Magnetic and Electric Fields around the Black Hole in Cyg X-1

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Abstract

Analysis of polarimetric observations of X-ray binary Cyg X-1/HDE 226868 including the data obtained by BTA-6m allows to estimate the magnetic field magnitude near the inner radius of the accretion disk. The magnetic field magnitude occurred to be \( \sim 10^8 \) G. For power law of radial dependence of magnetic field into an accretion disk we estimates the value of an index of power law. For the Cyg X-1/HDE 226868 system the value of this index appears non less then two. If one accepts as a characteristic scale of a magnetic field generation region the dyadosphere radius, one can estimate the charge magnitude of a black hole. For Cyg X-1 this magnitude appears to be \( \sim 0.01 M \sqrt{G} \), where \( M \) is a black hole mass.

1 Introduction

Cygnus X-1 is a X-ray binary star system consisting of a compact object of at least 8 solar masses and of an O9.7 Iab supergiant with the effective temperature \( T_e = 30000 \)K and luminosity \( L \approx 10^{38} \) erg s\(^{-1}\). This magnitude is approximately ten times higher than the X-ray luminosity of the compact object. X-ray and optical fluxes of this system are varied with the orbital period \( P_{\text{orb}} = 5^d.6 \). The light curve determines the mass function that appears quite low \( f(M) = 0.25M_\odot \). Nevertheless, taking into account the value of the inclination angle and the typical magnitude of OB-supergiant mass one can estimate the compact object mass not less than \( 8M_\odot \). It means that the X-ray compact object in the Cyg X-1 system is the black hole (see the last review by Cherepaschuk, 2001).

The observed X-ray spectrum of Cygnus X-1 is well described as a radiation from a geometrically thin plasma accretion disk around the black hole. The theory of such disks is now well developed, the basic classical work having made by Shakura and Sunayev (1973). The disk model reproduces quite well as the
soft so hard spectral components in high or low states of a disk. The main difficulty of the modern models is to explain the unusual transitions between these states.

There is an exciting problem of existence of magnetic field in the nearest environment of a black hole. This problem appears tightly connecting with another key problem how to extract energy from a rotating black hole. Many authors have considered various alternative mechanisms for extracting energy from a rotating black hole. Among them the most promising one is the well-known Blandford-Znajek mechanism (Blandford and 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 hole to the accretion disk (Blandford, 2001; Li, 2002; Li and 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 magnetosphere 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 AGNs (see, e.g., for review by Beskin, 1997). Recently Robertson and Leiter (2002) claimed an evidence for intrinsic magnetic moments in galactic black hole candidates.

Another new idea was presented recently by Ruffini et al. (2001, 2002) and Punsly (2001). It has been suggested that the observed features of gamma-ray bursters can be modelled by the presence of an electrically charged black hole. Preparata et al. (1998 and 2002) present a model of GRB 971214. They claimed that basic energy requirements of GRB sources can be easily accounted for by a pair creation process occurring in, so-called, the "Dyadosphere" that can be considered as the ergosphere of a charged black hole. The "Dyadosphere" is defined by Preparata et al. (2002) as the region outside the horizon of an electromagnetic black hole (EMBH) where electromagnetic field exceeds the critical value for \(e^+e^-\) pair production.

The energy of a fast rotating BH can be transferred into energy of strong relativistic jets. Namely this process was considered by Blandford and Znajek (1977). They estimated the energy value being extracted from a fast rotating BH due to a magnetic field strength \(B\):

\[
L_x \sim 6 \times 10^{38} a \left( \frac{M_{BH}}{M_\odot} \right)^2 \left( \frac{B}{10^8 G} \right) \text{erg s}^{-1}
\]

(1)

where \(a = \frac{l}{2GM}\) is the specific angular momentum of a black hole.

However the strong evidence of existence of the global magnetic field in the nearest environment of BH in the close binary systems was obtained from the direct polarimetric observations. Michalsky et al. (1975) have presented an evidence of variable circular polarization of the binary system Cyg X-1/HDE 226868, that was varied with the period of the binary system \(P_{\text{orb}} = 5.6\). They claimed the magnetic origin of this polarization. Below we shall consider all
combined observed data that give possibility to determine the magnetic field strength near the black hole in the Cyg X-1/HDE 226868 binary system. The results of spectropolarimetric observations in the spectral line HeII λ4686 made with BTA-6m telescope will be also presented. These data allow to derive the radial distribution of magnetic field in the accretion disk. If the characteristic size of the magnetic field region coincides with the Dyadosphere radius one can determine the value $Q$ of charge of black hole in the Cyg X-1/HDE 226868 binary system.

