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Hα variability of the B-type binary χ Aurigae

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Abstract. We report several new radial velocities of the early-type spectroscopic binary χ Aur derived from photographic and RETICON spectrograms. Improved orbital elements are computed and a new orbital period P $\doteq$ 676 days of this system is derived. The secondary component lines are invisible in the spectrum of the system with the supergiant primary. Spectral type of the secondary component is discussed.

The description of the spectrum χ Aur in the wavelength range from 6300 to 6700 Å is presented. Hα emission and its variability was discovered and Hα profile behaviour is described and analyzed.

Key words: binaries: spectroscopic – stars: individual: χ Aur – supergiants

1. Introduction

The star χ Aurigae (HD 36371 = HR 1843 = SAO 58164 = GC 6849; $\alpha_{2000} = 5^h 32^{min} 44^s, \delta_{2000} = 32^0 11' 31''$) is a 5th magnitude spectroscopic binary with a slightly eccentric orbit. The primary was recognized as an early-type supergiant, its spectral type was derived by Lennon et al. (1993) B4 Iab or by Seitter (1970) B5 Iab. The secondary has not been seen in the spectrum of χ Aur yet.

χ Aur is a member of the association Aur OB1. Humpreys (1978) published these parameters of χ Aur: l = 175.8°, b = –0.6°, m_V = 4.76 mag, the distance d = 912 pc, $(B-V)$ = 0.32 mag, M_V = –6.4 mag (the value derived from the distance modulus of Aur OB1 is given M_V = –7.1 mag), A_V = 1.26 mag.

The binary character of χ Aur was announced by Frost and Adams (1903), who discovered it as a spectroscopic binary from 3 spectrograms. Young (1916) obtained 88 spectrograms in visual region during years 1913 to 1916 at DAO Ottawa and derived a period of the system and described its orbit by following orbital elements: P = 655.16 $\pm$ 5.26 days
T_0 = 2420629.78 $\pm$ 9.56 days
ω = 135.52° $\pm$ 5.2°
e = 0.171 $\pm$ 0.026
K = 20.53 $\pm$ 0.57 km/s
γ = -0.15 ± 0.35 km/s
$a_1 \sin i$ = 182.3 $\times$ 10^6 km = 261.9 $\mathscr{R}_\odot$
$\mathscr{F}(\mathscr{M})$= 0.56 $\mathscr{M}_\odot$
Later spectroscopic observations of χ Aur were made by Henroteau (1920) who obtained 8 photographic spectrograms. Radial velocities derived by Henroteau agreed well with the elements given by Young (1916).

The spectrum of χ Aur in the vicinity of Hα was observed by Rosendhal (1973) on Nov 16, 1970 who obtained one spectrogram in the red region. He published radial velocities and equivalent widths of the lines Hα, HeI 6678 Å, CII 6578,82 Å Å and SiII 6347,71 Å Å. Rosendhal (1973) announced that the Hα line had been slightly asymmetric, with the red wing being sharper than the blue one but no emission in Hα had been observed that time.

Equivalent widths of 37 lines in visual and red spectral region of χ Aur spectrum were published by Lennon et al. (1993).

2. New spectroscopic observations

New spectroscopic data were obtained at the Ondřejov and the Rožen observatories during periods 1980 to 1982 and 1994 to 1996. The Ondřejov spectrograms were taken with 2-m reflector in Coudé grating spectrograph with dispersions of 8.54 Å/mm and 16.98 Å/mm, the Rožen spectrogram was taken by similar instrument of the Rožen observatory in 1982 with dispersion of 9.01 Å/mm.

The first set consists of 9 photographic spectrograms - 8 Ondřejov spectrograms (O3732 to O4619) and one Rožen spectrogram (R1293), IIaO-H_2 plates were used. Radial velocities of the strong lines from these spectrograms were measured by M.W. using the Abbe comparator and Fortran programs HEC10 and SPEL. Average values of measured *RV* are collected in the Table 1 which lists the numbers of plates, heliocentric Julian date of observations HJD, the orbital phase based on new orbital elements written in the last column of the Table 5, average radial velocities RV_H of the hydrogen lines from H_γ to H12, RV_{He} of the 9 strong helium lines in the wavelength interval from 3819 to 4387 Å Å, the radial velocities RV_m of the metallic lines SiII 3856, 4128, 4130 Å Å, NII 3995 Å, CII 3920, 4267 Å Å and the RV_{Ca} of the interstellar lines of calcium.

