COMMISSIONS 27 AND 42 OF THE IAU
INFORMATION BULLETIN ON VARIABLE STARS

Number 5950

Konkoly Observatory
Budapest
19 August 2010

HU ISSN 0374 – 0676

THE FIRST DISCOVERY OF A VARIABLE MAGNETIC FIELD IN X-RAY BINARY Cyg X-1=V1357 Cyg

KARITSKAYA, EUGENIA A.[1]; BOCHKAREV, NIKOLAI G.[2]; HUBRIG, SWETLANA [3]; GNEDIN, YURY N.[4]; POGODIN, MICHAIL A.[4]; YUDIN, RUSLAN V.[4]; AGAFONOV, MICHAIL I.[5]; SHAROVA, OLGA I.[5]

[1] Astronomical Institute of Russian Academy of Sciences, 48 Pyatnitskaya str., Moscow 119017, Russia

[2] Sternberg Astronomical Institute, Moscow, Russia

[3] Astrophysical Institute Potsdam, Potsdam, Germany

[4] Pulkovo Observatory of Russian Academy of Sciences, St. Petersburg, Russia

[5] Radiophysical Research Institute (NIRFI), Nizhny Novgorod, Russia

The X-ray binary Cyg X-1=V1357 Cyg=HDE 226868 is a microquasar containing the historically first black-hole candidate. Theoretical models describing processes in objects with black holes, like microquasars or active galactic nuclei, are dominated with the magnetic-disk-accretion paradigm. Nevertheless, no reliable measurements of magnetic fields in these systems were available so far. Shvartsman (1971) was the first to predict the existence of a magnetic field for Cyg X-1. He wrote that flickering X-ray emission from Cyg X-1 evidenced for the presence of a black hole and indicated the role of the magnetic field in accretion onto a black hole (Pustilnik & Shvartsman, 1974; Kaplan & Shvartsman, 1976). Since then, there were many attempts to search for the magnetic field of the optical component of the Cyg X-1 binary (the O9.7Iab supergiant), but all these efforts resulted in upper limits only.

Our spectropolarimetric observations were performed with the 8.2-m Very Large Telescope (VLT) of the European Southern Observatory (Cerro Paranal, Chile) in its service mode with the FORS 1 spectrograph in June/July, 2007 and in July, 2008 (Table 1). The spectra were obtained in the 3680–5129 Å spectral range with the spectral resolution of $R = 4000$ and the signal-to-noise ratio $S/N = 1500-3500$ for spectra of intensity (Stokes parameter I). Cyg X-1 was in its X-ray "hard state" at that time. 13 spectropolarimetric spectra with exposure times of ~ 1 hour were obtained during 13 nights.

The details on the observing technique with FORS 1 and data reduction can be found, for example, in Hubrig (2004); see also references therein. Using the method described there, we obtained the mean longitudinal magnetic field $\langle B_z \rangle$; it is the magnetic field component along the line of sight, averaged over the visible stellar hemisphere and weighted by the local emergent spectral line intensity. It is diagnosed from the slope of the linear regression of V/I versus $-\frac{g_{\rm eff} e}{4\pi m_e c^2}\lambda^2 \frac{1}{I}\frac{{\rm d}I}{{\rm d}\lambda}\langle B_z \rangle + V_0/I_0$, where V is the Stokes parameter measuring the circular polarization; I, the intensity observed in unpolarized light; $g_{\rm eff}$, the effective Landé factor; e, the electron charge; λ, the wavelength; m_e, the electron mass; c, the speed of light; ${\rm d}I/{\rm d}\lambda$, the derivative of the Stokes I parameter; V_0/I_0, a constant; and $\langle B_z \rangle$ is the mean longitudinal field. The method is statistical: to increase the sensitivity, we used all observed spectral lines simultaneously.

Cyg X-1 possesses a strong interstellar/circumstellar linear polarization that can produce a cross-talk with circular polarization within the FORS 1 analyzing equipment. Moreover, the derived $\langle B_z \rangle$ is relatively low. For this reasons, we had to take certain precautions in our magnetic field measurements of the binary and to adjust the method to such conditions. We removed all spectral features not belonging to the photosphere of the Cyg X-1 optical component (O9.7 Iab): interstellar lines, CCD flaws, the He II λ4686 Å emission line, lines with strong P Cyg components. Telluric lines being rather weak in the considered spectral range, we find no pollution from these lines in our low-resolution spectra.

