Sco X-1 and Cyg X-1: Determination of Strength and Structure of Magnetic Field in the Nearest Environment of Accreting Compact Stars

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Abstract. We estimated the magnetic field strength of compact stars in X-ray binaries Sco X-1 and Cyg X-1, via various methods of determination of magnetic fields. For Sco X-1 we used three independent methods. One of them is based on the correct account of the Faraday rotation of polarization plane in the process of electron scattering of X-rays from accreting neutron stars. Numerical calculations are made with use of first X-rays polarimetric data presented by Long et al. (1979). Other original method of determining the magnetic field developed by Titarchuk at al. (2001) is based on observed quasi-periodic oscillations (QPO) frequencies in X-ray binaries that can be considered as magnetoacoustical oscillations of boundary layer near a neutron star. The optical polarimetric data obtained in 70-th have been also used for estimation of magnetic field of the neutron star in Sco X-1 and of nearest environment around the black hole in Cyg X-1.

Key words: polarization – scattering – stars: magnetic stars: magnetic fields: acoustic oscillations: magnetoacoustic oscillations

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1. Introduction

For X-ray sources of type Sco X-1 the Compton scattering by electrons is very important for generation of the radiation spectrum. The Compton scattering produces the linear polarization of radiation from such type objects. The polarization of X-ray sources have been first considered by Rees (1975) and independently by Lightman & Shapiro (1975). They calculated the spectrum of polarized radiation from an accretion disk.

But the spectrum of polarized radiation is drastically changed due to the Faraday rotation of the polarization plane in a magnetic field. Gnedin & Silant’ev (1980, 1997) (see also the book by Dolginov et al. 1995) have calculated the spectrum of polarized radiation for the various astrophysical objects with magnetic fields taking into account the Faraday rotation effect and suggested the new method of determination of stellar magnetic field with the spectrum of broad band linearly polarized radiation (see, for example, Gnedin & Silant’ev 1984; Gnedin et al. 1988). The application of their method to accretion disks around supermassive black holes (AGNs, QSOs) has been recently developed by Gnedin & Silant’ev (2002).

The first rough estimation of a magnetic field of Sco X-1, based on the first X-ray polarimetric observation made by Long et al. (1979), was done by Gnedin & Silant’ev (1980).

Recently Titarchuk et al. (2001) presented the detail model of quasi-periodic oscillations (QPO) of Sco X-1 using a large set of Rossi X-ray Timing Explorer (RXTE) data for this object. The QPOs have been observed not only into kHz range, but also at 6 Hz. There is an almost linear correlation between Sco X-1’s kHz and 6 Hz QPOs. They identify the 6 Hz frequencies as acoustic oscillations of a Keplerian disk around the neutron star (NS) that is formed after radiation pressure near the Eddington accretion rate destroys the disk. They showed that the disk is placed near one NS radius from the surface of NS. It is the remarkable fact that they could estimate the Sco X-1 magnetic field. It appears to be $0.7 \times 10^6 G$ at about one NS radius above the NS surface.

Let us remind also that still Gnedin & Shulov (1971) and Nikulin et al. (1971) claimed some evidence of circularly polarized light of Sco X-1 in optical spectral range. Though the followed measurement (see Illing & Martin 1972) did not confirm the existence of circular polarization for Sco X-1, Kemp et al. (1972) claimed the possible existence of the strong nonstationary circular polarization state. They called this state as a “flaring polarization”. Nevertheless the situation with determination of magnetic field of Sco X-1 was unclear till now. The last results by Titarchuk et al. (2001), allow to reconsider this situation and to compare the results of various methods of magnetic field estimations.

