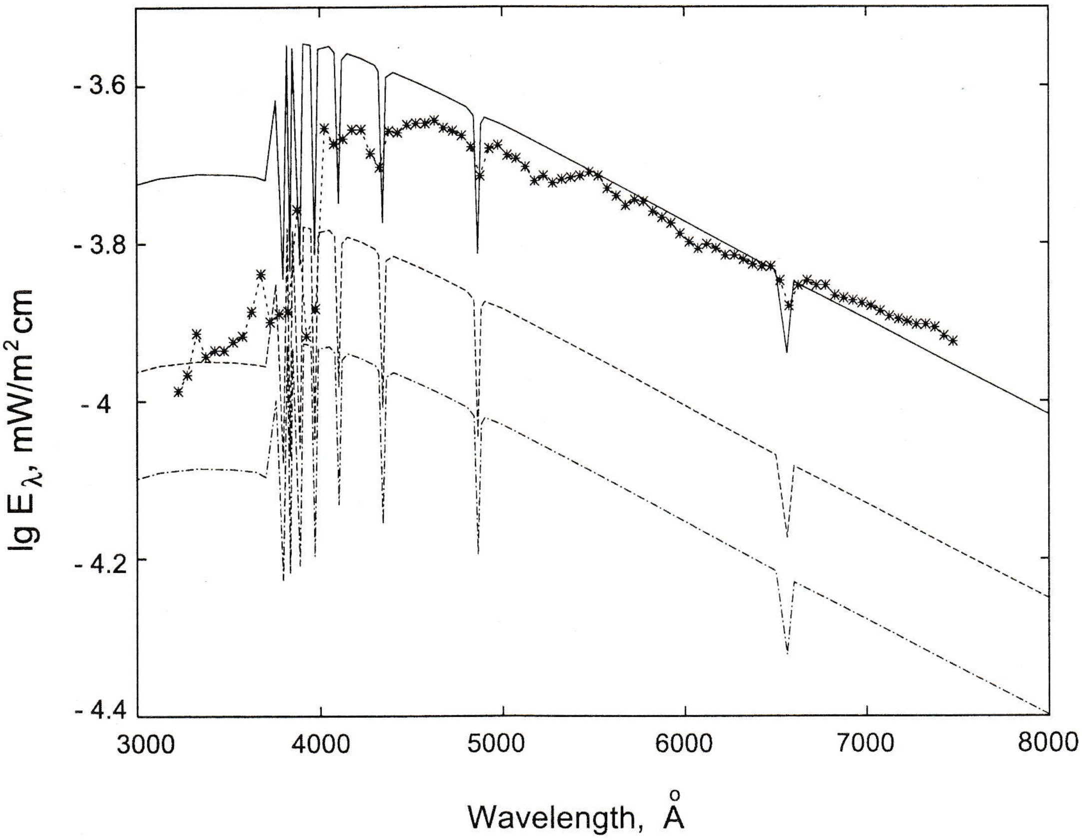

Figure 1: *The observed energy distribution in the continuous spectrum of 41 Dra (dots) at the level of the Earth's atmosphere* $\lg E_\lambda$ $(\mathrm{mW} \cdot \mathrm{m}^{-2} \cdot \mathrm{cm}^{-1})$ *vrs theoretical calculations. The solid line is the total radiation of the two components. Long dashes — component radiation with* $T_{eff} = 6500^\circ K$, $\lg g = 3.98$, $R = 1.90 R_\odot$. *Short dashes — component radiation with* $T_{eff} = 6500^\circ K$, $\lg g = 4.11$, $R = 1.60 R_\odot$. *A distance to the system is* $d = 43.5$ *pc.*

Table 3: *Atmosphere parameters of the components Aa and Ab*

T_{eff}^{Aa}	R_{Aa}	$\lg g_{\mathrm{Aa}}$		T_{eff}^{Ab}	R_{Ab}	$\lg g_{\mathrm{Ab}}$	
		$M/M_\odot$				$M/M_\odot$	
		1.26	2.00			1.18	1.90
6750	1.73	4.05	4.25	6750	1.46	4.18	4.38
6500	1.87	3.99	4.19	6500	1.57	4.11	4.32
6300	1.99	3.93	4.13	6300	1.67	4.05	4.26
6000	2.21	3.84	4.07	6000	1.84	3.97	4.21

widths and the profiles of hydrogen lines are crucially dependent on effective temperature and gravity acceleration variations on the star's surface. That is why, the determination of these parameters for most of the stars with the normal solar chemical composition is done on the basis of analysis of hydrogen lines. To determine the atmosphere parameters of the 41 Dra components, the lines H_α, H_β, H_γ and H_δ are used in the present paper. The study of the system linear spectrum is impeded by the fact that the 41 Dra com-

