MAGNETIC FIELD MEASUREMENT IN BLACK HOLE
X-RAY BINARY CYGNUS X-1

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E.A. Karitskaya¹, N.G. Bochkarev², S. Hubrig³, Yu.N. Gnedin⁴,
M.A. Pogodin⁴, R.V. Yudin⁴, M.I. Agafonov⁵, O.I. Sharova⁵

(1) Astronomical Institute of RAS, 48 Pyatnitskaya str., Moscow, 119017, Russia, karitsk@sai.msu.ru.
(2) Sternberg Astronomical Institute 13 Universitetskij pr., Moscow, 119991, Russia.
(3) ESO, Chile.
(4) Central Astronomical Obseravtory at Pulkovo RAS, St.-Petersburg, 196140, Russia.
(5) Radiophysical Research Institute (NIRFI), 25/12a B.Pecherskaya str., Nizhny Novgorod, 603950, Russia.

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Abstract

X-ray binary Cygnus X-1 is microquasar containing historically first candidate to black hole. Paradigm of magnetic disc accretion dominates in theoretical models describing processes taking place in objects containing black holes such as microquasars and active galactic nuclei. Nevertheless up to now there were no reliable measurements of magnetic fields in these systems. The first prediction of the Cyg X-1 magnetic field was done by V.F.Shvartsman ¹. He wrote that Cyg X-1 X-ray emission millisecond flickering evidences the presence of a black hole and points to the magnetic field role in accretion onto a black hole ²,³. From that times there were many of attempts to search for the Cyg X-1 magnetic field but all of these efforts indicated upper limits only. Our VLT FORS1 2007 and 2008 observations revealed a presence of a magnetic field in the system. For the first time we obtained on the level of 6 standard deviations ($\sigma$) a magnetic field of the order of 130 G on the surface of the Cyg X-1 optical component (O-supergiant) and observational estimation on a 4$\sigma$ level of a magnetic field on a outer part of accretion structure (about 600 G) in accordance with theoretical prediction. Scaling this field value to black hole vicinity we showed that the field is strong enough to explain the X-ray millisecond flickering and can explain it. Our result presents the first direct determination of magnetic field in accreting disk around a black hole.

Cyg X-1/HDE226868 is a X-ray binary system with the orbital period P=5.6d, whose relativistic component is the first candidate black hole (BH). The optical component (O9.7 Iab supergiant) is responsible for about 95% of the system optical luminosity. The remaining 5% are due to the accretion structure (disc and surrounding gas) near BH.

Though the investigation of Cyg X-1 are being carried out over 40 years and have resulted in ∼1000 publications, geometrical and physical parameters the system remain unclear. The same is also true for some phenomena observed in this system including e.g. long time periodic and aperiodic variations and flares.

Both linear and circular polarizations was detected in Cyg X-1 optical continuum and investigated in 1970s. Linear interstellar and circumstellar polarization reaches a value of ∼5% ⁴. Its strength and position angle change on the scale of years ⁵. Kemp ⁶ detected a component of an amplitude ∼0.25% which is variable over the orbital phase $\phi$. This component shows complicated and variable dependence from $\phi$. Similar behaviour was found for circular polarization discovered in 1972 ⁷,⁸. Interstellar circular polarization does not exceed 0.04%, and variable component with the period of 2.8/5.6d is about 0.02% ⁹. While intrinsic circular polarization is most probably generated by a magnetic field, the intrinsic linear polarization in Cyg X-1 is usually explained by electron scattering on non-symmetrical gas structures (e.g. 10−13).

Theoretical estimations of the strength of the magnetic field in Cyg X-1 were based on optical polarization ⁴,¹⁵. Upper limits $B < 350$ G for the optical component and $B < 500$ G for the outer part of
accretion disc were found. The 6-m telescope spectropolarimetric observations show $B < 1000$ G for the outer part of the disc $^{16}$.

Our method of the study of the presence of a magnetic field is based on measurements of the circular polarization (the Stokes parameter $V$) in optical spectra produced by Zeeman effect. The method of the determination of the mean (averaged over the picture plane) longitudinal magnetic field $\langle B_z \rangle$ is described in full detail by $^{17}$. The method is statistical: to increase the sensibility there are used simultaneously all observed spectral lines. Value $\langle B_z \rangle$ is obtained $^{17-19}$ from the slope of least squares linear regression of

$$Y = V / I$$

and

$$X = -4.67 \times 10^{-13} \times g_{eff} \times \langle B_z \rangle \times \lambda^2 \times (1/I) \times dI/d\lambda.$$  

Here $I$ is intensity of radiation, $\lambda$ is wavelength in angstroms, $g_{eff}$ is effective Lande factor.