We start with the detail description of presented methods of magnetic field estimations of compact stars emitting X-rays.
2. Linear Polarization Spectrum of X-ray Radiation from Magnetized Disks and Envelopes Around a Compact Star

The X-ray radiation of a compact star (neutron star, black hole), scattered on electrons of the envelope of an accreting matter, acquires linear polarization. It is well known, however, that integral polarization from a spherical envelope is equal to zero due to total compensation of directions of electric vectors from various areas of this envelope. If magnetic field is absent, the nonzero net polarization requires nonspherical shape of the scattering electron envelope. If there is the presence of a magnetic field in the circumstellar electron envelope, the situation is radically changed. The scattered radiation undergoes the Faraday rotation of its polarization plane due to the propagation in a magnetized plasma.

The angle of the Faraday rotation $\chi$ is determined by the expression (see Gnedin & Silant’ev 1980, 1997)

$$\chi = \frac{1}{2} \delta \tau_T \cos \theta,$$

$$\delta = \frac{3 \omega_B e}{2 r_e \omega^2} \approx 1.2 \left( \frac{B}{10^6 G} \right) \left( \frac{1 \text{keV}}{\hbar \omega} \right)^2,$$

where $\tau_T$ is the Thomson optical thickness of the envelope, $\theta$ is the angle between the directions of a magnetic field $B$ and radiation propagation $n$, $r_e = e^2/m_e c^2$ is classic electron radius, $\omega_B = eB/m_e c$ is the cyclotron frequency.

If the magnetic field increases, the angle $\chi$ increases too and partly polarized scattered radiation begins to undergo the Faraday rotation. The rotation angles $\chi$ are different for waves scattered in different volumes along the line of sight $n$, and, as a result, the total radiation from all volume elements will be depolarized (see Fig. 10 from the review by Gnedin & Silant’ev 1997).

The spectrum of polarized radiation from a spherically symmetric envelope has been calculated by Gnedin & Silant’ev (1980). For a spherical envelope with the dipole magnetic field only the magnetic equator volumes don’t produce the Faraday rotation of polarization plane because of for these volumes $\cos \theta \approx 0$ and $\chi \approx 0$. As a result, only the radiation scattered in equatorial volumes acquires net polarization in the plane $(nM)$, where $n$ and $M$ are the directions of line of sight and dipole magnetic field, correspondingly. Namely this radiation alone gives rise to non-zero integral polarization from the magnetized envelope. The shape of the spectrum of the integral linear polarization has a bell-shaped form. Indeed, for very short wavelengths the Faraday rotation angles tend to zero and the integral polarization disappears due to spherical symmetry of the envelope. For very long wavelengths the angles of Faraday’s rotation increase and the near equatorial region with $\chi \approx 0$ decreases what diminishes the integral polarization. So, the
maximum integral polarization corresponds to such magnetic field strengths and wavelengths when the mean rotation angle $\chi \approx 1$. The process of strong depolarization begins with the values of magnetic field and wavelengths when $\delta \tau > 1$ (see Eq. (1)).

For disk-like electron envelope without the true absorption with $\tau \gg 1$ we have for outgoing radiation (see Silant’ev 2002):

$$P_l(n, B) \approx 0.914 \frac{1 - \mu^2}{1 + 2\mu} \frac{1}{\sqrt{1 + \delta^2 \cos^2 \theta}}. \quad (2)$$

where $\mu = \cos \vartheta$, and $\vartheta$ is the angle between the line of sight $n$ and the normal to the disk surface. The terms without the square root describe roughly the polarization degree $P_l(n)$ of radiation in the absence a magnetic field. So, the formula can be written as

$$P_l(n, B) \approx \frac{P_l(n)}{\sqrt{1 + \delta^2 \cos^2 \theta}}. \quad (3)$$

Later we shall use this formula for the estimation of magnetic field in the environment of the source Sco X-1.

For the spherically symmetric optically thin envelope around the neutron star with the dipole magnetic field the degree of linear polarization of X-rays scattered into this envelope can be estimated by the expression

$$P_l(n, B) = \tau f(R_0/R_s; \delta_s \tau_0; \theta) \sin^2 \theta. \quad (4)$$

Here $R_0/R_s$ is the ratio of the envelope radius to the neutron star radius, $\delta_s$ is the depolarization parameter (1) that corresponds to the stellar equatorial magnetic field strength. The function $f$ is tabulated by Gnedin & Silant’ev (1980, 1984).

