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Some Developments of the Weak Stellar Magnetic Field Determination Method for the Example of Cygnus X-1

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Abstract. Some developments of measurements of the weak stellar magnetic fields by the least square technique applied to spectropolarimetric data are proposed and used for the X-ray binary Cyg X-1 = HDE 226868 (the optical counterpart is an O 9.7 supergiant).

Keywords. Stars: magnetic fields, techniques: polarimetric, techniques: spectroscopic, methods: statistical, stars: early-type, stars: individual (Cyg X-1 = HDE 226868 = V1357 Cyg), (stars:) supergiants, (ISM:) extinction, X-rays: binaries, black hole physics

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In contrast to the stars with strong magnetic fields (mainly A and late B types), luminous O-stars have usually weaker field and significant interstellar / circumstellar linear polarization (up to $\sim 10\%$).

Any spectropolarimeter has cross-talk between linear and circular polarization within the instrument. It creates a spurious circularly polarized wavelength-dependent continual component of radiation for stars with linear polarization.

As a result, more and more often targets for magnetic field measurements have spectra of Stokes parameter V (measuring circular polarization) and spectra of ratios V/I (I is Stokes parameter for total intensity) containing wavelength-dependent continual components $C_V(\lambda)$ and $C_{V/I}(\lambda)$, where λ is the wavelength.

Bochkarev & Karitskaya (2011) proposed some developments of measurements of the weak stellar magnetic fields by the least square technique applied to spectropolarimetric data and used them for the X-ray binary Cyg X-1 = HDE 226868 (the optical counterpart is an O 9.7 supergiant).

The parameters of the object are: magnitude $m_V = 9^m$; $> 95\%$ of optical radiation is produced by the O9.7 Iab star; interstellar extinction $A_V = 3.36^m$; interstellar/circumstellar linear polarization $\sim 5\%$; stellar wind $M_{dot} \sim (2-3) * 10^{-6}\ M_{sun}$/yr; chemical peculiarities (mainly He, N, Si excess); and rotation velocity $V \sin i = 95$ km/s.

Our observations were made at the Very Large Telescope (VLT) 8.2 m (Mount Paranal, Chile) in the spectropolarimetric mode of the FORS1 spectrograph with resolution $R = 4000$ in the range $3680 - 5129 \AA$, with signal-to-noise ratio $S/N = 1500 - 3500$ (for I) from June 18 to July 9, 2007 and from July 14 to July 30, 2008 (Cyg X-1 in hard X-ray state). A total of 13 spectra of intensity I and circular polarization V were obtained (Karitskaya *et al.* 2009, Karitskaya *et al.* 2010).

The mean longitudinal magnetic field $\langle B_z \rangle$ was determined by statistical processing of the $V(\lambda)$ and $I(\lambda)$ spectra using the equation: $\frac{V}{I} = -C_Z\, g_{\rm eff}\, \lambda^2 \frac{1}{I} \frac{{\rm d}I}{{\rm d}\lambda} \langle B_z \rangle + \frac{V_0}{I_0}$ (e.g., Landstreet 1982), where $g_{\rm eff}$ is the effective Lande factor, $C_Z = \frac{e}{4\pi m_e c^2} = 4.67 * 10^{-13} \AA^{-1} G^{-1}$,

$\frac{V_0}{I_0} = const$. The least squares method is used for the $\langle B_z \rangle$ calculation (e.g., Hubrig *et al.* 2004).

The sources of noise in the $\langle B_z \rangle$ measurements, which should be removed from the I- and V/I-spectra, are: 1) interstellar lines and narrow diffuse interstellar bands (DIBs); 2) defects (including residual cosmic ray tracks not removed by the standard observation processing); 3) He II 4686 $\AA$ line with profile including the accretion-structure emission component; and 4) the emission components of the lines showing the P Cyg effect. In addition, we removed some λ intervals containing noise only. We found no pollution by telluric lines in our spectra.

The slope value $S = \mathrm{d}C_{V/I}/\mathrm{d}\lambda \sim 10^{-6}\AA^{-1}$ varied irregularly from night to night. The most probable reason for the V/I-spectra sloping is the cross-talk between linear and circular polarization within the FORS1 analyzing equipment.

The application of the least squares method without correcting for the V/I trend results in distorted or even spurious $\langle B_z \rangle$ values and in a distorted accuracy of these values. That happens for at least 2 reasons: 1) strong violation of Gauss statistics by the residuals; 2) appearance of $\langle B_z \rangle$ spurious component $\propto (\Delta\lambda_D/\lambda)^2 * \mathrm{d}C_{V/I}/\mathrm{d}\lambda$. Here $\Delta\lambda_D$ is the spectral line width.

For our Cyg X-1 FORS1 observations, spurious $\langle B_z \rangle$ from single spectral line and sloped V/I continuum without any Zeeman feature is several Gauss. To avoid any influence of the V/I-continuum slope on $\langle B_z \rangle$ measurements, we subtracted the linear trends from V/I spectra. In the case of our Cyg X-1 observations, the uncorrected slopes of the V/I-spectra create $\langle B_z \rangle$ shifts from -20 to -84 G (Bochkarev & Karitskaya 2011).

We normalized the I-spectra using a pseudo-continuum. The wavelength dependence of the I-continuum $C_I(\lambda)$ is produced by: the source energy distribution, interstellar reddening, broad DIBs, atmospheric extinction, and the sensitivity of the detector. The I-spectrum slopes reach $|\mathrm{d}(\log(I(\lambda))/\mathrm{d}(\log(\lambda))| \sim 20$. The removal of the slope gives a $\langle B_z \rangle$ correction up to ~ 20 G. It is usually less than the statistical errors $\sigma(\langle B_z \rangle)$, which are $\geqslant 20 - 30$ G.

The value of the mean longitudinal magnetic field in the optical component (O 9.7 Iab supergiant) changes regularly with the orbital phase, and reaches a maximum of 130 G ($\sigma \approx 20$ G) (Karitskaya *et al.* 2009, 2010).

The measurements based on the Zeeman effect were carried out over all the observed supergiant photosphere absorption spectral lines. Similar measurements over the emission line He II λ4686 Å yielded a value of several hundred Gauss with a smaller significance level. The emission component of this line originates in the outer parts of the accretion structure. So we measure $\langle B_z \rangle$ in this region (Karitskaya *et al.* 2009, 2010).

We got $\langle B_z \rangle \sim 100$ G for the star's photosphere. The gas stream carries the field on to the accretion structure; the gas is compressed by interaction with the structure's outer rim. Gas density is increased by a factor of 6-10 (we obtained several hundred Gauss). According to the Shakura – Sunyaev magnetized accretion disc model at $3R_g$: $B \sim 10^9$ G. Taking into account radiative pressure predominance inside $\sim 10 - 20R_g$, we get: $B(3R_g) \sim (2-3)10^8$ G. Such magnetic fields can be responsible for the observed X-ray flickering.

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References

Bochkarev, N. G. & Karitskaya, E. A. 2011, in D. O. Kudryavtsev, & I. I. Romanyuk (eds.), *Magnetic Stars* (N.Arkhyz: SAO RAS publ.), p. 199

Hubrig, S., Szeifert, T., Schöller, M. *et al.*, 2004, *A&A*, 415, 685

Karitskaya, E. A., Bochkarev, N. G., Hubrig, S. *et al.*, 2009, *astro-ph* 0908.2719

Karitskaya, E. A., Bochkarev, N. G., Hubrig, S. *et al.*, 2010, *Inf. Bull. Variable Stars*, 5950, 1

Landstreet J. D. 1982, *ApJ*, 258, 639

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