Some Developments of the Weak Stellar Magnetic Field Determination Method on the Example of Cyg X-1

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ABSTRACT. Some developments of measurements of the weak stellar magnetic fields by the least square technique applied to spectropolarimetrical data are proposed and used for the X-ray binary Cyg X-1=HDE 226868 (the optical counterpart is an O9.7 supergiant). The V/I circular polarization spectra obtained during our spectropolarimetric FORS1 VLT observations have variable sloped continuum components not belonging to the object. It is shown that such components should be removed, otherwise these false sloped continua yield biased results. For HDE226868 the mean longitudinal magnetic field bias ∆<Bz> varies from 20 G to 100 G, which is comparable to its value. The slopes of I-spectra have smaller influence on <Bz> result but they should be subtracted too. We also consider the initial I- and V/I-spectra cleaning, effects from the deviating points, and their influence on the results of <Bz> measurements.

By using these developments we could detect magnetic field in Cyg X-1. That is the first successful measurement of magnetic field in a binary with a black hole. The value of the mean longitudinal magnetic field in optical component (9.7 Iab supergiant) changes regularly with the orbital phase reaching its maximum of 130 G (∆ ≈ 20 G).

The measurements based on Zeeman effect were carried through over all the observed supergiant photosphere absorption spectral lines. Similar measurements over the emission line He II 4686 A yielded a value of several hundreds Gauss with a smaller significance level.

Sources of wavelength-dependant circular polarization of optical continuum

- In contrast to previously studied stars (mainly A and late B types), luminous O-stars have usually significant interstellar / circumstellar linear (up to ~ 10 %) and weak circular (< 0.05 %) polarization in optical continuum.
- Any spectropolarimeter has cross-talk between linear and circular polarization within analysing equipment. It creates a false circularly polarized wavelength-dependant continual component of radiation for stars with linear polarization.

→ As a result, more and more often targets for magnetic field measuring has spectra of Stokes parameter ***V*** (measuring circular polarization) and ratio ***V/I*** (***I*** is Stokes parameter for total intensity) containing wavelength-dependant continual components $C_V(\lambda)$ and $C_{V/I}(\lambda)$, λ is wavelength.

Cyg X-1 = HDE 226868 observations

- Very Large Telescope (VLT) 8.2 m (Mount Paranal, Chile);
- Spectropolarimetry with FORS1 spectrograph;
- Resolution R=4000;
- Range 3680-5129 A;
- S/N = 1500 – 3500 (for I);
- since June 18 over July 9, 2007
- since July 14 over July 30, 2008

(Cyg X-1 in X-ray hard state)

13 nights of 1-hour observations

→ **13 spectra of intensity I and circular polarization V** were obtained.

X-ray binary Cyg X-1 = HDE 226868:

Magnitude $m_V = 9^m$

> 95% of optical radiation from O9.7 lab star;

Interstellar extinction A_V=3.36^m.

Interstellar/circumstellar linear polarization ~5%.

Stellar wind (Mdot ~ 5*10^{-6} Msun/yr).

Chemical peculiarities (excess mainly He, N, Si).

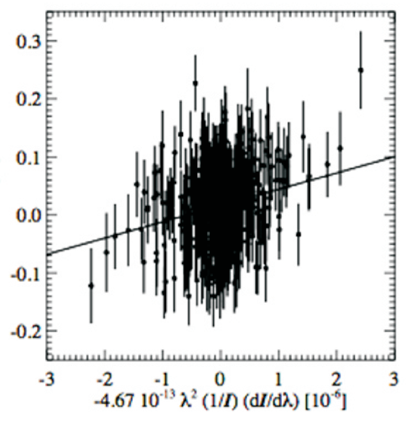
Moderate rotation velocity $V \sin i$ = 95 km/s.

The method of the magnetic field measurment

Mean longitudinal magnetic field ‹B_z› was determined by statistical processing of spectra of circular polarization V(λ) and intensity I(λ), using equation (e.g. Landstreet 1982):

$$\frac{V}{I} = -\frac{g_{\rm eff}\, e\lambda^2}{4\pi m_e c^2}\,\frac{1}{I}\,\frac{dI}{d\lambda}\,\langle \mathcal{B}_z\rangle$$

where g_{eff} is the effective Lande factor, $C_z = e/(4\pi m_e c^2)$ = 4.67*10^{-13} Å^{-1} G^{-1}. Least squares method (LSM) used for ‹B_z› calculation (for details see, e.g., Bagnulo et al. 2002, 2006; Hubrig *et al.* 2004).