In the region of the depolarization when $\delta_s \tau > 1$ the asymptotic expression of the function $f$ takes a place:

$$f \approx (\delta_s \tau)^{\frac{n-1}{n+2}} \sim (\omega/\omega_0)^{\frac{2(n-1)}{(n+2)}}. \quad (5)$$

Here $n$ is the exponent of radial dependence of the electron density in the envelope: $N_e \sim r^{-n}$ ($n \neq 0$). The value $\omega_0 = (3\omega_B c/2r_e)^{1/2}$. If, for example, $n = 2$, the function $f$ drops with frequency decrease as $f \sim \omega^{-1/2}$. For $\delta_s \tau \ll 1$ (large frequencies) the spectrum of polarization degree has universal dependence: $P_l \sim \omega^{-4}$.

3. Magnetic Field Estimation from Magnetoacoustic Oscillations in Neutron Star Binaries

The original method to determine the magnetic field around neutron stars based on observed kHz and viscous quasi-periodic oscillations (QPO) frequencies has recently been proposed by Titarchuk et al. (2001). They have analyzed magnetoacoustic wave formation on the layer between a neutron star surface and the inner edge of a Keplerian disk and
derived formulas for the magnetoacoustic wave frequencies for different regimes of radial transition layer oscillations. As a result they demonstrated that one can use the QPO as a new kind of probe to determine the magnetic field strengths of neutron stars in the binaries.

For the two extreme (acoustic and magnetic) cases Titarchuk et al. (2001) have been obtained an approximate formula for the magnetoacoustic frequency $\omega_{MA}$:

$$\omega_{MA} \approx \left\{ \left( \frac{\beta_S}{\pi} \right)^2 \frac{V_S^2}{4(r_{out} - r_{in})^2} + \left( \frac{\beta_M}{\pi} \right)^2 \left( \frac{\alpha+2}{4} \right)^2 \frac{V_A^2}{V_A^2} \left( \frac{r_{out}}{r_{out}} \right)^2 \right\}^{1/2}. \tag{6}$$

Here $V_S$ is the sound velocity, $V_A$ is the Alfven velocity, $r_{out}$ and $r_{in}$ are the outer and the inner radii of a transit layer. The index $\alpha$ is related to the multipole magnetic field through the expression of $V_A^2 \sim r^{-\alpha}$, so that $\alpha = 6, 8, 10$ are for the dipole, quadrupole, and octupole, respectively.

The parameters $\beta_S$ and $\beta_M$ are determined by the transcendental equation (see Titarchuk et al. 2001):

$$\tan \beta = -\frac{2(\alpha - 2)\beta}{(\alpha + 2) \left\{ \frac{\eta \beta^2}{(\eta - 1)^2} + \left[ \frac{\alpha - 2}{\alpha + 2} \right]^2 \right\}}, \tag{7}$$

where $\beta = z_{out} - z_{in}$ and $\eta = z_{out}/z_{in} = (r_{out}/r_{in})^{(\alpha+2)/2}$, $z_{out}$ and $z_{in}$ are z-axis for the transit layer.

Titarchuk et al. (2001) estimated approximately the values of $\beta_S$ and $\beta_M$:

$$\beta_M \approx \frac{\pi}{2} + \frac{2}{\pi} \left[ \frac{(\pi/2)^2 \eta}{(\eta - 1)^2 + \frac{1}{4}} \right], \tag{8}$$

for $\alpha = 6$ and

$$\beta_S \approx \left\{ 1.5 / \left[ 1 + 1.5\eta/(\eta - 1)^2 \right] \right\}^{1/2} \tag{9}$$

for $\alpha = 0$ (the pure acoustic case).