2 Polarimetric Observations of Cyg X-1 and Determination of the Magnetic Field Strength near the Black Hole

The first determination the magnetic field strength near the compact object in the Cyg X-1/HDE 226868 binary system have been made in a result of observing circular optical polarization of this system (Kemp et al., 1972, Michalsky et al., 1975, 1977). The magnitude of the circular polarization have been estimated at the level of $P_V = (4.8 \pm 0.5) \times 10^{-4}$. The detail analysis shows that this polarization can not be of interstellar origin, i.e., can’t be generated, for instance, in a result of conversion of the intrinsic linear polarization of this system into the circular one onto the oriented interstellar dust grains (see, for example, Dolginov et al., 1995), because this mechanism requires too high value compare to observational intrinsic linear polarization of this system. It requires the magnitude of the intrinsic linear polarization, at least, at the level $P_l \approx 2\%$ that contradicts to observations. The real polarimetric observations give the magnitude of intrinsic linear polarization at the level only $P_l \approx 0.2\%$. Therefore seems naturally the explanation of observed circular polarization as a magnetic origin. This polarization can appear in a result of scattering of a light by electrons in surrounding plasma (see, for example, Dolginov et al., 1995, Gnedin and Silant’ev, 1997). The magnitude of magnetic field is readily estimated by

$$P_V \sim \frac{\omega B}{\omega} \sim 6 \times 10^{-2} \left( \frac{B}{10^6 G} \right) \left( \frac{\lambda}{4500 \AA} \right)$$

where $\omega_B = \frac{eB}{m_ec}$ is the cyclotron frequency, and $\omega$ is the radiation frequency. The magnetic field strength $B \sim 10^6$G corresponds namely to the observed value $P_V \approx 5 \times 10^{-4}$ circular polarization. It is evident that the magnetic field of such magnitude cannot exist at the surface of the supergiant HDE 226868. Therefore one can make the conclusion that an accretion disk namely is the origin of the magnetic field of such magnitude.

One ought to consider the value $B \approx 10^6$G as only the lower limit of the real magnetic field value in the accretion disk because of the dilution effect by the stellar optical light of HDE 226868 itself. Usually one estimates the accretion disk optical luminosity at the level of $\geq 1\%$ of the total optical luminosity of
the binary system Cyg X-1/HDE 226868. It means that the real strength of magnetic field is of order of $B \approx 10^7 \div 10^8$ G.

The next important stage of searching magnetic field in the system Cyg X-1/HDE 226868 is connected with the first polarimetric observations of this system in X-ray spectral range. The X-ray polarimetric observations have been made by Long et al. (1980) with the Bragg crystal polarimeter aboard OSO8. The marginal detection of the time-averaged polarization was given for Cyg X-1 at the level: $P(2.6\text{KeV}) = 2.4\% \pm 1.1\%$ and $P(5.2\text{KeV}) = 5.3\% \pm 2.5\%$. Unfortunately, the observational results occurred at the low confidence level, only $\sim 2\sigma$. Nevertheless, if one suggest that the decrease of net polarization for the energy $E = 2.6\text{KeV}$ due to the effect of Faraday depolarization (see Gnedin and Silant’ev, 1980, 1984, 1997, and Dolginov et al., 1995) it is possible to derive the magnetic field strength in the nearest environment of the black hole where X-ray radiation is generated.

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

$$\chi = \frac{1}{2} \delta \tau_T \cos \theta; \quad \delta = \frac{3 \omega B c}{2 r_e \omega^2} \approx 1.2 \left( \frac{B}{10^6 \text{G}} \right) \left( \frac{1\text{KeV}}{\hbar \omega} \right)^2$$

(3)

where $\tau_T$ is the optical thickness of the region of electron scattering, $\theta$ is the angle between directions of magnetic field $\vec{B}$ and radiation propagation $\vec{n}$, $r_e = \frac{e^2}{m_e c^2}$ is the classical electron radius.