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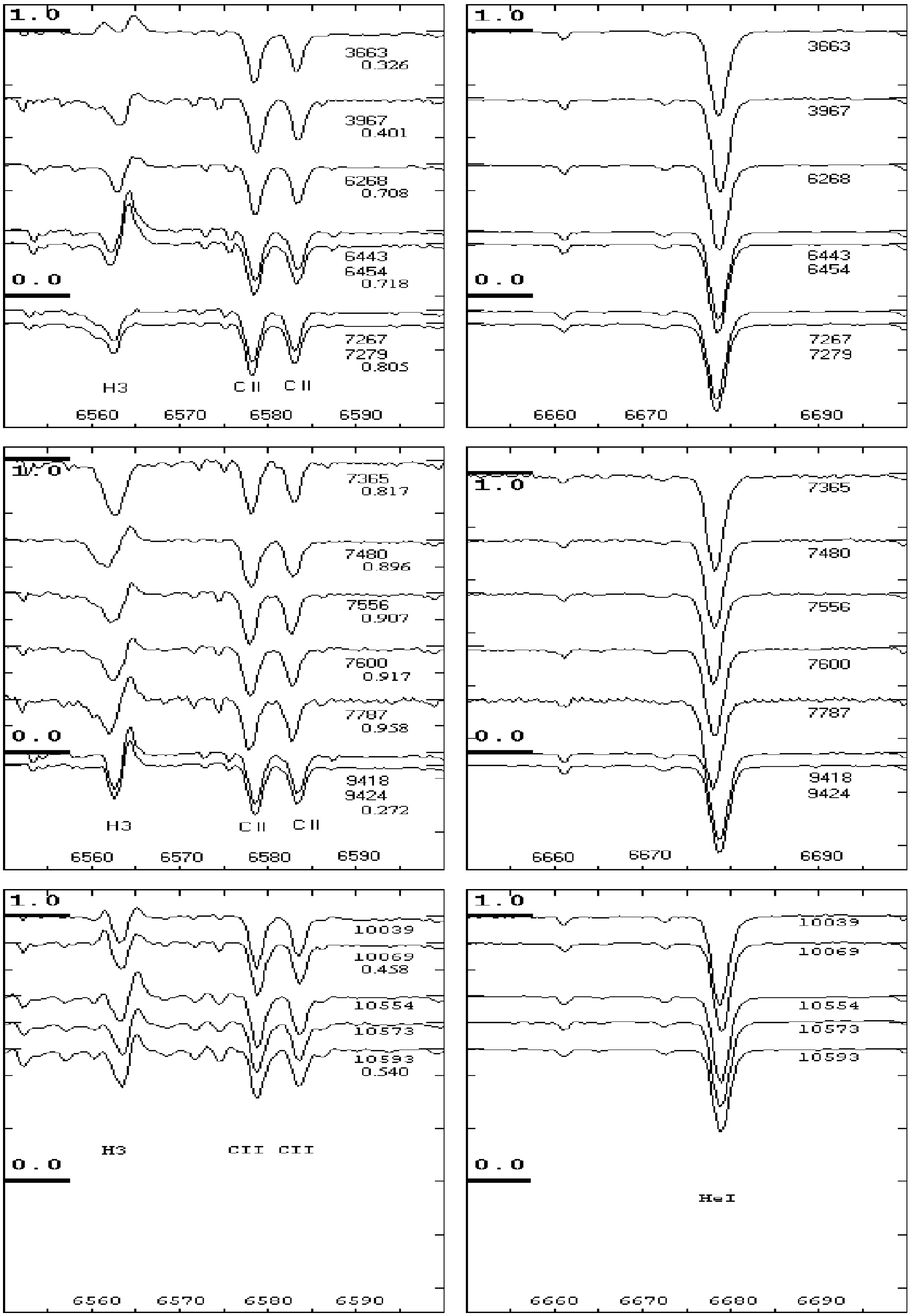

Fig. 1. Observed variability of the Hα profile and CII 6578,82 Å Å and HeI 6678 Å lines in the χ Aur spectrum