Substituting the sound velocity $V_S = (kT/m_p)^{1/2}$ and the Alfven velocity $V_M = B(r_{out})/(4\pi\rho)^{1/2}$ one can estimate the magnetic field strength at the outer boundary of the transition layer. Then using the multipole law for the magnetic field one can also estimate the magnetic field strength at the neutron star surface.

4. Magnetic Field Estimation from Circular Polarization of Optical Light of a Binary System

The broad-band polarimetry of the optical continuum radiation is the effective direct method of the magnetic field estimation. The electromagnetic wave which is incident
onto plasma with a magnetic field produces oscillations of electron velocity. As a result
an additional Lorentz force appears:

$$\mathbf{F} = \mathbf{F} \left( \frac{\omega_B}{\omega}, \mathbf{E} \times \mathbf{B} \right),$$

(10)

which depends on the ratio of the cyclotron frequency to radiation one and on the angle
between the directions of wave’s electric vector $\mathbf{E}$ and the magnetic field $\mathbf{B}$.
As a result of the action of this Lorentz force magnetized plasma acquires dichroism and birefringence
properties, becoming similar to any anisotropic medium. In a magnetized plasma two
types of electromagnetic waves (normal modes or normal waves) with different types of
elliptical polarization should be propagated. These normal waves are usually called or-
dinary (O.W.) and extraordinary (E.O.W.) with their intrinsic refraction indices, phase
velocities and polarization. O.W. behaves as an usual electromagnetic wave in a plasma
without a magnetic field. For E.O.W. transport coefficients for various emission (magneto-
obremsstrahlung) and scattering (electron scattering) processes have resonance at
cyclotron frequency $\omega_B$ (in detail see Dolginov et al. 1995).

In the case when the radiation frequency $\omega$ is much larger than the cyclotron frequency
$\omega_B$, the radiation is predominantly circularly polarized:

$$P_V = 2(\omega_B/\omega) \cos \theta; \quad P_l \sim P_V^2 \sim (\omega_B/\omega)^2.$$

(11)

One of the most important case is the cyclotron resonance: $\omega \approx \omega_B$ (remember that
$\omega_B/\omega \simeq 0.93 \cdot 10^{-8} \lambda(\mu m)B(G)$ ). For the optical range this case corresponds to magnetic
field strengths $B \sim 10^7 \div 10^8 G$. At cyclotron resonance the plasma radiation is completely
polarized:

$$P_l = \frac{\sin^2 \theta}{1 + \cos^2 \theta}; \quad P_V = \frac{2 \cos \theta}{1 + \cos^2 \theta}; \quad P_l^2 + P_V^2 = 1.$$

(12)

In our case of the close binary system with a magnetized neutron star the optical
radiation of the accreting disk or plasma envelope around a neutron star can be circularly
polarized. As a result the estimation of the neutron star magnetic field strength can be
obtained from the measured optical circular polarization.

5. Sco X-1: Estimation of Magnetic Field Strength

The X-ray polarization of Sco X-1 was searched by Long et al. (1979). Multiple observa-
tions of Sco X-1 were carried out with the Bragg crystal polarimeter aboard OSO8. An
unambiguous detection of the time-averaged polarization was obtained for Sco X-1 which
has a polarization $P_l = (0.39 \pm 0.20)\%$ at 2.6 keV and $P_l = (1.31 \pm 0.40)\%$ at 5.2 keV.
These data give a signature of the polarization fall at energy values below 5.2 keV. If one
suggests that this fall is due to the Faraday depolarization effect one can estimate the
magnetic field strength at an environment of the neutron star in Sco X-1 binary system. The ratio $P_l(2.6\,\text{keV})/P_l(5.2\,\text{keV}) \approx 0.3$.