Our spectropolarimetric observations were conducted with the European South Observatory Very Large Telescope (VLT) 8.2 m (Cerro Paranal, Chile) in service mode with the FORS1 spectrograph in the range 3680-5129 Å, spectral resolution $R=4000$, signal-to-noise ratio $S/N = 1500 - 3500$ (for spectra of intensity) in 2007 from June 18 to July 9 and in July, 2008 (see Table 1). The system Cyg X-1 was at that time in its X-ray “hard state”. 13 spectropolarimetric spectra with exposure time of ~1 hour were obtained during 13 nights. For our observations we adopt effective Lande-factor $g_{eff}=1.07$ according $^{20}$.

The used method has been already applied (and carefully tested) in previous studies of bright magnetic stars $^{17-19}$ which usually do not have significant interstellar or intrinsic linear polarization and have rather strong $\langle B_z \rangle=500-2000$ G. In contrast, Cyg X-1 has $\langle B_z \rangle$ weaker and strong interstellar / circumstellar linear polarization. For this reason we had to meet some precautions in the magnetic field measurements of this system and to adapt the method for such conditions.

Before $\langle B_z \rangle$ calculations we clean carefully V/I spectra from any features which could distort results. We excluded features alien to photosphere of Cyg X-1 optical component: 1) the wavelengths of interstellar lines; 2) defects (including weak residual cosmic ray tracks remained after standard observation processing); 3) HeII 4686 emission line and 4) emission components of the lines with strong P Cyg effect. We did not found the pollution by telluric lines in our spectra.

The continua of the recorded V/I spectra show slight slopes. The continuum level drop 0.05% - 0.15% within our spectral range 3680-5129 Å varied from night to night. This behaviour cannot be explained by Cyg X-1 interstellar or/and intrinsic circular polarization. The probable reason could be a presence of a cross-talk between linear and circular polarization within the FORS1 analysing equipment. In agreement

| Date          | JD     | Orbital phases | Optical component (O-star) $\langle B_z \rangle$, G | Outer part of accretion structure $\langle B_z \rangle$, G $\sigma$, G $\langle B_z \rangle$ $\sigma$ |
|---------------|--------|----------------|---------------------------------|-------------------------------------------------|
| 18-19 June '07 | 2454270.768 | 0.650          | -6 28 -0.2                      | -780 177 4.4                                    |
| 19-20 June '07 | 2454271.778 | 0.830          | 37 22 1.7                       | 5 104 0.05                                     |
| 20-21 June '07 | 2454272.760 | 0.006          | 58 21 2.8                       | 126 174 0.72                                   |
| 25-26 June '07 | 2454277.808 | 0.907          | 22 28 0.8                       | -257 222 -1.15                                 |
| 29-30 June '07 | 2454281.707 | 0.603          | 48 20 2.4                       | 235 260 0.90                                   |
| 9-10 July '07  | 2454291.766 | 0.400          | 101 18 5.5                      | 128 89 1.4                                    |
| 14-15 July '08 | 2454662.711 | 0.641          | 49 23 2.1                       | -260 221 -1.2                                  |
| 15-16 July '08 | 2454663.684 | 0.816          | 22 22 1.0                       | -95 122 -0.78                                  |
| 16-17 July '08 | 2454664.692 | 0.995          | 80 23 3.5                       | -380 231 -1.6                                  |
| 17-18 July '08 | 2454665.692 | 0.174          | 24 19 1.3                       | 25 117 0.21                                   |
| 23-24 July '08 | 2454671.704 | 0.247          | -16 20 -0.8                     | -93 82 -1.1                                   |
| 24-25 July '08 | 2454672.728 | 0.430          | 27 19 1.4                       | 449 112 4.0                                   |
| 30-31 July '08 | 2454678.676 | 0.500          | 128 21 6.2                      | 56 189 0.29                                   |
with previous studies of Cyg X-1 linear polarization in optical range.\(^5\) This effect is observed only in the continuum and does not distort S-shape V profiles of spectral lines caused by Zeeman effect (hereinafter Zeeman S-waves).

To avoid any impact of the continuum slope on our \(^\langle B_z \rangle\) measurements, we subtracted linear trends from V/I spectra. After removal of slopes the \(^\langle B_z \rangle\) becomes lower by 20-80 G depending on the slope values (all \(^\langle B_z \rangle\) corrections are negative).

We normalized I-spectra by pseudo-continuum following\(^18,19\). I-continuum is produced by the source energy distribution, interstellar reddening, broad diffuse interstellar bands (DIBs) as well as atmospheric extinction and detector sensitivity. Its slope reaches \(\frac{d(\log(I(\lambda))}{d(\log(\lambda))}\sim20\). The slope removing gives \(^\langle B_z \rangle\) correction up to \(\sim20\) G. It is usually less than the statistical errors \(\sigma(\langle B_z \rangle)\sim20-30\) G, see table 1.