Table 1. Radial velocities of the four spectral lines sets from the Ondřejov photographic spectrograms of χ Aur

Plate	HJD	phase	RV_H	RV_{He}	RV_m	RV_{Ca}
O3732	44469.601	0.083	-12.2	-14.9	-23.5	-3.0
O3754	44485.550	0.106	-26.7	-21.1	-26.9	-1.6
O3858	44574.462	0.238	-2.8	-1.4	-1.7	4.5
O4173	44851.573	0.647	20.4	15.3	16.8	5.1
O4313	44952.449	0.796	-9.3	-7.6	-7.7	-0.2
O4332	44982.477	0.840	-16.4	-7.3	-16.8	-10.7
O4364	45006.281	0.876	-1.1	-1.7	-13.5	7.1
O4619	45211.618	0.179	-7.6	-3.7	-5.5	8.7
R1293	45275.596	0.274	-3.7	-2.3	-1.2	-1.6

Remarks: Orbital phases are computed from new orbital elements derived in this work.

Table 2. The discussion of masses of primary and secondary components and dimensions of the binary system

$M_1.sin^3i$ $\mathscr{M}_\odot$	$M_2.sin^3i$ [$\mathscr{M}_\odot$]	q	K_2 [km/s]	$a_2.sini$ [$\mathscr{R}_\odot$]	$a.sini$ [$\mathscr{R}_\odot$]
40	12.6	3.15	70	920	1212
35	11.7	2.99	66	873	1164
32	11.0	2.88	63	842	1133
28	10.2	2.73	60	798	1089
25	9.6	2.61	58	761	1053
22	8.9	2.48	55	722	1014
15	7.1	2.11	47	615	907
10	5.6	1.77	39	516	809
6	4.3	1.41	31	410	703
3	3.0	1.00	22	292	584

Remarks: Our final orbital elements were accepted for computing these parameters of the binary pair.

The second set - our new spectroscopic observations of χ Aur were carried out at the Ondřejov observatory during the years 1994 and 1996. In this case the RETICON detector RL-1872F/30 in Coudé focus Cd700 was used. Nineteen new spectrograms of χ Aur were obtained in the spectral range from 6300 to 6700 Å with dispersion of 8.56 Å/mm. These spectrograms were reduced by T.R. using the SPEFO program. Table 3 contains a list of the stellar and interstellar lines of the primary component identified in the RETICON spectrograms, their wavelength and average values of their equivalent widths EQW and central intensities CI. The interstellar lines described in that table "is" are identified by Herbig (1975). The lines of the secondary component are not visible in our spectrograms.

Radial velocities of the stellar lines were measured: radial velocity of the HeI 6678 Å line, RVs of the CII 6578,82 Å Å lines, RVs of the SiII 6347,71 Å Å lines and radial velocities of the line NeI 6402 Å. Other NeI lines are too weak and merging in the noise and telluric lines to measure their radial velocities precisely. Measured radial velocities from all 19 RETICON spectrograms are plotted in the Fig. 3 in two plots. In the first plot squares denote HeI 6678 Å lines, asterisks are used for CII 6578,82 Å Å lines and crosses denote SiII 6347,71 Å Å lines. In

Table 3. Equivalent widths and central intensities of the lines measured in RETICON spectrograms of χ Aur

Line Å	Identification	EQW [Å]	CI [continuum=1]
6333.43	NeI	0.050	0.972
6347.09	SiII	0.370	0.819
6371.36	SiII	0.274	0.866
6376.08	is	0.042	0.971
6379.30	is	0.093	0.921
6382.99	NeI	0.050	0.971
6402.25	NeI	0.139	0.923
6425.7	is	0.025	0.983
6445.4	is	0.041	0.972
6506.54	NeI	0.078	0.960
6562.82	Hα	see Fig. 2	
6578.03	CII	0.380	0.807
6582.85	CII	0.296	0.848
6613.63	is	0.144	0.897
6660.71	is	0.045	0.964
6678.15	HeI	0.887	0.661
6699.4	is	0.032	0.977

Remarks: "is" in the column Identification denotes the interstellar lines identified by Herbig (1975).