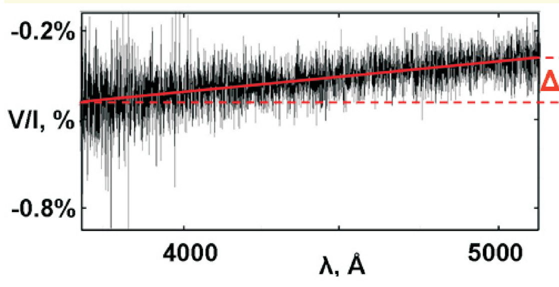


Sources of noise of <B> measurements, which should be removed from *I*- and *V/I*-spectra

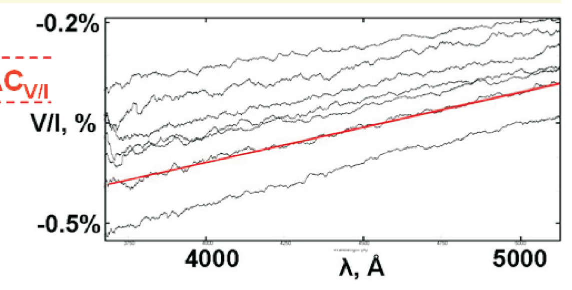
- 1) interstellar lines and narrow diffuse interstellar bands (DIBs);
- 2) defects (including residual cosmic ray tracks that remained after the standard observation processing);
- 3) He II 4686A line with complicated profile including the accretion-structure emission component (the second emission line Hα is situated outside the spectral range of our VLT observations);
- 4) emission components of lines with P Cyg effect.
- In addition we removed some λ intervals containing no observed lines besides noise.
- We found no pollution by telluric lines in our spectra.

Observed V/I-spectra slopes (*V/I-trends*)

Slope value $S = dC_{V/I}/d\lambda$ ~ 10^{-6}Å^{-1} is irregularly varied from night to night.



V/I-spectrum Cyg X-1 for a night (black line) and its linear regression (red slop line)



All V/I-spectra of 2008 smoothed by 50A-width Gauss filter (black lines) and the linear regression shown in the left box (red line)

The most probable reason of the V/I-spectra slopes is a **cross-talk** between linear and circular polarization within the FORS1 analysing equipment.

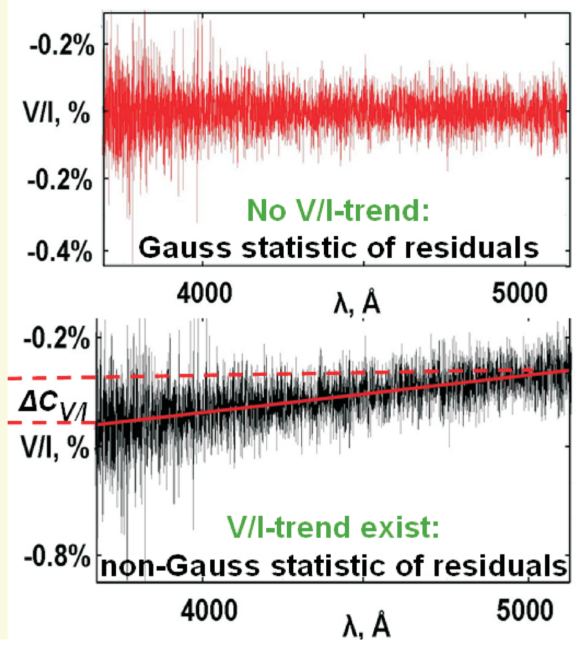
Influences of the V/I-trends on results of ‹B_z› measurements

Application of a least squares method (LSM) to data with **non-removed V/I trend results in distorted or even false <Bz> value and its significance**.

There are at least 2 reasons for it:

1) **Strong violation of residuals Gauss statistic;**
2) **Appearance of false <Bz> component.**

False ‹B_z› component is $\sim (\Delta\lambda_D / \lambda)^2 * dC_{V/I} / d\lambda$



Corrections of Cyg X-1 optical component ‹B_z› produced by the V/I-continuum slope removing

- For our Cyg X-1 FORS1 observations false ‹B_z› from single spectral line and sloped V/I continuum without Zeeman S-waves is several Gauss.
- To avoid any influence of the V/I-continuum slope on our ‹B_z› measurements, we subtracted linear trends from V/I spectra.
- For our Cyg X-1 VLT observations non-removed V/I-spectra slopes create <Bz> shifts from 20 to 84 G.
- All ‹B_z› corrections are negative.