After abovementioned reductions the residual deviations of least squares linear regression become to follow to the Gauss function satisfactorily up to \(\pm3.6\ \sigma(V/I)\), where \(\sigma(V/I)\) is standard deviation of V/I. It is mean that the level of significance corresponds to Gauss statistics now. Small number of points has larger deviations. Weak cosmic ray tracks can be a source of such deviations. Therefore we excluded from our analysis any pixel showing residual deviations exceeding 3.6 \(\times\ \sigma(V/I)\).

The results of our measurements are presented in table 1 and figure 1. To verify our results we used some tests: 1) each spectrum was divided in two halves at mid-wavelength; we checked that \(^\langle B_z \rangle\)-values determined over each half separately were in agreement within error-bars. 2) We repeated \(^\langle B_z \rangle\) calculation using fragments of spectra, which include strong absorption lines (deeper than 4%) only; \(\sim1/3\) spectral points were used; \(^\langle B_z \rangle\)- values were consistent with the previous measurements using the whole spectral regions within 1.5 sigma \((\langle B_z \rangle)\). 3) Zeeman S-waves for the strongest lines were found. In Fig. 2a we show an example of a distinct Zeeman feature in the HeI line at \(\lambda4026\) Å.

We should note that the element overabundance on the factor from 2 to 10 in the Cyg X-1 optical component stellar atmosphere\(^22-25\) enforces the spectral lines and Zeeman S-waves. It increases accuracy of \(^\langle B_z \rangle\) measurements.

As a next step of our study we investigated the spectral line HeII\(\lambda4686\) Å separately. Due to the presence of a strong emission component in the line profile it was omitted from the earlier analysis. In fact, this line has compound profile consisting of absorption (originating in the stellar photosphere) and emission (originating in the accretion structure) components. Certainly, the accuracy of the measurement of the magnetic field using just one line is considerably worse compared with measurement using the whole spectrum. Nevertheless, our analysis shows that for two spectra accuracies of estimations exceed \(4\sigma\) level: \(^\langle B_z \rangle=-780+/-177\) G in 2007 for the orbital phase \(\varphi=0.65\) and \(^\langle B_z \rangle=449+/-112\) G in 2008 for \(\varphi=0.43\). Zeeman S-wave in V-spectrum smoothed over 3 Å and its correspondence to the \(dI(\lambda)/d\lambda\) wave is presented on figure 2b.

To find He II \(\lambda4686\) Å line formation regions we constructed Doppler tomogram (the binary system image in velocity space) on the base of our VLT observational data. We used new Doppler tomogram reconstruction technique worked out by Agafonov\(^24\), so-called Radioastronomical Approach (RA). This RA method includes an effective CLEAN procedure and allows to reconstruct well the 2D velocity field with very small number of 1D profiles (5-10 spectra may be sufficient), see as example the figure 1 in\(^25\). The tomography map constructed on the base of all 13 HeII\(\lambda4686\) Å line VLT profiles obtained by us in 2007 and 2008 is presented in figure 3. It shows that HeII\(\lambda4686\) Å line emission regions are located near the point L1 in the Roche lobe model and near the "hot spot" or "hot line"\(^26\) on the outer part of the accretion structure. But for the different observational seasons Cyg X-1 tomogram maps may differ from one another – matter flow changes at the scale of years\(^27-28\). Therefore we constructed also tomograms using our VLT-profiles separately for 2007 and 2008. They show a similar result. Consequently \(^\langle B_z \rangle\) derived from HeII emission line is located in outer parts of accretion structure. Its values 400-800 G are in agreement with estimation\(^15\).

Our main conclusions are the following: We discovered a longitudinal magnetic field averaged over the picture plane \(^\langle B_z \rangle\sim100\) G in the photosphere of Cyg−X-1 optical component. Real magnetic field can exceed \(^\langle B_z \rangle\). Magnetic field was detected at high confidence level (about 6\(\sigma\)) near orbital phase \(\varphi=0.4\) in 2007, and \(\varphi=0.5\) in 2008. Dependence of \(^\langle B_z \rangle\) from \(\varphi\) is more complicated than for magnetic dipole and is probably changed during one year (figure 1). The magnetic field structure variation may be the reason of some long-time variations of matter flowing process in this binary system.