Using Eq. (3), we obtain for the 5.2 keV case
\[
\delta \cos \theta \simeq \sqrt{(P_l(\text{n})/1.31)^2 - 1}.
\]

The choice of $P_l$ depends on the angle of inclination of a disk. It is clear that we are to take $P_l \geq 1.31\%$. As a result we have the estimation:
\[
B \geq 2.3 \times 10^7 \sqrt{(P_l/1.31)^2 - 1}\,\text{G}.
\] \hspace{1cm} (13)

This estimation takes place for the model of optically thick inclined disk. If we choose $P_l \simeq 2$, we obtain $B \geq 2.6 \times 10^7\,\text{G}$. Analogous estimation for the 2.6 keV case gives $B \geq 2.8 \times 10^7\,\text{G}$, i.e. in range of observational errors both estimations coincide one with another. It seems the polarized radiation forms at the inner part of accretion disk where the temperature is higher.

Another estimation follows from the model of spherical electron envelope in dipole magnetic field. Considering that the polarization 1.31\% corresponds to the position at the polarization spectrum curve which is near maximum, i.e. $\delta_s/\eta^3 \sim 1$, we obtain
\[
B_s \geq 2.3 \times 10^7 \frac{\eta^3}{\tau}\,\text{G}.
\] \hspace{1cm} (14)

Here, $\eta = R_0/R_s$ is the ratio of the envelope radius to the neutron star radius and $\tau$ is the Thomson thickness of the envelope. Taking $\eta \simeq 2$ and $\tau \simeq 0.25$, we obtain from (14) the estimation $B_s \simeq 7 \times 10^8\,\text{G}$, or the value $B \simeq 10^8\,\text{G}$ in the region of an envelope. The estimations (14) considerably greater than those from (13). In reality this difference is more considerable because the condition $P_l(5.2\,\text{keV})/P_l(2.6\,\text{keV}) \simeq 3.3$ can be carried out only if $\delta_s > \eta^3/\tau$.

Another way of estimation of Sco X-1 magnetic field is to use observed kHz and viscous QPO frequencies. This method was developed by Titarchuk et al. (2001). They used the best-fit parameters of Sco X-1 transition layer and determined the magnetic field strength $B_{TL} = (1.0 \pm 0.05) \times 10^6\,\text{G}$ and $R_{TL} = 2.12 \times 10^6\,\text{cm}$ in the transition layer. An extrapolation of the magnetic field from $R_{TL}$ towards the neutron star radius gives us $B_s = 8 \times 10^6\,\text{G}$ and $B_s = 3.3 \times 10^7\,\text{G}$ for the dipole and octupole fields, respectively. These values appear close to the X-ray polarimetric estimation of neutron star magnetic field given by (13).

Third way of estimation of Sco X-1 magnetic field is connected with observations of circular polarization of optical light in Sco X-1 binary system.

Gnedin and Shulov (1971) and Nikulin et al. (1971) claimed occasional appearance of appreciable and variable circular polarization of optical light of Sco X-1 (see, also, Severny & Kuvshinov, 1975). Though Illing & Martin (1972) didn’t confirm these results, Kemp et al. (1972) claimed also evidence of the occasional appearance of circular polarization of Sco X-1 that was named by them as "flaring polarization".
The net circular polarization of Sco X-1 was estimated with Eq. (11). Gnedin & Shulov (1971) made the observations of circular polarization in the yellow-red light that corresponds the effective wavelength $\lambda_{eff} = 0.64\mu m$. For their case estimation (11) give the following value of the magnetic field strength:

$$B \geq 2 \cdot 10^6 \left( \frac{P_V}{0.01} \right) G.$$  

This value corresponds quite well to the magnetic field magnitude derived by Titarchuk et al. (2001). However, the magnitude (11) should be considered only as the low limit for the real magnetic field of the neutron star because one need to take into account the contribution of the optical companion in the radiation of the accreting disk of Sco X-1 system. Therefore the real value of the neutron star magnetic field must be increased at least an order and reaches the value at the level $\geq 10^7 G$.