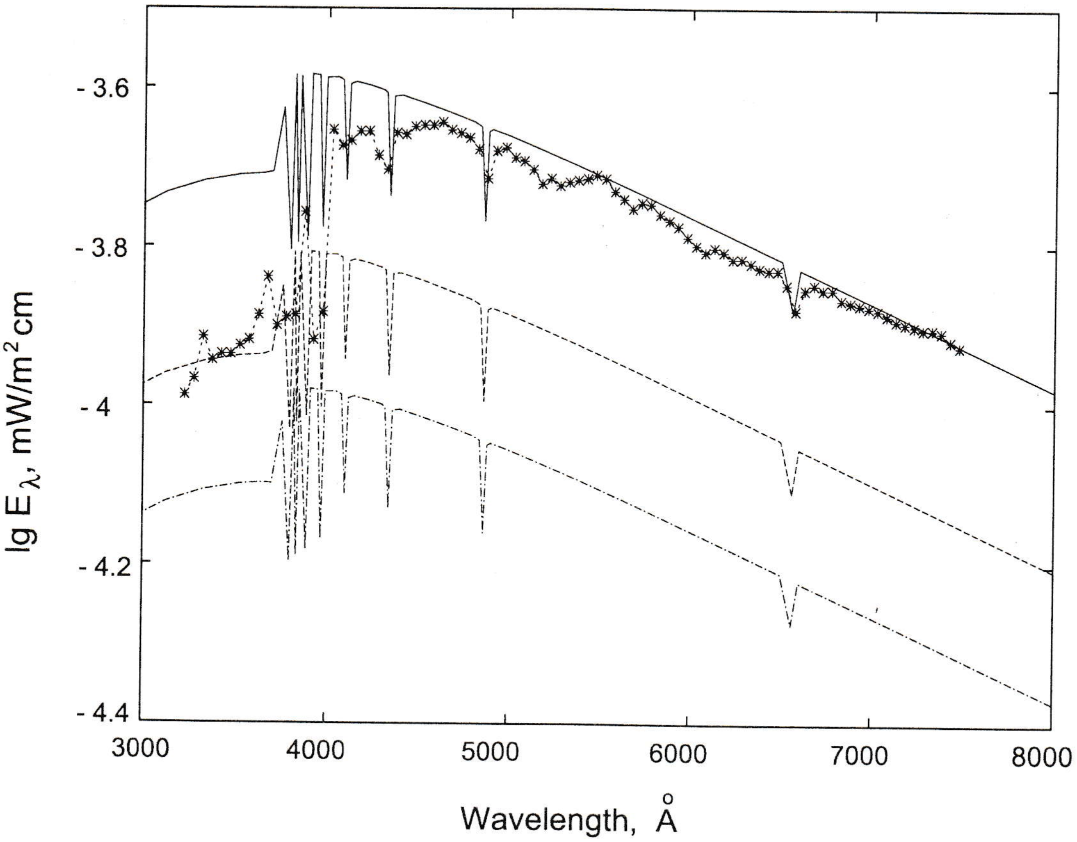

Figure 2: *The same as in Fig. 1. Long dashes — component radiation with* $T_{eff} = 6000°K$, $\lg g = 3.85$, $R = 2.19R_\odot$. *Short dashes — component radiation with* $T_{eff} = 6000°K$, $\lg g = 4.08$, $R = 1.61R_\odot$. *The distance to the system is* $d = 44.5\,pc$.

Table 4: *Luminosity difference* ($\Delta \lg E_\lambda$) *of the components observed in 41 Dra and theoretical difference for models with different parameters of the atmospheres of the components*

λ, Å	41 Dra	Model				
		(6500,3.99,4.11)	(6500,4.19,4.32)	(6300,3.93,4.05)	(6300,4.13,4.26)	(6000,3.84,3.97)
5000	0.160±0.016	0.148	0.174	0.154	0.171	0.150
5450	0.192±0.012	0.148	0.172	0.154	0.170	0.150
6000	0.184±0.020	0.147	0.170	0.153	0.168	0.151
6500	0.152±0.020	0.147	0.169	0.152	0.167	0.153
7000	0.176±0.040	0.147	0.159	0.157	0.166	0.153
8500	0.164±0.056	0.148	0.165	0.152	0.163	0.153
12390	0.204±0.080	0.150	0.161	0.152	0.163	0.155

ponents have nearly the same spectra. That is why, the contribution of one of the components to the net spectrum cannot be neglected even in a first approximation. At different moments of time the shifts of the summed-up spectra are different, which results from the orbital motion. This circumstance should also be taken into account in the analysis. Here we are studying the hydrogen lines from the spectra obtained in 2000 December, when the radial velocity difference of the components was 8–10 km/s, and in 2001 January-February, when this difference approached 18 km/s. The equivalent widths and the central depths of the hydrogen lines from the spectra mentioned are listed in Table 5.