Further we found \(^\langle B_z \rangle\sim600\) G in outer parts of the accretion structure surrounding the BH. It is in agreement with Shvartsman’s ideas\(^3\), that gas stream carries the magnetic field to the accretion structure and the gas is compressed by a factor of \(\sim10\) due to the interaction with the structure of the outer rim.
Gas density is increased and magnetic field is increased up to $B \sim 600$ G at a distance from BH $6 \times 10^{11}$ cm = $2 \times 10^{5} \times R_{g}$ ($R_{g}$ is graviation radius). According to Shakura-Sunyaev 30 magnetized accretion disc standard model at $3 \times R_{g}$, $B \sim 10^{9}$ G. Taking into account radiative pressure predominance inside $\sim 10 - 20 R_{g}$, we get $B(3 \times R_{g}) \sim (2 - 3) \times 10^{8}$ G. The measured value of the magnetic field strength at the marginal orbit of the Cyg X-1 black hole corresponds quite well to the Magnetic Coupling model with equipartition between kinetic and magnetic energy densities.

If the X-ray millisecond flickering is related to the magnetic nature, then the accreting matter magnetic energy flux must exceed the X-ray emission fluctuating component luminosity. X-ray emission originates at $R < 30 \times R_{g}$. Inside the sphere of this radius the magnetic energy amounts to $10^{40}$ erg. The radial velocity of magnetized plasma at $30 \times R_{g}$ in Shakura-Sunyaev accretion disk is $\sim 1.5$ km/s (we adopt viscosity parameter $\alpha = 1$, because magnetic viscosity is big 31−32). The time of matter fall is $\sim 1000$ s. Magnetic energy flux is $10^{37}$ erg/s which is equal or exceed the flickering component power $(0.5 - 1) \times 10^{37}$ erg/s. So, magnetic energy dissipation permits to account for the X-ray flickering.

From abovementioned estimations the Cyg X-1 black hole magnetic moment is about $10^{30} G \times cm^{3}$. According to 33 such object belongs to Magnetic Extremely Compact Object (MECO) class.

So VLT FORS1 2007-2008 observations permit to detect the presence of a magnetic field in Cyg X-1. It is the pioneer measurement in black hole systems. The field can be responsible for X-ray millisecond flickering. Our result points to necessity of taking into account of magnetic field impact on the matter fluid structure in Cyg X-1.

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**Figure captions**

**Figure 1.** The mean longitudinal magnetic field of the Cyg X-1 optical component $\langle B_z \rangle$ (in Gauss) vs. the orbital phase $\phi$. Full squares: 2007 data; full triangles: 2008 data. Error bars are 68% confidence intervals. The phases of orbital period 5.6 days were calculated with ephemerides $^2$, $\phi = 0$ corresponds to the time, when BH component is located behind the optical component (O9.7 Iab supergiant). a, The graph for 2007. b, The graph for 2008. c, The graph for 2007 and 2008 together.

**Figure 2.** Examples of Zeeman S-waves. Two examples showing accordance of wavelength dependence of intensity normalized to continuum $I/I_c$ to Zeeman S-waves of $V/I$ spectra are given. a, An example for absorption spectral lines originated in atmosphere of O-star component of Cyg X-1 binary system: Zeeman S-wave (down box) in the region of HeI $\lambda$4026Å line (upper box) observed July 9, 2007 when $\langle B_z \rangle$ was high (see table 1). b, Evidence of magnetic field in accreting gas following from HeII $\lambda$4686Å emission line analyzes for June 18, 2007. The line on the upper panel shows the observed HeII $\lambda$4686Å spectral line profile $I/I_c$. Horizontal line is pseudo-continuum level. Solid line on the down panel shows $V/I$ spectrum smoothed over 3 Å. The dashed line on the panel shows in arbitrary units the expected Zeeman S-wave shape $(dI/d\lambda)/I (V/I \sim (dI/d\lambda)/I)$, where I was smoothed over 3 Å. Vertical solid line shows the centre of HeII $\lambda$4686 Å emission.

**Figure 3.** Doppler tomogram of Cyg X-1 in HeII $\lambda$4686 Å. It is constructed on the base of 13 VLT spectra from 2007-2008 and shows brightness of emission in HeII $\lambda$4686 Å spectral line on velocities plane $(V_x,V_y)$. Thin lines are isophots of different levels shown on the right part of figure (in relative units). The zero level corresponds to “pseudo-continuum”; negative values correspond to absorption and positive ones – to emission. The dashed line shows the Roche lobe of black hole (BH). The almost filling its Roche lobe optical component is drown by solid line. The Roche lobes are constructed for the mass ratio $q = M_X/M_O = 1/3$. Here $M_X$ is the mass of X-ray emitting component (BH) and $M_O$ is the mass of optical component (O-star). Ovals represent outer parts of the accretion disks with radii $r_d = 0.2$ and 0.25 of the distance between mass centers of the components.
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