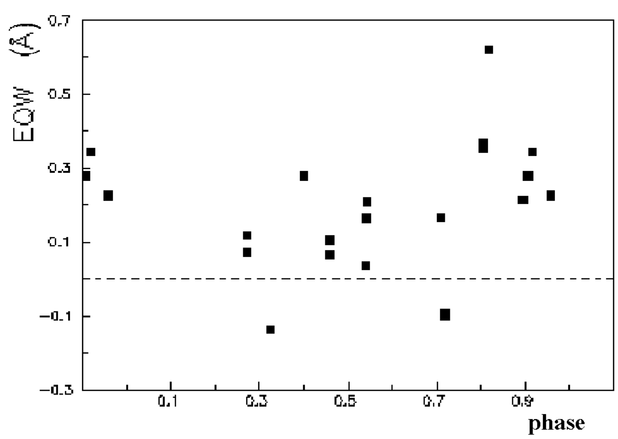

Fig. 2. The total equivalent width variability of the Hα line as a function of the orbital phase

the second plot asterisks denote Hα absorption. The full line is a theoretical radial velocity curve (graph B) plotted in the Fig. 4. The orbital phase is computed according to the final parameters written in the last column of Table 5.

The differences in radial velocities of the lines are observed. The differences between radial velocities of CII and SiII lines are very significant. During our observational campaign we found differences $\Delta RV_{CII-SiII}$ in the range from +3.9 to +9.7 km/s with the average value of +6.3 km/s, $\Delta RV_{HeI-CII}$ in the range from –3.1 to +3.7 km/s with average value of –0.4 km/s. This effect is also noted in work of Rosendhal (1973). He published for one spectrogram $\Delta RV_{CII-SiII}$ = +11.1 km/s and $\Delta RV_{HeI-CII}$ = –0.4 km/s. This effect could be explained well by combination of the silicon stellar lines with the interstellar

Table 4. Orbital parameters of χ Aur derived only from Young's data

Parameter	Young (1916)			Young FOTEL (sol. 1)			Young FOTEL (sol. 2)		
P [days]	655.16	±	5.26	663.49	±	10.41	675.51	±	3.75
T_0 [HJD]	20629.78	±	9.56	20625.41	±	46.09	20627.39	±	35.24
ω [^{o}]	135.52	±	5.2	132.94	±	15.81	133.95	±	18.12
e	0.171	±	0.026	0.153	±	0.061	0.134	±	0.056
K_1 [km/s]	20.53	±	0.57	20.65	±	2.40	20.65	±	2.40
γ [km/s]	-0.15	±	0.35	0.27	±	0.74	0.60	±	0.77
$a_1 . \sin i$ [$\mathscr{R}_\odot$]	261.9			265.0			272.2		
$\mathscr{F}(\mathscr{M})$ [$\mathscr{M}_\odot$]	0.56			0.57			0.60		
σ [km/s]	4.33			2.36			1.89		
epoch	51.64			50.99			50.08		

Remarks: The "epoch" gives the number of epochs elapsed in observational interval from JD 16636 to 50195.

Table 5. Orbital parameters of χ Aur derived from new RETICON and from all radial velocity data of χ Aur

Parameter	RETICON data graph (A)			all data			all data graph (B)		
P [days]	640.2 fixed			661.01	±	0.33	676.85	±	0.21
T_0 [HJD]	49795.3	±	67.0	22690.9	±	45.8	22754.3	±	46.1
ω [^{o}]	172.0	±	33.5	174.1	±	24.3	181.7	±	24.3
e	0.165	±	0.049	0.151	±	0.067	0.116	±	0.048
K_1 [km/s]	22.8	±	7.4	19.4	±	1.7	22.0	±	2.9
γ [km/s]	5.6	±	1.5	3.80	±	0.94	3.28	±	0.71
$a_1 . \sin i$ [$\mathscr{R}_\odot$]	283.7			250.6			291.8		
$\mathscr{F}(\mathscr{M})$ [$\mathscr{M}_\odot$]	0.75			0.48			0.73		
σ [km/s]	3.18			1.24			0.95		
epoch	52.84			51.20			49.98		

Remarks: The "epoch" gives the number of epochs elapsed in observational interval from JD 16636 to 50195.