Before applying the procedures for the magnetic field measurements, we removed linear trends, mainly caused by the cross-talk between linear and circular polarization within the FORS 1, from our V/I-spectra. This seems to be an appropriate step since, as follows from Nagae *et al.* (2009), the optical-range linear polarization of Cyg X-1 has no significant spectral line features. Therefore, according to our estimates, the cross-talk can produce only a false V continuum slope and does not significantly distort the S-shaped V profiles of spectral lines caused by Zeeman effect (hereafter, Zeeman S-waves). The Stokes I spectra were normalized to the pseudo-continuum I_c, which is produced by the source energy distribution, interstellar reddening, broad diffuse interstellar bands (DIBs), as well as atmospheric extinction and detector sensitivity. After these reductions, the residual deviations of the least-squares linear regression follow the Gauss function up to $\pm 3.6\sigma(V/I)$, where $\sigma(V/I)$ is the standard deviation of V/I, i.e. the level of significance corresponds to the Gauss statistics now.

Table 1. Magnetic field from VLT spectropolarimetric observations of the X-ray binary Cyg X-1.

Date	JD*	Orbital phase	$\langle B_z \rangle$, G	σ, G	significance $\mid \langle B_z \rangle / \sigma \mid$
18-19 June 2007	2454270.768	0.650	−6	28	0.2
19-20 June 2007	2454271.778	0.830	37	22	1.7
20-21 June 2007	2454272.760	0.006	58	21	2.8
25-26 June 2007	2454277.808	0.907	22	28	0.8
29-30 June 2007	2454281.707	0.603	48	20	2.4
9-10 July 2007	2454291.766	0.400	101	18	5.5
14-15 July 2008	2454662.711	0.641	49	23	2.1
15-16 July 2008	2454663.684	0.816	22	22	1.0
16-17 July 2008	2454664.692	0.995	80	23	3.5
17-18 July 2008	2454665.692	0.174	24	19	1.3
23-24 July 2008	2454671.704	0.247	−16	20	0.8
24-25 July 2008	2454672.728	0.430	27	19	1.4
30-31 July 2008	2454678.676	0.500	128	21	6.2

*JD is the Julian date of the middle of observation; orbital phases φ are according to the ephemeris from Brocksopp *et al.* (1999): φ=0 corresponds to the optical component in front; σ is the standard deviation.

To verify our results (see Table 1), we used several tests: (1) each spectrum was subdivided in two halves at mid-wavelength to check that $\langle B_z \rangle$ values determined over each half separately were in agreement within error bars. (2) We repeated $\langle B_z \rangle$ calculations using fragments of spectra that include strong absorption lines (deeper than 4%) only: ~1/3 spectral points were used and $\langle B_z \rangle$ values were found in agreement with our earlier measurements using the whole spectral range within 1.5 $\sigma(\langle B_z \rangle)$. (3) Zeeman S-waves were found for the strongest lines.

Our measurements of $\langle B_z \rangle$ at different orbital phases, φ, are presented in Table 1 and Fig.1 a. It follows from Fig.1 a that $\langle B_z \rangle$ varies periodically with the orbital phase (two waves for period), reaching 130 G ($\sigma = 20$ G) at phase 0.5. Figure 1 b, presenting moving-average points (calculated as the mean of each consecutive 3 points of Fig.1 a), shows the regular variability component clearer. The dependence of $\langle B_z \rangle$ on φ is more complicated than for a magnetic dipole and has probably changed from 2007 to 2008.