Analogous values for the models with parameters close to the atmosphere parameters of the system components are collected in Table 6. The calculations were performed for the corresponding models by the programme BALMER with the parameters of hydrogen line broadening computed by Vidal et al. (1969).

Table 5: *Equivalent widths (W_λ, mÅ) and residual intensities (r_λ) in the centres of hydrogen lines in the spectra of 41 Dra*

Date	H_α		H_β		H_γ		H_δ	
	W_λ	r_λ	W_λ	r_λ	W_λ	r_λ	W_λ	r_λ
10.11.2000			5117.4	0.182	4931.2	0.175		
13.11.2000			5120.4	0.157				
14.11.2000	5065.4	0.180						
	5070.8	0.183						
12.01.2001			5050.6	0.149	5100.0	0.178	5122.0	0.236

Table 6: *Equivalent widths (W_λ, mÅ) and residual intensities (r_λ) in the centres of hydrogen lines for the model atmospheres with parameters close to those of the 41 Dra components*

T_{eff}°K	lg g	H_α		H_β		H_γ		H_δ	
		W_λ	r_λ	W_λ	r_λ	W_λ	r_λ	W_λ	r_λ
Aa									
6750	4.05	5426	0.255	6056	0.208	6240	0.178	6456	0.167
6500	3.98	4789	0.281	5179	0.204	5317	0.174	5519	0.165
6500	4.19	4915	0.282	5239	0.204	5309	0.175	5434	0.167
6300	3.93	4166	0.291	4369	0.208	4478	0.179	4616	0.172
6300	4.13	4242	0.293	4368	0.209	4428	0.257	4567	0.256
6000	3.85	3484	0.301	3541	0.210	3589	0.183	3705	0.179
Ab									
6750	4.18	5530	0.254	6109	0.209	6256	0.233	6475	0.226
6500	4.11	4848	0.283	5189	0.205	5289	0.175	5478	0.167
6500	4.32	4719	0.296	4964	0.212	5072	0.184	5233	0.177
6300	4.05	4169	0.294	4326	0.210	4417	0.182	4551	0.175
6300	4.26	4081	0.305	4172	0.218	4237	0.191	4373	0.186
6000	3.97	3408	0.309	3424	0.218	3483	0.191	3585	0.187
Aa+Ab									
6500	3.98	4768	0.340	5181	0.229	5260	0.206	5480	0.197
6500	4.11								
6500	4.19	4838	0.344	5135	0.233	5210	0.210	5425	0.203
6500	4.32								

Comparison of the observed line equivalent widths with theoretical calculations shows the parameters of the system components to be similar to those chosen from the energy distribution in the spectrum. We fail, however, to fit completely the observed hydrogen line profiles with the theoretical ones. The observed line equivalent widths may possibly be distorted by errors in plotting the continuous spectrum whose location on small portions of echelle spectra is found with an accuracy of 0.01–0.02, which can produce an error of ±1000 mÅ in the presence of extended to 5 Å wings of hydrogen lines. Comparison of the profiles can be made with higher confidence. Fig. 3 exhibits a comparison of the net spectra (Aa+Ab) with the observed contours. The summation of the profiles was done by the programme developed on our own, which allowed for the shift of spectra due to the difference in radial velocities and in luminosities of the components.

The theoretical profiles represent the observed ones with sufficient assurance everywhere but for the line centres (±0.1Å), which may be associated with taking inadequate account of absorption in the uppermost atmospheric layers.

5. Conclusions

The whole set of available observations of the binary system 41 Dra, having the lines of both components in the spectrum, is described by the following parameters:

component Aa – $T_{eff}^{\rm Aa} = 6500$°K, $\lg g_{\rm Aa} = 3.99$, $R_{\rm Aa} = 1.87 R_\odot$,

component Ab – $T_{eff}^{\rm Ab} = 6500$°K, $\lg g_{\rm Ab} = 4.11$, $R_{\rm Ab} = 1.61 R_\odot$.