Table 6. The secondary component discussion (M_1 = 18 $\mathscr{M}_\odot$ M_{V1} = −6.4 mag)

i °	M_2 [$\mathscr{M}_\odot$]	Sp. type$_2$	M_{V2} [mag]	M_V [mag]	Sp. type$_2$	M_{V2} [mag]	M_V [mag]
90-75	8.1	B2-3 V	-2.2	-6.42	F0 – G2	-5.0 – -4.5	-6.66 – -6.57
		B3 III	-3.0	-6.45	Ib		
		B7 II	-4.2	-6.53			
55	9.5	B2 V	-2.5	-6.43	A2 Ib	-5.2	-6.71
		B3 III	-3.0	-6.45			
40	12.5	B1 V	-3.3	-6.46	B7-8 Ib	-5.8	-6.89
		B2 III	-3.7	-6.48			
30	18.3	B0 V	-4.0	-6.51	B1 Ib	-5.9	-6.94
		B1 III	-4.5	-6.57	B5 Iab	-6.4	-7.15
25	36.7	09 V	-4.5	-6.57	B0 Ib	-6.1	-7.01
					B0 Iab	-6.5	-7.20

Remarks: The most probable candidate for the secondary component of χ Aur is a faint B-type main sequence star or a late-type supergiant.

contributions of the SiII lines (the distance of χ Aur is about 1 kpc and the existence of the interstellar SiII lines in its spectrum is probable) and telluric lines Atm H_2O 6347.305 Å and Atm H_2O 6371.568 Å with near wavelengths. Mainly the profiles of the line cores of stellar SiII 6347.091 Å and 6371.359 Å lines with FWHM about 1.5 Å are changed during the orbital motion of χ Aur with radial velocity amplitude 22 km/s ($\Delta\lambda$ is 0.21 Å in the wavelength of 6350 Å).

We observed radial velocity differences about 4 km/s between spectrograms obtained in one day interval (spectrograms 10554, 10573 and 10593) but not in intervals of about several hours long during one night (spectrograms 6443 and 6454, 7267

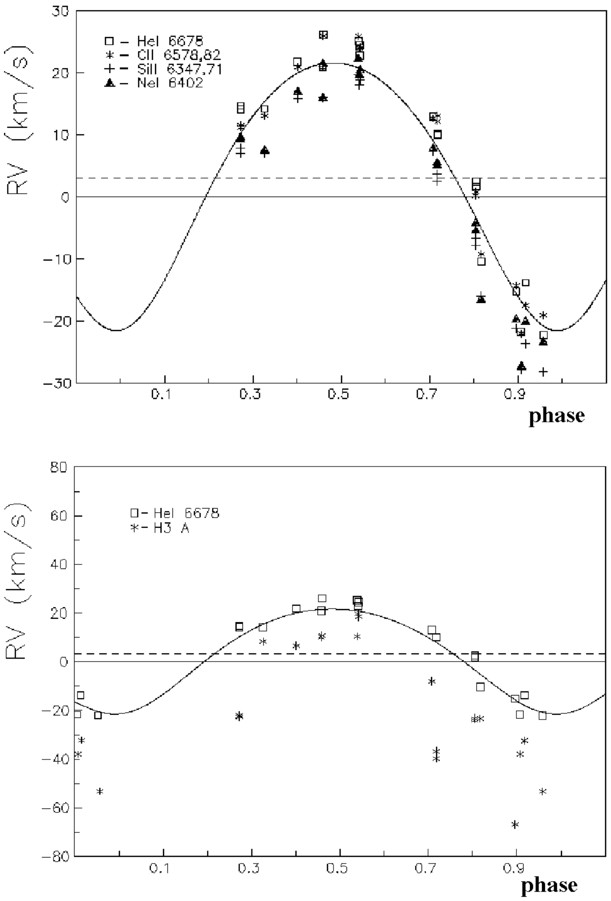

Fig. 3. Measured radial velocities of HeI, metals and Hα absorption lines in χ Aur spectrum from RETICON spectrograms *Remarks:* The full line curve in these two plots is the radial velocity curve plotted in the graph B (see the Fig. 4) computed from our new orbital elements.