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

The spectra of polarized radiation scattered in a spherically symmetric magnetized envelope, and also in optically thick scattering disk have been calculated by Dolginov et al., 1995, Gnedin and Silant’ev, 1997, Silant’ev, 2001.

For an accretion disk the Stokes parameters have been derived by Silant’ev, 2001:

$$Q(\vec{n}, \vec{B}) = -\frac{F}{2\pi J_1} \frac{1 - g}{1 + g (1 - k \mu)^2 + (1 - q)^2 \delta^2 \cos^2 \theta^2}$$

$$U(\vec{n}, \vec{B}) = -\frac{F}{2\pi J_1} \frac{1 - g}{1 + g (1 - k \mu)^2 + (1 - q)^2 \delta^2 \cos^2 \theta^2}$$

(4)

Here $\vec{n}$ is the line of sight direction, $\theta$ is the angle between the line of sight and the magnetic field $\vec{B}$, $\mu = \cos \vartheta$, where $\vartheta$ is the angle between the line of sight and the normal to the surface of the accretion disk, $q = \frac{2a}{r_T}$ is the ratio between the cross-sections of absorption and electron scattering. The values of constants $J$, $g$ and $K$ are tabulated by Silant’ev, 2001. He also published there the dependencies of polarization of an accretion disk radiation on various magnitudes of $\mu$, $q$ and $\delta$. 
From Eq.(4) it is evident that with increase of the depolarization parameter \( \delta \) and the magnetic field strength \( B \) respectively, the polarization drops as \( P_l \sim \frac{1}{\delta} \sim \frac{1}{\lambda^2 B} \) where \( \lambda \) is the radiation wavelength. For the quite large values of \( \delta \gg 1 \) the angular dependence of net polarization on the angle \( \theta \) has narrow maximum into the angular interval \( \Delta \theta \sim \frac{1}{(1-q)\delta} \).

Using the polarimetric observations in X-ray spectral range one can estimate the magnetic field strength near the black hole itself, if one suggests that the decrease of polarization at the energy \( E = 2.6 \text{keV} \) is due to the depolarization effect. Then the requirements of \( \delta(E = 2.6 \text{keV}) \gg 1 \) allows to get the following estimation of the magnetic field strength in the nearest environment around the black hole in Cyg X-1 system: \( B \geq 3 \times 10^7 \text{G} \).

Independent estimation of a magnetic field of optical radiation region around the Cyg X-1 black hole can be too made via the measured intrinsic linear polarization of Cyg X-1/HDE 226868. This polarization has been discovered by Nolt et al. (1975). The amplitude of the variable polarization occurred quite low at the level of \( \sim 0.2\% \), with the very complex pattern of variability. Nolt et al (1975) claimed the discovery of various types of polarization variability with 39\(^d \) and 78\(^d \) periods and of long-term variability. The possible mechanisms of this variability have been in detail discussed by Karitskaya, 1979, 1981 and by Bochkarev et al., 1979. Unfortunately, the real explanation of observed linear polarization of Cyg X-1 is absent up to date.

If one accepts the accretion matter around the black hole as a real source of the observed optical polarization it is necessary to increase the intrinsic optical polarization of the black hole environment at least in \( \sim 100 \) times, because of the high dilution of polarized radiation by the optical light of the supergiant HDE 226868. Its luminosity is estimated at the level of \( L_0 \approx (1 \div 3) \times 10^{39} \text{erg/s} \). Let us remind the X-ray luminosity of Cyg X-1 is estimated as \( L_X \sim 8 \times 10^{37} \text{erg/s} \) (see, for example, Cherepaschuk, 2001). We consider the case when the optical radiation is generated near the black hole as a result of reprocessing of X-ray by nearest accretion matter. It means that the real magnitude of net linear polarization from the nearest accreted mater can reach magnitude at the level \( P_l \geq 10\% \). Such high value polarization can be dare say produced in a result of single scattering in outflows such as a magnetized wind or dynamical corona.