This is the remarkable thing that three independent estimations give close values for the magnetic field strength in Sco X-1 system.

It should be noted that the case of accretion disk with the chaotic (turbulent) magnetic fields gives the same estimation (13) as for some regular magnetic field with appropriate choice of the angle $\theta$ (see formulas in Silant’ev, 2002). Besides, the model with chaotic magnetic fields explains naturally the "flaring" character of circular polarization that is due to the fluctuations of a magnetic field.

6. Cyg X-1: Estimation of Magnetic Field Strength in a Plasma Near the Black Hole

How to extract energy from a rotating black hole is important issue in astrophysics. Many people have considered various alternative mechanisms for extracting energy from a rotating black hole. Among them the most promising one is the famous Blandford-Znajek mechanism (Blandford & Znajek 1977). In this mechanism a Kerr black hole is assumed to connect with surrounding matter with magnetic field lines. The magnetic field lines thread the black hole's horizon and its rotation twists the magnetic field lines and transports energy and angular momentum from the black holes to the accretion disk (Blandford 2001; Li 2002; Li & Paczynski 2000, and references therein).

A magnetic field connecting a black hole to a disk has important effects on the balance and transfer of energy and angular momentum. The global structure of black hole magnetospheres involving axisymmetric magnetic field and plasma injected from an accretion disk has been extensively investigated for explaining various observational features of transient X-ray binaries and active galactic nuclei (see, e.g., for the review by Beskin 1997).

Recently Robertson & Leiter (2001) claimed an evidence for intrinsic magnetic moments in black hole candidates.
The Electro-Magnetic Black Hole theory has been recently developed by Ruffini (2002). He has applied this theory to the analysis of the GRB phenomenon. He showed the structure of burst and afterglow of GRB can be explained within the theory based on the vacuum polarization process occurring in an Electro-Magnetic Black Hole.

Unfortunately there is no till now the direct evidence of the presence magnetic field in near environment around a black hole.

The marginal evidence of X-ray polarization of Cyg X-1 allows in the accretion disk around the compact X-ray object (black hole) (Weisskopf et al. 1977, Long et al. 1980) with the Bragg crystal polarimeters aboard OSO8. The detection of the time-averaged polarization was obtained for Cyg X-1 at the level: \( P(2.6\,\text{keV}) = 2.4\% \pm 1.1\% \) and \( P(5.2\,\text{keV}) = 5.3\% \pm 2.5\% \). If the decrease of polarization at 2.6 keV one explains as a result of the Faraday depolarization, the estimation of a magnetic field strength via Eq. (2) gives \( B \geq 10^7\,\text{G} \). It is curious that this magnetic field magnitude is quite sufficient to explain the famous result of measurement by Michalsky & Swedlund (1977) of variable optical circular polarization of Cyg X-1: \( P_V \approx 5 \cdot 10^{-4} \).

### 7. Conclusion

We estimated the magnetic field magnitudes of two X-ray binaries: Sco X-1 and Cyg X-1. We used for estimation two different methods. One of them is connected with correct account of the Faraday rotation of polarization plane in the process of scattering of X-ray radiation (method developed by Gnedin and Silant’ev 1980, 1984, 1997). Another original method of determining the magnetic field of the objects like Sco X-1 is developed by Titarchuk et al. (2001). This method is based on observed quasi-periodic oscillations (QPO) frequencies in X-ray binaries and their interpretation as magnetoacoustic oscillations in neutron star binaries. It is remarkable that both methods give close results: magnetic field strength of neutron star in Sco X-1 appears at the level of \( B_S \approx 10^7\,\text{G} \). It is wonderful that measurements of optical circular polarization of Sco X-1 give the same estimation of neutron star magnetic field in Sco X-1 (see Eq. (15) with taking into account the fact that optical radiation is generated in outer layers of the accretion disk comparatively far away from the neutron star itself).

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