Nevertheless, all the particularities of the radiation flux from the system cannot be explained within the stationary two-component pattern. First of all the uncertainties are connected with the discrepancies in

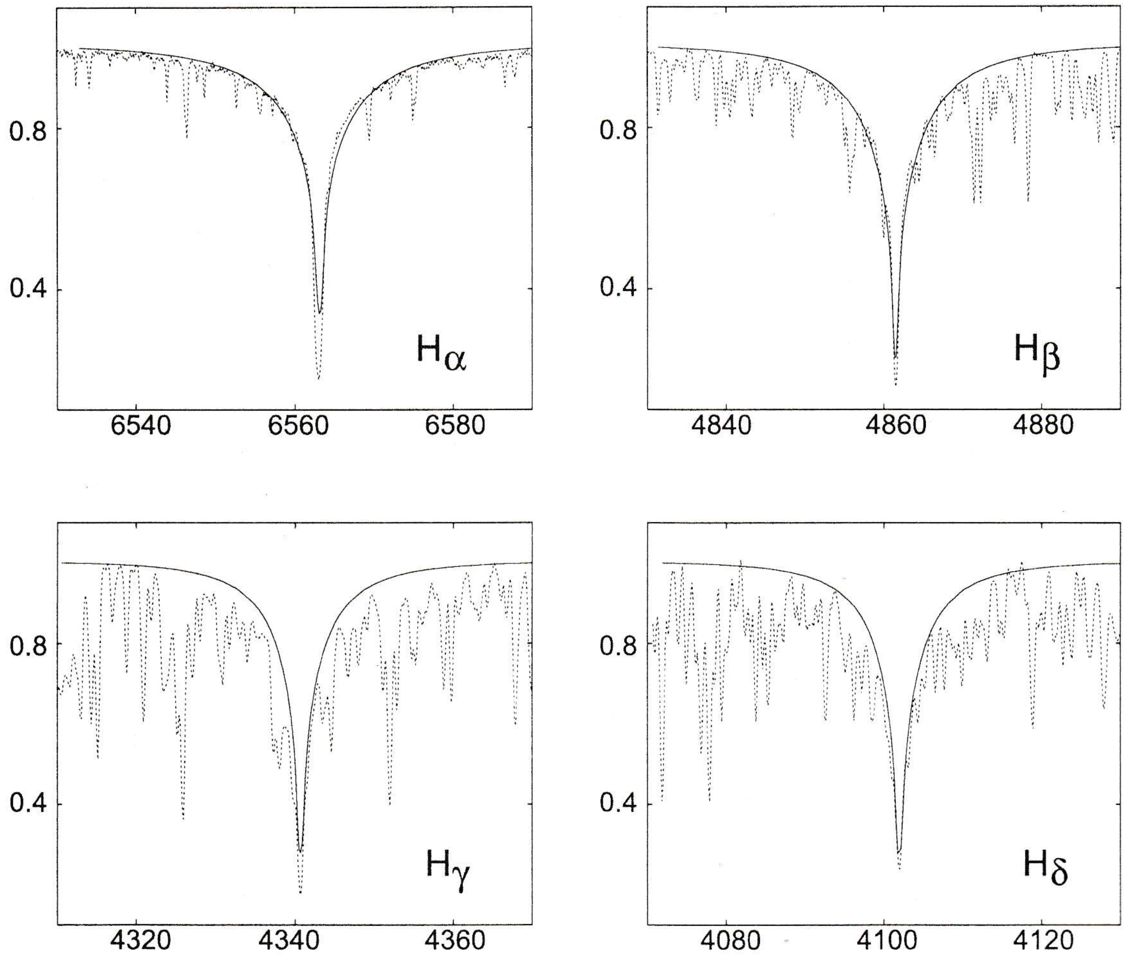

Figure 3: *The observed profiles (dashes) of hydrogen lines vrs the total theoretical profiles of the two components.* H_α *(14.11.2000 - Z3818)*, H_β *(10.11.2000 - o04)*, H_γ *(12.01.2001 - o0405)*, H_δ *(12.01.2001 -o0203). The theoretical profiles were calculated for the components with* $T_{eff} = 6500°K$, $\lg g = 3.98$, *and* $T_{eff} = 6500°K$, $\lg g = 4.11$. *The component luminosity ratio is* $L_{\rm b}/L_{\rm a} = 0.7$. *The difference of the component radial velocities for the spectra obtained in 2000 — 8 km/s, for those obtained in 2001 — 18 km/s.*

the hydrogen line intensities, profiles and energy distribution in the region 3700–8000 Å, from hydrogen lines the temperature must be above 6500° K, from the spectrum slope it must be lower. Besides, similar discrepancies exist also for the Balmer discontinuity the value of which is characteristic of effective temperatures higher than 6500° K, whereas the slopes of the Balmer and Pashen jumps demand lower temperatures. Possibly these discrepancies can be eliminated by adding absorbing and reemitting matter to the system. The problem of the variations related to the orbital motion, which must exist in 41 Dra, is to be solved. The suggestion made by Balega et al. (1997a) concerning the variations of luminosity difference between the system components from $0\overset{m}{.}2$ to $0\overset{m}{.}3$ at λ 6050 Å can serve as indirect evidence for their existence.

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