Spectral and polarimetric observations of the star HD 37022 (θ^1 Ori C)

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Abstract. HD 37022 (0^1 OriC) is a young star of spectral type 07 V, the brightest star in the Trapezium of the Orion Nebulae (M42). It has a synchronous spectral variability in the optical, ultraviolet and X-rays regions with a period P = 15.422^d. For the explanation of this variability many authors suggest a magnetic rotator modulating the stellar wind. During 1996-97 we made a series of observations of θ^1 Ori C at the 6 m telescope of SAO RAS, using the circular polarization analyzer and hydrogen-line magnetometer, to make sure that a magnetic field exists in this star. In this paper we publish the results of measurements of the effective magnetic field and Stokes parameters. The value of the effective magnetic field is within the measurement errors and apparently not more than 500 G.

1. Introduction

HD 37022 (θ^1 Ori C) is the brightest (m_V = 5.13) star in the Trapezium of the Orion Nebula (M42). The star is in intensive star formation region and obviously has arrived on the Main Sequence not long ago. The spectral type is 07 V (Conti & Leep, 1974). The spectral variability has been found by Conti (1972). The star has variable emission lines caused by collision processes in the stellar wind. Conti & Alschuler (1971) and Conti (1972) have found also variable inverse P Cyg profile in the line Hen Л4686. The properties of the stellar wind of θ^1 OriC have been studied by Howarth & Prinja (1989), and therein they have determined physical parameters of the star: M^* = $40M_\odot$, T_{eff} = 40000 K, R^* = $8R_\odot$. Stahl et al. (1993, 1996) have established that the emission strength in the lines H_α and HeI varies periodically and determined the period of these variations, $P = 15.^d422 \pm 0.^d002$. Walborn & Nichols (1994) and Stahl et al. (1996) observed strong variations of the absorption lines $C^{IV}\lambda1548$, $\lambda1551$ with the same period. They have also discovered the appearance of high velocity features in these lines when the emission in H_α is a maximum. The absorptions of the stellar wind lines are weakest when the emission features in H_α and HeIIλ4686 are at their maximum. The photospheric lines HeI, HeII, C^{IV} and OIII vary in phase, the absorption in these lines on the contrary is strongest when the emission features are at maximum. Gagne et al. (1997), studying the variability in the X-rays region, have found that the emission in X-rays reaches a maximum when the emission in H_α is at its maximum.

The appearance of a magnetic field in θ^1 Ori C has first been suggested by Walborn (1981). To explain the synchronous periodical variations in the absorption and emission lines in different spectral regions Stahl et al. (1993, 1996) have supposed a magnetic rotator model. A period of $15.^d422$ has been interpreted as the rotation period, and spectral variations as the modulation of the stellar wind by the magnetic field. They have assumed the magnetic field to have a dipole configuration, the angles between the rotational axis of the star and the line of sight i and between the rotational and magnetic axes β are suggested equal to 45°, also they assume the dipole may be strongly decentred. Gagne et al. (1997), studying X-ray variability, analyse several possibilities for explanation of this phenomenon: 1) the origin of the emission is caused by collision of the stellar wind with the invisible companion, 2) the coronal emission from the invisible star which is not on the main sequence yet, 3) the periodical variations of the density, 4) the absorption of the magnetospheric X-rays in the wind, 5) the magnetospheric eclipses. In Gagne's opinion the ROSAT data except the first three scenarios. The lines do not show considerable variability of the radial velocity and the period of variations of the X-ray emission and H_α does not correspond to the nonradial pulsations caused by density variabilities in the stellar wind of O-stars. The last two scenarios require a magnetic field. Babel & Montmerle (1997), basing on the X-ray observations, predict the surface intensity of the field B^* ~ 270-370 G. Balega et al. (2000), using speckle interferometry methods, have found that

θ^1 Ori C is a close binary system with a separation of ~ 33 mas. However this fact can not explain the variability with the period of $15.^d422$ because the period of such a system must be about ten years. Thus, the magnetic rotator hypothesis has so far remained the most attractive.

As proposed by N. E. Piskunov, in 1996 we started regular observations of θ^1 Ori C at the 6 m telescope using special polarimetric optics: an analyzer of circular polarization (Najdenov κ Chountonov, 1976) and a hydrogen-line magnetometer (Shtol' et al., 1985). We measured the effective magnetic field and Stokes parameters for a direct search for the magnetic field. Simultaneously and independently of us J.-F. Donati and G. A. Wade (1999) also tried to find the magnetic field.

2. Equipment and data reduction

To search for the longitudinal component of the magnetic field, we have done Zeeman spectroscopy of θ^1 Ori C using the first and second cameras of the Main Stellar Spectrograph (MSS) of BTA with analyzers of circular polarization (Najdenov & Chountonov, 1976 and Chountonov, 1997), and 1160 x 1040 CCD with a pixel size of 16 x 16 (Chountonov & Glagolevskij, 1997) as the detector. The spectral region λ, spectral range $\Delta\lambda$, resolution R, and inverse linear dispersion D for the first and second cameras are given in Table 1.