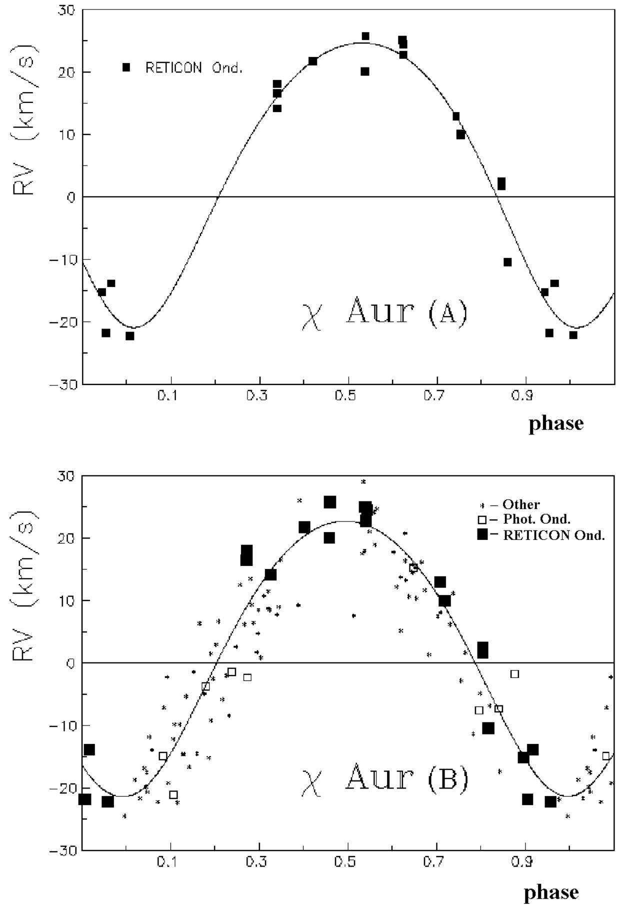

Fig. 4. New radial velocity curves of χ Aur*Remarks:* The upper plot shows the radial velocity curve computed only from RETICON data (orbital elements A), the lower plot shows the radial velocity curve computed from all RV data of χ Aur (orbital elements B). This one represents the final set of the orbital elements derived in this work.

and 7278, 9418 and 9424). The differences were observed in all stellar lines present in the observed interval. This might be the reason of a radial velocity scatter of the older photographic observations and imprecise determining of the orbital period and other orbital elements (see next section). This can be seen well in the Fig. 3. The cause of this effect is unknown for us yet.

3. Radial velocity curve and new orbital elements

Young (1916) used 91 radial velocity measurements to derive orbital period and other orbital elements of the orbit of the χ Aur written in the Sect. 1. The next radial velocity measurements were carried out by Henroteau (1920), Rosendhal (1973) and in this paper. We plotted new radial velocities curve and computed new orbital elements from three sets of radial velocity measurements:

- the first set contains only Young‘s average radial velocities,
- the second one contains only 19 our RETICON measurements of RV of the line He 6678 Å,
- the third one contains the older measurements mentioned above together with Henroteau‘s, Rosendhal‘s and our new 9 photographic average radial velocities and 19 RETICON radial velocities of helium line HeI 6678 Å.

Only the radial velocities of the line HeI 6678 Å was used from the RETICON spectrograms. The absorption minimum of the line Hα does not represent the line center since the line is filled in by the variable wind emission. The profiles of the other metal lines are changed by the interstellar contributions and telluric lines (see above).

In these sets old photographic radial velocities were weighted by 1, newer Ondřejov photographic radial velocities by 3 and RETICON ones by the value of 8.

Orbital elements were computed using the program RVSIMPL (T.R.) with preliminary results and then using the program FOTEL (Hadrava, 1990) under several initial conditions, with several sets of the input parameters and the input data sets mentioned above. Radial velocity curve of χ Aur has several new solutions with orbital periods 640.2, 661.01, 663.49, 675.51 or 676.86 days. Used input data set and derived orbital elements are written in the Table 5 (only Young‘s data were used) and in the Table 5 (the second and the third data sets were used).