Influence of I-spectra slopes on ‹B_z›

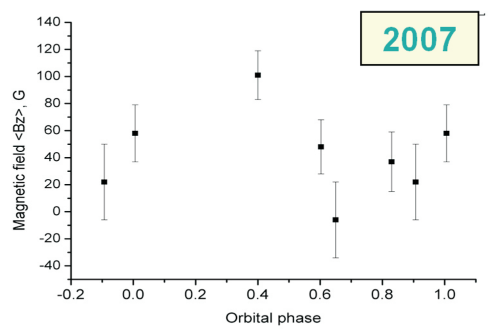
- We normalized I-spectra by pseudo-continuum.
- Wavelength dependence of I-continuum I(λ) is produced by:
  - -- the source energy distribution,
  - -- interstellar reddening,
  - -- broad diffuse interstellar bands (DIBs),
  - -- atmospheric extinction,
  - -- used equipment detector sensitivity.
- I-spectrum slopes reach |d(log(I(λ))/d(log(λ))| ~ 20.
- The slope removing gives ‹B_z› correction up to ~ 20 G.
- It is usually less than the statistical errors σ(‹B_z›) ~ 20 − 30 G.

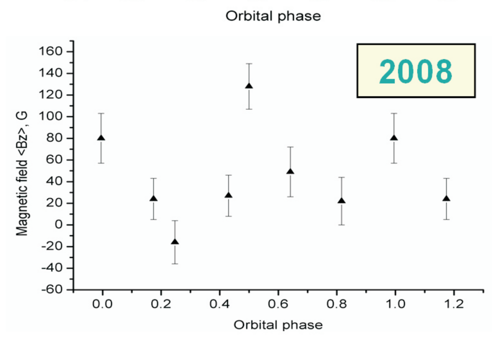
Results of <Bz> measurements of Cyg X-1 optical component

Date	Orbital phase	<Bz>, G	
18/06/07	0.650	-6+-28	
19/06/07	0.830	+37+-22	
20/06/07	0.006	+58+-21	(~ 3 σ)
25/06/07	0.907	+22+-28	
29/06/07	0.603	+48+-20	
09/07/07	0.400	+101+-18	(about 6 σ !)
14/07/08	0.641	+49 +-23	
15/07/08	0.816	+22 +-22	
16/07/08	0.995	+80 +-23	(> 3 σ)
17/07/08	0.174	+24 +-19	
23/07/08	0.247	-16 +-20	
24/07/08	0.430	+27 +-19	
30/07/08	0.500	+128 +-21	(about 6 σ !)

Tests:

1) Each spectrum was divided in two halves at mid-wavelength; <Bz>, determined over each half separately were coincided within error.
2) "Zeeman S-waves" for the strongest lines (e.g. HeI 4026 A) were found.
3) Deviations have Gauss statistic up to >3.5 sigma. It is an accuracy estimation control.





He II 4686 A Line Formation Region

According to Doppler tomogram (the binary system image in velocity space) He II 4686 A line emission regions are connected with outer parts of accretion structure.

Analysis of He II 4686 A spectral line

The line has compound profile: absorption (star photosphere) + **emission (accretion structure)**

It was omitted from the earlier analysis! Now we investigate it separately.

The accuracy of magnetic field measuring over 1 line considerably lower than from all lines.

But estimations on 4 sigma level was found for orbital phases 0.65 (2007) and 0.43 (2008):