The instrumental shifts were corrected using observations of standard stars which have no magnetic fields. In the Л5800-5900 region the shifts were determined also from interstellar lines NaI Л5890, 5896 observed in the spectra of θ^1 Ori C. Observations with a new analyzer (Chountonov, 1997) have allowed us to correct instrumental shifts in a different way. In the analyzer provision is made for alternating spectra with different circular polarizations. As the instrumental shift remains constant after this alternation and the magnetic shift changes the sign, the instrumental shift can be corrected by a comparison of two spectra observed one after another.

The observations were obtained with the context NICE (Knyazev & Shergin, 1995) of the ESO MIDAS. For the data reduction we used the context *long* of MIDAS and the programmes written by D. Kudryavtsev (2000) for the reduction of Zeeman spectra in MIDAS.

For the measurements of the linear and circular polarization in the continuum we employed the hydrogen-line magnetometer-spectropolarimeter of the BTA prime focus (Shtol' et al., 1985). The measurements were obtained in three spectral ranges Л4370-4470,4500-4605 4720-4820 A simultaneously. We obtained 5 measurements with an accuracy of 0.01%.

Table 1: *The characteristics of the Main Stellar Spectrograph of the 6 m telescope*

	λ(Å)	$\Delta\lambda$	R (Å)	D (Å/mm)
1 cam	4000–6000	80	0.20	5.2
2 cam	4000–5000	140	0.35	9.0
	5000-6000	210	0.50	14

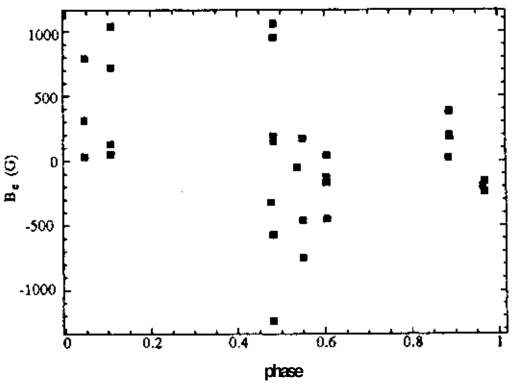

Figure 1: *The measurements of the effective magnetic field from the absorption lines.*

3. Observations

The magnetic field measurements of θ^1 Ori C are very difficult. The effective temperature is about 40000 K, and only a few rather broad lines of the highly ionized elements C^{IV}, OIII, NIII and also HeI, HeII and hydrogen lines are observed. We have obtained 32 spectra in different wavelength regions and 5 measurements of the Stokes parameters (see Table 2). More than half of the spectra have been observed in the λ5800 region where the lines CIV λ5801.51, 5812.14, HeI λ5875.7 and interstellar lines NaI λ5889.95, 5895.92 are situated. Besides that, we have several spectra with the lines NIII λ4379.20, HeI λ4471.47, 4713.14, HeII λ4541.59, 4685.70, OIII λ5592.37 and H_α λ6562.82.

4. Analysis of the observational data

In searching for the magnetic field we have measured the Zeeman splitting between left- and right-circularly polarized spectra. The value of the effective magnetic field was calculated by the standard formula. Some spectra have been removed because of the bad S/N ratio or cosmic ray hits in the line region. Table 3 presents the measurements of the field from the absorption lines.

We may state that if the field exists, its strength does not outmeasure the accuracy of measurements. The standard root-mean-square error for such mea-

Table 2: *Journal of the observations*

JD 2450000+	phase	spectral region (Å)	notes
413.383	0.476	5800	
413.391	0.476	5800	
414.290	0.535	5800	
414.307	0.536	5800	
415.309	0.601	5600	
415.319	0.601	5600	
415.331	0.602	5400	
415.344	0.603	5800	
415.354	0.604	5800	
416.488	0.677	4500	
417.535	0.745	4400	
467.165	0.963	5870	1 cam.
467.177	0.964	5800	1 cam.
467.236	0.968	5800	1 cam.
499.250	0.044	5800	
499.264	0.045	5800	
500.216	0.106	5800	
500.227	0.107	5800	
500.242	0.108	4500	
534.266	0.314		magn.
705.476	0.416	4540	1 cam.
705.490	0.417	4540	1 cam.
705.533	0.420		magn.
705.551	0.421	6560	1 cam.
705.569	0.422	6560	1 cam.
706.486	0.481	5870	1 cam.
706.501	0.482	5800	1 cam.
706.510	0.483	5800	1 cam. *
707.523	0.549	5800	*
707.540	0.550	5800	*
707.569	0.552		magn.
709.499	0.677		magn.
710.583	0.747		magn.
774.413	0.886	4700	*
774.423	0.887	4700	*
774.432	0.887	4500	*
774.438	0.888	4500	*