One can estimate the resulting polarization by using calculations of polarization of radiation from a central light source (a star) surrounded by a thin magnetized shell made by Dolginov et al, 1995, (see the paragraph 9 of section 4 of their book). In a rough model of magnetized spherically symmetric electron shell surrounding the accretion disk of the central black hole the net polarization can reach magnitude \( P_l \sim 10\% \) for \( \delta \tau_{Sh} \approx 10 \) where \( \tau_{Sh} \) is the optical thickness of a shell respect to electron scattering. In true it is valid only for the case when the line of sight is perpendicular to the magnetic field direction. If one suggests that \( \tau_{Sh} \approx 0.1 \), then the magnetic field strength in optical region of the disk can be easily estimated from the expression

\[
\delta = 0.8 \left( \frac{B}{1G} \right) \left( \frac{\lambda}{1\text{mM}} \right)^2
\]
The Eq. (5) allows to estimate the magnetic field strength in the region of optical radiation generation as \( B \approx 500 \, G \). A number of models of accretion disk gives the value of the corona inner radius as \( \sim 100R_g \), where \( R_g = \frac{2GM_B}{c^2} \) is the gravitational radius. For dipolar magnetic field the estimation of the magnetic field strength in nearest environment of the black hole gives \( B(3R_g) \sim 10^7 \, G \) that is close to previous estimations.

3 Estimation of a Charge of the Black Hole in Cyg X-1/HDE 226868 Binary System

Accreting black holes can release enormous amounts of energy to their surroundings in quite different forms. The idea of a black hole endowed with electromagnetic structure (EMBH) has recently become very popular. Still in 1971 Ruffini and Wheeler proposed the famous "uniqueness theorem" stating that black holes can only be characterized by their mass-energy \( E \), charge \( Q \) and angular moment \( l \). This idea has been recently developed by Ruffini (2002), Ruffini and Vitagliano (2002) (see refs therein). Various models of particle accelerations near black holes have been widely discussed at last time in connection with the studies of synchrotron radiation and inverse Compton scattering from jets observed over a wide spectral range, from radio to gamma rays. Preparata et al. (2002) formulated the derivation of, so-called, "Dyadosphere" that was defined as the region outside the horizon of an EMBH where the electromagnetic field exceeds the critical value for \( e^+e^- \) pair production. They expressed the outer radius of dyadosphere in the form:

\[
R_{ds} = \left( \frac{\hbar}{m_e c} \right)^\frac{1}{2} \left( \frac{GM}{c^2} \right)^\frac{1}{2} \left( \frac{m_p}{m_e} \right)^\frac{1}{2} \left( \frac{e}{q_p} \right)^\frac{1}{2} \left( \frac{Q}{\sqrt{GM}} \right)^\frac{1}{2} \approx 1.12 \times 10^8 \sqrt{\mu \xi} \, cm
\]

(6)

where \( m_p = (\hbar c/G)^{0.5} \) is the Planck mass and \( q_p = (\hbar c)^{0.5} \) is the Planck charge, \( \mu = \frac{M}{M_\odot} \), \( \xi = \frac{Q}{Q_{max}} \).

Another model of EMBH has been recently developed by Shatsky (2001, 2003, Shatsky and Kardashev, 2002). He suggested a mechanism that combines a unipolar inductor and strong gravitational black hole effects. In the result he showed that the black hole electric charge can be expressed in terms of the magnetic field at the disk center \( B_0 \) as follows:

\[
Q = \frac{\pi}{2} \Omega R^2 a B_0
\]

(7)

where \( \Omega \) is the Keplerian rotation frequency, \( R \) is the disk radius and \( a \) is the distance from the center where located two charges \( \pm Q \). In this model the electric field of the disk element can be presented as the field from two charges \( \pm Q \), located inside the disk.