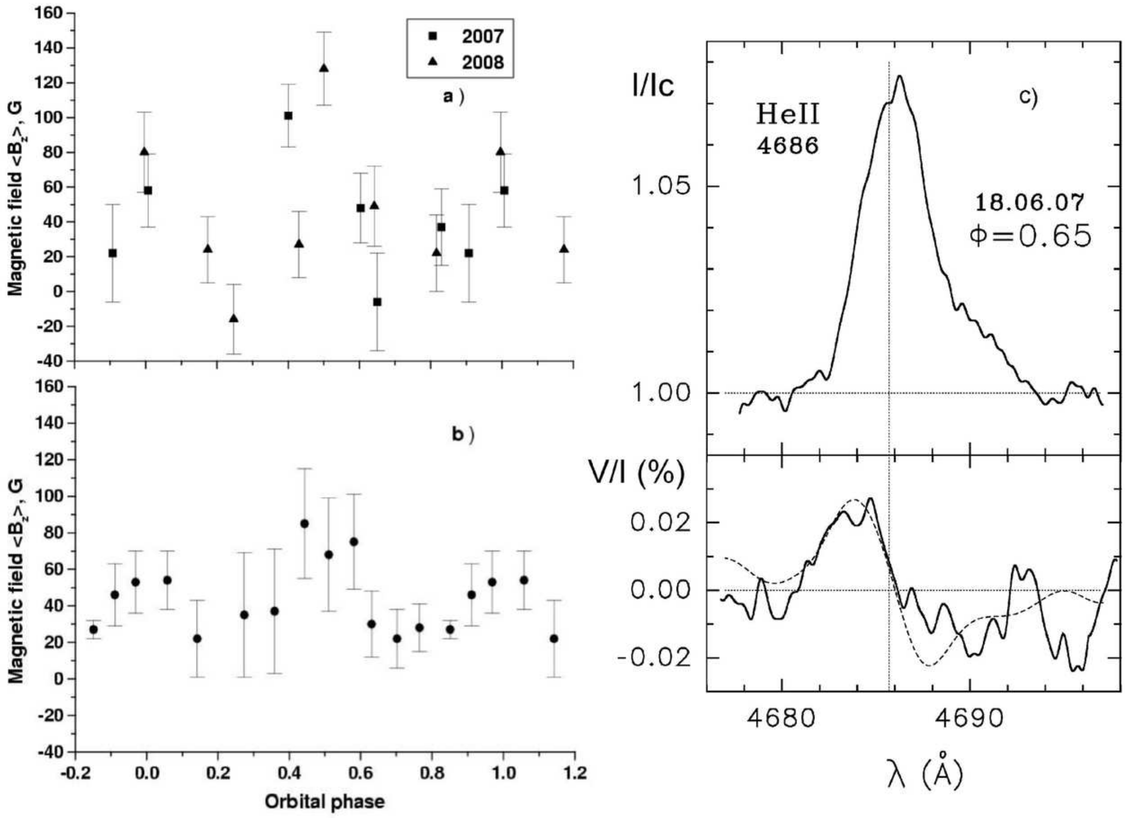

Figure 1. **a**, The mean longitudinal magnetic field of the Cyg X-1 optical component $\langle B_z \rangle$ (in Gauss) *vs.* the orbital phase φ for 2007 and 2008. **b**, The moving average points calculated as the mean of each consecutive 3 points of the panel **a**. **c**: The He II λ4686 Å spectral line profile I/I_c for June 18, 2007 (top); the solid curve in the bottom panel shows the observed V/I spectrum smoothed over 3 Å. The dashed curve displays the expected Zeeman S-wave shape $(dI/d\lambda)/I \propto V/I$, where I is smoothed over 3 Å. The good agreement between these curves demonstrates the possible existence of a rather large magnetic field in the region of forming He II λ4686 Å emission.

At the next step of our study, we investigated the He II λ4686 Å spectral line 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 a compound profile consisting of absorption (originating in the stellar photosphere) and emission (originating in the accretion structure) components. Certainly, the accuracy of the magnetic-field measurements using just a single line is considerably worse compared to those using the whole spectrum. Nevertheless, our analysis shows the results for the two spectra at the 4σ level: $\langle B_z \rangle = -730 \pm 170$ G for the orbital phase $\varphi = 0.65$ in 2007 and $\langle B_z \rangle = -420 \pm 106$ G for $\varphi = 0.43$ in 2008. The Zeeman S-wave in the V-spectrum smoothed over 3 Å and its correspondence to the $dI/d\lambda$ wave is presented in Fig.1 c for June 18, 2007.