The uncertainty in the solution is probably caused by very short observation intervals of this long period variable:

in years	JD-2400000
1903.6 to 1903.8	16636 to 16740
1913.9 to 1916.3	20110 to 20988
1920.9 to 1921.0	22666 to 22676
one observation in 1970.9	40907
1980.6 to 1982.8	44469 to 45275
1994.1 to 1996.3	49372 to 50195

and probably by the day to day radial velocity differences mentioned in the section above. A comparison of all our solutions from the Table 5 and the Table 5 was made. For all data the values of RMS error of one measurement of unit weight were computed (in the tables represented by the sign σ). The last row of the tables contains the number of epoch elapsed in time interval from JD 16636 to 50195.

The best fitting set of the orbital elements of χ Aur which can be accepted as the final one is written in the fourth column of the Table 5 with the orbital period of 676.86 days. Radial velocity curves for parameters written in the second (graph A) and in the fourth (graph B) columns of the Table 5 can be compared in the Fig. 4.

The new value of the orbital period 676.85 days differs significantly from the value given by Young (1916). The period derived by Young seems to be erroneous. The secular change of this parameter derived by the programme FOTEL does not seem to be actual. Secular changes of any orbital element were not found out.

4. Spectrum of χ Aur and physical parameters of both components

One of our aims was to find lines of the secondary component χ Aur and derive precise parameters of the system orbit. Unfortunately secondary lines are not visible in the spectrum. We used the Fortran program KOREL (Hadrava, 1995) for spectrum disentangling analysis of the observed profiles of the lines HeI 6678 Å, CII 6578,82 Å Å and SiII 6347,71 Å Å. No secondary lines were found by using this method. We can estimate, that the equivalent widths of the secondary lines are less then 1% of the primary ones.

The primary component lines are dominating in the spectrum. By comparing with the synthetic spectrum (programme SYNSPEC, T_{ef} = 13000 K, log g = 2.5) we estimated the rotational velocity of the primary v_{rot1}. sin i = 50 km/s and then the rotational period is about 4.6 day. In the spectrum we observe only primary lines, the invisibility of the secondary lines is probably caused by small brightness of the secondary star (see Table 6), gravitational widening of lines and maybe quicker rotation of the secondary in this detached system where none of the stars fills its Roche lobe.

In the Table 2 there are compared masses M_1 and M_2 of both components, the velocity amplitude K_2 and semiaxis a_2 of the secondary component orbit and semiaxis a with respect to the inclination i of the system. From the spectral type B5 Iab of the primary component its physical parameters could be derived M_1 = 18.2 $\mathscr{M}_\odot$, R_1 = 44.8 $\mathscr{R}_\odot$ (Straižys and Kuriliene, 1981). Then from new orbital elements with respect of inclination i = 90° could be derived a = 960 $\mathscr{R}_\odot$ and for the secondary its mass M_2 = 8 $\mathscr{M}_\odot$.

To our knowledge no eclipses are observed in χ Aur system. The spectral type and other physical parameters of the secondary component depend on the system inclination i. Predicted spectral types of the secondary with respect of primary mass M_1 = 18 $\mathscr{M}_\odot$, absolute magnitude M_{V1} = -6.4 mag and inclination dependence are discussed in the Table 6. The candidates for the secondary are B-type stars of the luminosity classes from III to V or from B to K supergiants with M_V in the interval -5.9 to -4.3 mag. Due to the nonexistence of the strong secondary lines of the early type star and due to the nonexistence of the lines of the late type star in the spectrum of χ Aur we can deduce that the secondary can be a faint main sequence star of spectral type B V or a supergiant of the spectral type F and later (Straižys and Kuriliene, 1981).

5. Hα shape and its variability

Rosendhal (1973) observed Hα of the χ Aur only in the absorption with the equivalent width of +0.89 Å and the profile of the line was asymmetric. Leitherer (1987) accepted this value and for M=15 $\mathscr{M}_\odot$ and R=66 $\mathscr{R}_\odot$ derived the escape velocity v_0 = 300 km/s and the terminal velocity v_{term} = 450 km/s, Hα luminosity L(Hα) = 7.6 $L_\odot$ and mass loss rate $\dot{M} = 1.2 \times 10^{-7}$ $\mathscr{M}_\odot$/yr.