For estimation of a charge magnitude of the Cyg X-1 black hole we use the value of a intrinsic magnetic moment of this black hole that has been recently estimated by Robertson and Leiter (2002). They tested the hypothesis that the
power law part of the quiescent emissions of the black hole candidates might be magnetospheric origin. They derived proposed magnetic moments and rates of spin for them and predicted their quiescent luminosities. For Cyg X-1 the estimated magnitude of the intrinsic magnetic moment appeared \( m = 1.26 \times 10^{30} \text{ G cm}^3 \). Let us suggest that the characteristic scale dimension of magnetic field generation and the dyadosphere radius coincide one to other. Then, using the estimated by Robertson and Leiter value of the intrinsic magnetic moment of the black hole in Cyg X-1 and obtained from polarimetric observations the magnetic field strength \( B \approx 3 \times 10^7 \text{ G} \) one may obtain the value of the Cyg X-1 dyadosphere radius directly from polarimetric observations:

\[
R_{ds}(\text{CygX-1}) = 3.5 \times 10^7 \text{ cm}
\]  

(8)

Comparing Eqs. (6) and (7) one can estimate the electric charge magnitude of the black hole in Cyg X-1:

\[
Q = 7.8 \times 10^{-3} \left( \frac{10M_\odot}{M_{BH}} \right) Q_{\text{max}}
\]  

(9)

Quite similar estimation can be obtained if one proposes the electron-position jet region radius in the Cyg X-1 nonthermal corona as the magnetic field region radius. Maccarone and Coppi (2002) estimate this radius as \( R_{\text{car}} \approx 10^8 \text{ cm} \). Then the magnitude of a probable electric charge for the Cyg X-1 black hole appears as

\[
Q \approx 0.08 \left( \frac{10M_\odot}{M_{BH}} \right) Q_{\text{max}}
\]  

(10)

Now we can estimate the rotation rate of the black hole in Cyg X-1 with use of Shatsky model (see Eq.(7)). Accepting the distance \( a \approx h \approx (0.1 \div 1)3R_g \), where \( h \) is the height of the accretion disk, one can estimate the rotation rate \( \Omega \) of the black hole that is producing the charge \( Q \approx 0.08Q_{\text{max}} \):

\[
\Omega \approx \frac{2Q}{\pi a R^2 B_0} \approx 20 \left( \frac{Q}{0.1} \right) \left( \frac{3 \times 10^7 \text{ G}}{B_0} \right) \ 
\]  

(11)

It means that rotation period of the Cyg X-1 black hole \( P \approx 0^\prime.03 \div 0^\prime.3 \) depending on our estimation of the charge magnitude (see Eqs. (9), (10)).

4 The Radial Structure of Magnetic Field in the Accretion Disk

The spectral and spectropolarimetric observations of the Cyg X-1/HDE 226868 were made by BTA-6m telescope at 2001 July, with UAGS spectrograph and CCD analyzer of circular and linear polarization. The diffraction slit with a dispersion 1300 \( \text{mm}^{-1} \) have been used. This slit provides the spectral resolution 1.5\( \text{Å/pixel} \) in the 3500 – 9000\( \text{Å} \) range. During observations the seeing was not higher 1".5. The reprocessing was made with the standard MIDAS program.
The results of observations are presented at Fig.1. The spectropolarimetric observations have been carried out near the spectral line of HeII$\lambda$4686, that is usually proposed to be generated in an accretion disk. The upper limit of the circular polarization net in HeII$\lambda$4686 line appears as $P_0 < 0.2\%$. One can estimate the constraints of a magnetic field strength in the region of HeII lines generation: $B(R_{HeII}) < 10^3 G$.

The HeII$\lambda$4686 line is produced in the region of the high temperature $T_e(R_{HeII}) \approx 10^5 K$. The standard theory of an accretion disk (Shakura and Sunayev, 1973) determines the following radial temperature distribution:

$$T_e(R) = T_{in} \left( \frac{R_{in}}{R} \right)^{3/4}$$  \hspace{1cm} (12)

where $R_{in}$ and $T_{in}$ are the radius and temperature at the disk inner radius, respectively.

Suggesting that the inner radius corresponds to the marginal orbit radius $R_{in} = 3R_g = 6GM/c^2$ and $kT_e \approx 1 K$, i.e. corresponds to X-ray temperature one can readily derive the helium ionization radius

$$R_{HeII} = R_{in} \left( \frac{T_{in}}{T_{HeII}} \right)^{4/3}$$  \hspace{1cm} (13)

For the Cyg X-1 black hole with the mass magnitude $M_{BH} = 10 M_\odot$ we have $R_{HeII} = 1.4 \times 10^3 R_g$. If one now suggests the power low of magnetic field radial distribution

$$B = B_0 \left( \frac{R}{3R_g} \right)^{-\delta}$$  \hspace{1cm} (14)

where $B_0 = B(3R_g)$, it is easy to determine the value $\delta$ of a power law index. Choosing the values of magnetic field strengths as $B_0 = 10^8 G$ and $B(R_{HeII}) \approx 10^2 G$, one can derive the value $\delta \approx 2$. This is the first experimental determination of the index of a magnetic field radial dependence in accretion disks.