To exclude the influence of the stellar-photosphere absorption component of

He II $\lambda4686$ Å, we subtracted the model-atmosphere line profile for each φ. We calculated it by the method described, for example, in Karitskaya *et al.* (2005). The subtraction changes numerical values of $\langle B_z \rangle$ but does not distort the qualitative result: the presence of a magnetic field of the order of $(300-1000)\ G$, on a significance level about $(2.5-3.5)\sigma$ in the region of formation of the $\lambda4686$ Å emission. The emission component of He II $\lambda4686$ Å originates in the outer part of the accretion structure. This is demonstrated with the Doppler tomogram (the binary system image in velocity space) constructed by us on the base of He II $\lambda4686$ Å profiles for Cyg X-1 from our VLT observations (Karitskaya *et al.*, 2009) and Terskol observations (Karitskaya *et al.*, 2005).

Consequently, $\langle B_z \rangle$ derived from the He II emission line is located in outer parts of the accretion structure. Its value, ~ 600 G, is in agreement with Shvartsman's ideas (Kaplan & Shvartsman, 1976) that the gas stream carries the magnetic field to the accretion structure and the gas is compressed by a factor of ~ 10 due to interaction with the structure of the outer rim. Along with the increase of gas density, the magnetic field is increased to $B \sim 600$ G. It takes place at a distance 6×10^{11} cm $= 2 \times 10^5 R_g$ from the black hole (Bochkarev, Karitskaya & Shakura, 1975), where R_g is the gravitation radius. According to Shakura & Sunyaev (1973), we get $B \sim 10^9$ G at $3R_g$ for the magnetized accretion disc standard model. Taking into account the radiative pressure predominance inside $\sim 10-20R_g$, we get $B(3R_g) \sim (2-3) \times 10^8$ G. Then the magnetic energy flux is 10^{37} erg/s, equal to or exceeding the luminosity of the X-ray flickering component. Actually, the region of main energy release for X-ray binaries extends from $5R_g$ to $27R_g$, and there should be a maximal frequency $F \sim 100$ Hz for Cyg X-1 (e.g., Sunyaev & Revnivtsev 2000). Thus, magnetic energy dissipation permits to account for the X-ray flickering.

Our results demonstrate that the VLT FORS1 observations of 2007–2008 permit to detect the presence of a magnetic field in Cyg X-1. These are the pioneer measurements in a black hole system. The field can be responsible for X-ray flickering. Our results point to necessity of taking into account the impact of the magnetic field on the matter-flow structure in Cyg X-1.

Acknowledgements: We would like to acknowledge ESO for granting VLT observations in service mode. The work was partially supported by RFBR grants 06-02-16843, 09-02-01136, 09-02-00993, 07-02-00535, and the grant of Support to Leading Scientific Schools of Russia 6110.2008.2.

References:

Bochkarev, N.G., Karitskaya, E.A. & Shakura, N.I., 1975, *Sov. Astr. Lett.*, **1**, 118
Brocksopp, C. et al., 1999, *A&A*, **343**, 861
Hubrig, S., Kurtz, D. W., Bagnulo, S. et al., 2004, *A&A*, **415**, 661
Karitskaya, E.A. et al., 2005, *As.Ap.Trans.*, **24**, 383
Karitskaya, E.A. et al., 2009, arXiv:0908.2719v1 [astro-ph.SR]
Kaplan, S.A. & Shvartsman, V.F., 1976, In: *Origin and evolution of galaxies and stars (Nauka, Moscow)*, 319
Nagae, O. et al., 2009, *A.J.*, **137**, 3509
Pustilnik, L.A. & Shvartsman, V.F., 1974, *IAU Symp.*, **64**, 213, In: C.Dewitt-Morrette (Ed.), Gravitational radiation and gravitational collapse. **64** (Dordrecht, Reidel)
Shakura, N.I. & Sunyaev, R.A., 1973, *A&A*, **24**, 337
Shvartsman, V.F., 1971, *Soviet Astr.*, **15**, 377
Sunyaev, R. & Revnivtsev, M., 2000, *A&A*, **358**, 617