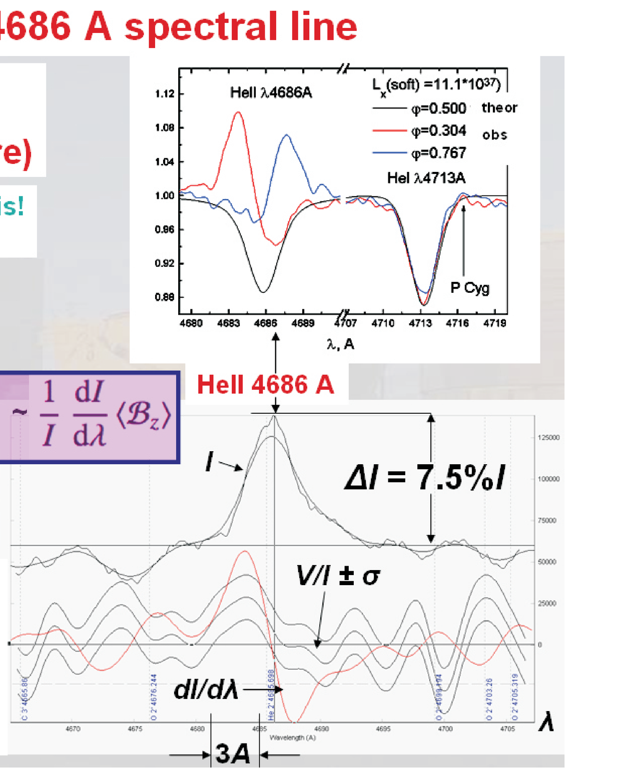
<Bz>=-730+/-170 G

<Bz>=+420+/-105 G

<Bz> reality is confirmed:

- by "Zeeman S-wave" in V-spectrum smoothed over 3 A (see +/- 1 sigma corridor on right figure);
- by its correspondence to the $dI(\lambda)/d\lambda$ wave.

$$\frac{V}{I} \sim \frac{1}{I}\,\frac{dI}{d\lambda}\,\langle \mathcal{B}_z\rangle$$



Cyg X-1 Magnetic Field

We got ***B*** **~ 100 G** for the star photosphere.

Phase dependence is more complicated than for dipole field model (may be quadrupole for 2008) and evidently has time variations.

The quadrupole is inclined in respect to the system axis of rotation.

Near orbital phase 0.5 (X-ray source in front) we look at magnetic pole.

Near orbital phase 0.0 we see the other magnetic pole.

Gas stream carries the field on to the accretion structure; the gas is compressed by interaction with outer rim. Gas density is increased on a factor 6-10: **B ~ 600 G** at a distance 6*10^{11} см = 2*10^5 R_g.

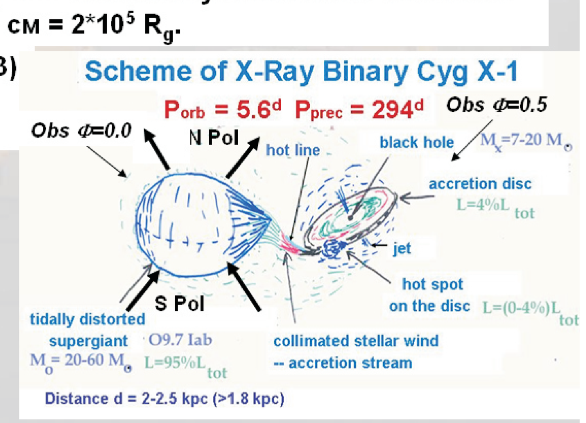
According to Shakura-Sunyaev (1973) magnetized accretion disc standard model

$$B(R) = B(R_g)\left(\frac{R_g}{R}\right)^{5/4}$$

→at 3 R_g $B \sim 10^9$ G.

Taking into account radiative pressure predominance inside ~10--20 R_g, we get:

$B(3\,R_g) \sim (2—3)\ 10^8$ G.



Near black hole the magnetic energy flux is 10^{37} erg/s which exceed the flickering component power.

So magnetic energy can account for the flickering.

The main results are reported in:

- E.A.Karitskaya, N.G.Bochkarev, S.Hubrig, Yu.N.Gnedin, M.A.Pogodin, R.V.Yudin, M.I.Agafonov, O.I.Sharova Magnetic Field in X-ray Binary Cyg X-1, 2009, arXiv: astro-ph 0908.2719
- E.A.Karitskaya, N.G.Bochkarev, S.Hubrig, Yu.N.Gnedin, M.A.Pogodin, R.V.Yudin, M.I.Agafonov, O.I. , 2010, The first discovery of a variable magnetic field in X-ray binary Cyg X-1 = V1357 Cyg, IBVS, No. 5950, 1
- Karitskaya, Eugenia A.; Bochkarev, N.G.; Hubrig, S.; Gnedin, Yu.N.; Pogodin, M.A.; Yudin, R.V.; Agafonov, M.I.; Sharova,O.I., The magnetic field in the X-ray binary Cyg X-1. In: Cosmic Magnetic Fields: from Planets to Stars and Galaxies, Eds. K. G. Strassmeier, A.G. Kosovichev, J. Beckman, Cambridge Univ. Press,. IAU Symp. 259, 2009, p. 137-138.

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