Fig. 1 illustrates two wavelength intervals (from 6550 to 6600 Å with the Hα and CII lines and from 6650 to 6700 Å with the HeI 6678 Å line) of the χ Aur spectrum from 19 RETICON spectrograms obtained at Ondřejov observatory from January 1994 to May 1996. The lines HeI 6678 Å and CII 6578,82 Å Å follow the orbital motion of the primary. The profile of the Hα is variable mostly with emission peaks (not announced yet). The line Hα can be seen in majority of our RETICON spectrograms in the absorption and in the emission as well. Its profile has a variable character.

Due to this fact three radial velocities, equivalent widths and central intensities for Hα were measured – for the absorption minimum, for the emission peaks at the red and at the blue wings of the line. Equivalent widths of the absorption EQW_A, of the red emission peak EQW_{ER}, of the blue emission peak EQW_{EB} and total equivalent width EQW_{total} and central intensities of the absorption CI_A, of the red emission peak CI_{ER} and of the blue emission peak CI_{EB} for Hα were measured. The total equivalent width as a function of the orbital phase is plotted in the Fig. 2. The maximum and minimum values of the EQW_{total} are +0.62 Å (line only in absorption) or -0.14 Å (two emission peaks are visible). The Hα emission extends to $\pm$ 3 Å ($\pm$ 140 km/s).

Radial velocities of the absorption minimum $RV_{H\alpha A}$, of the red emission peak $RV_{H\alpha ER}$ and of the blue emission peak $RV_{H\alpha EB}$ were measured as well. But the absorption minimum does not represent the line center. The actual photospheric absorption is filled in by the emission.

Hα profile is a result of the combination of the photospheric absorption profile with the emission profile, the emission fills in asymmetrically the photospheric line. The presence of the Hα in emission in many early-type supergiants spectra is known for many years. It originates in a wind region close to the primary supergiant (Leitherer, 1987). Hα line formation in the extended expanding atmospheres of the supergiants is described in detail in the paper published by Puls et al. (1996).

P Cyg profile is dominating in the spectrum of χ Aur, nevertheless, once we observed the line Hα only in absorption and sometimes two emission peaks were observable. We did not find any periodicity of the Hα variability. In time intervals of about several hours or night to night observed profiles are nearly identical (files 6443 and 6454, 7267 and 7279, 9418 and 9424, 10039 and 10069, 10554 and 10572 and 10593). The profile changes seem to be irregular. We can estimate that the profile of the Hα varies in the time scale from 1 week to 2 months. Less conspicuous profile variability can be seen in the P Cyg profile in the time scale of about a week. This variability can correspond with the rotation period of the primary of 4.6 day.

Such time scales of the Hα variability can indicate mechanisms which operates on the Hα line formation in the atmosphere of the supergiant as gravitational oscillations of the star, its rotation, orbital motion, presence of the magnetic field and its instabilities etc. (Ebbets, 1982). The reason for the Hα variability in the case of χ Aur is not known precisely yet.

6. Conclusions

- The Hα emissions and Hα variability were announced, the P Cyg profile of this line is dominating in the spectrum of χ Aur. We did not find any periodicity in Hα profile changes. Only continuous monitoring of these variations in the future can give us new results.
- From older and new Ondřejov photographic and RETICON radial velocity measurements we computed the radial velocity curve and a set of orbital elements of χ Aur with new orbital period of the system: P = 676.85 $\pm$ 0.21 days
  T_0 = HJD 2422754.2 $\pm$ 46.1
  ω = 181.7° $\pm$ 24.3°
  e = 0.116 $\pm$ 0.048
  K_1 = 22.0 $\pm$ 2.9 km/s
  γ = 3.28 $\pm$ 0.71 km/s
  $a_1 \sin i$ = 291.8 $\mathscr{R}_\odot$
  $\mathscr{F}(\mathscr{M})$= 0.73 $\mathscr{M}_\odot$
  But new RETICON measurements are needed in the interval of the orbital phase 0.00 to 0.35 mainly for better determining of orbital period and systemic velocity. In this interval only the older Young's observations exist.
- We found radial velocity fluctuations which are probably the reason of problems with determining of the orbital period of the system. Regular monitoring of radial velocities is needed for confirmation of this phenomenon.
- Spectral lines of secondary are not visible in the new RETICON spectrograms obtained at Ondřejov. Physical parameters and spectral types of both components were discussed. The most probable candidate for the secondary component is a faint B-type main sequence star or a late-type supergiant.

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