1 cam. — the observations with the 1st camera
magn. — the observations with the magnetometer
* — the observations with the new analyzer

Table 3: *The measurements of the effective magnetic field from the absorption lines*

JD 2450000+	phase	line	B_e, G
413.391	0.476	CIV 5801	−320
414.307	0.536	CIV 5801	−50
415.344	0.603	CIV 5801	−130
415.344	0.603	CIV 5812	−170
415.354	0.604	CIV 5801	+40
415.354	0.604	CIV 5812	−450
467.177	0.964	CIV 5812	−200
467.236	0.968	CIV 5801	−160
467.236	0.968	CIV 5812	−240
499.250	0.044	CIV 5801	+310
499.264	0.045	CIV 5801	+30
499.264	0.045	CIV 5812	+790
500.216	0.106	CIV 5801	+50
500.216	0.106	CIV 5812	+130
500.227	0.107	CIV 5801	+1040
500.227	0.107	CIV 5812	+720
706.486	0.481	CIV 5801	−570
706.486	0.481	CIV 5812	−1240
706.501	0.482	CIV 5801	+190
706.501	0.482	CIV 5812	+950
706.510	0.483	CIV 5801	+1060
706.510	0.483	CIV 5812	+150
707.523	0.549	CIV 5801	+170
707.523	0.549	CIV 5812	−460
707.540	0.550	CIV 5801	−750
774.413	0.886	HeI 4713.143	+20
774.423	0.887	HeI 4713.143	+380
774.432	0.887	HeII 4541.59	+200
774.438	0.888	HeII 4541	+180

surements is about 100 G for the stars with a large number of narrow lines. Since in the case of HD 37022 we have only a limited number of rather wide lines, the error increases. In each spectrum there are only 1-2 lines suitable for measurements. In spite of the high S/N ratio, we evaluate the accuracy of field measurements from one line at approximately 500 G. The results of our measurements are shown in Fig. 1. It follows from our measurements that the value of the longitudinal magnetic field does not exceed several hundred Gauss. The attempts of construction of an effective magnetic field curve with half and double periods have not given a satisfactory result either.

Donati &; Wade (1999) have reported on possible existence of circular polarization with a magnitude of about 4% in the continuous spectrum of HD 37022. However, our observations do not show any significant differences between spectra with different circular polarizations either in the continuum or in the lines.

Besides spectral observations we have performed measurements with the magnetometer-spectropolarimeter (see Table 4) which measures the Stokes parameters with a high S/N ratio. The device was adjusted for the polarization measurements in three regions of the continuum simultaneously: λ4370-4470, 4500-4605, 4720-4820. As you can see from Table 4 all the parameters are equal to zero within the measurement errors.

Perlustrating the spectra, we have found that at the phase around 0.0 there are weak (~ 1% at most) emission features in the lines HeI λ5875.7, CIV λ5801.51, 5812.14. We ought to note that in Stahl's

Table 4: *Measurements of the Stokes parameters*

JD 2450000+		Q (%)	U (%)	V (%)
534.266	0.314	-0.210 ± 0.026		$+0.013 \pm 0.053$
705.533	0.420	$+0.082 \pm 0.009$	-0.145 ± 0.016	$+0.001 \pm 0.011$
707.569	0.552	$+0.030 \pm 0.015$	-0.058 ± 0.014	-0.011 ± 0.011
709.499	0.677	$+0.077 \pm 0.011$	-0.043 ± 0.020	$+0.004 \pm 0.013$
710.583	0.747	$+0.054 \pm 0.019$	-0.003 ± 0.020	$+0.018 \pm 0.011$

model the magnetic dipole axis at phase 0.5 is aligned with the line of sight and at phase 0.0 the axis is perpendicular to it.

5. Discussion

The periodical synchronous variability of spectral lines in the visible, ultraviolet and X-ray regions requires some global factor explaining this phenomenon. As such a factor, many investigators suggest the magnetic field covering all the surface of the star and causing modulation of the stellar wind.

As our data show, with the equipment and methods we have we can not give a definite answer concerning the presence of the magnetic field in θ^1 Ori C. This is due to the scarcity of the lines and strong rotational broadening. In this case we can only evaluate the upper limit for the value of the effective magnetic field which is not more than 500 G. Neither can we exclude that the configuration of the stellar magnetic field differs from a dipole.

Apart with our measurements Donati and Wade (1999) have also got a negative result searching for the magnetic field of θ^1 Ori C and determined the upper limit of the dipole strength as 1.6-2 kG. However they report on the very strong (~ 4%) circular polarization in the stellar spectrum. In our 5 measurements there is neither linear nor circular polarization. Apparently these discrepancies are caused by different rotation phases and/or by different phases of the binary system. It is possible also that different spectral regions could cause such discrepancies. We do not discard the influence of the nebula in which the star is imbedded.

Probably a long-term monitoring of θ^1 Ori C with a higher resolution and echelle spectrographs, which cover a large wavelength region, can provide new results.

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