5 Conclusions

Polarimetric observational data of X-ray binary Cyg X-1/HDE 226868 allows to estimate the magnetic field strength near the last marginal orbit of a black hole as $B_0 \approx 10^8 G$. If one suggests that the characteristic scale size of the magnetic field region is the same as a dyadosphere radius (Preparata et al., 2002; Ruffini et al., 2003) one can estimate the charge value of the Cyg X-1 black hole. It occurs at the level $\sim 1\%$ of its maximal magnitude $M\sqrt{G}$. At the basis of BTA-6m spectropolarimetric data of Cyg X-1 the radial distribution of the magnetic field in the accretion disk was estimated. The power law index appeared $\delta \geq 2$.

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References

[1] Beskin V.S., 1997, Usp. Fiz. Nauk, v.167, p.689.

[2] Blandford R.D., 2001, Galaxies and their Constituents at Highest Angular Resolution, Proc. IAU Symp. 205, ed. R.T. Schilizzi (San Francisco, ASP 2001), p.10; astro-ph/0110397

[3] Blandford R.D., Znajek R.L., 1977, MNRAS, v.176, p.465.

[4] Bochkarev N.G., Karitskaya E.A., Sunayev R.A., Shakura N.I., 1979, Sov.Astron.Zh., v.5, p.185.

[5] Cherepashuk A.M., 2001, Usp. Fiz. Nauk, v.171, p.864.

[6] Dolginov A.Z., Gnedin Yu.N., Silant’ev N.A., 1995, in "Propagation and Polarization of Radiation in Cosmic Media", Gordon and Breach Publs., Amsterdam.

[7] Gnedin Yu.N., Silant’ev N.A., 1980, SvAL, v.6, p.344.

[8] Gnedin Yu.N., Silant’ev N.A., 1984, Ap.Sp.Sci., v.102, p.175.

[9] Gnedin Yu.N., Silant’ev N.A., 1997, Basic Mechanisms in Light Polarization in Cosmic Media, Harwood Academic Publ., Amsterdam.

[10] Karitskaya E.A., 1979, Sov.Astron.Circ., No 1088, p.1.

[11] Karitskaya E.A., 1981, Sov.Astron.Zh., v.58, p.146.

[12] Kemp J.C., Wolstencroft R.D., Swedlund L.B., 1972, Ap.J.Lett., v.173, L118.

[13] Li L.-X., 2002, astro-ph/0202364.

[14] Li L.-X., Paczynski B., 2000, Ap.J., v.534, L197.

[15] Long K.S., Chanan G.A., Novick R., 1980, Ap.J., v.238, p.710.

[16] Maccarone T.J., Coppi P.S., 2002, astro-ph/0204235

[17] Michalsky J.J., Stokes G.M., Stokes R.A., 1977, Ap.J.Lett., v.216, L35.

[18] Michalsky J.J., Swedlund J.B., Stokes R.A., 1975, Ap.J.Lett., v.198, L101.

[19] Nolt I.G., Kemp J.G., Rudy R.J., Rodostitz J.V., Caroff L.J., 1975, Ap.J.Lett., v.199, L27.

[20] Preparata G., Ruffini R., Xue S.-S., 1998, Astron.Astrophys., v.338, L87.

[21] Preparata G., Ruffini R., Xue S.-S., 2002, astro-ph/0204080

[22] Punsly B., 2001, Black Hole Gravitohydromagnetics, Springer.
[23] Robertson S.L., Leiter D.J., 2002, Ap.J., v.565, p.447; 2002, astro-ph/0208333

[24] Ruffini R., 2002, astro-ph/0209264

[25] Ruffini R., Bianco C.L., Chardonnet P., Fraschetti F., Xue S.-S., 2001, Ap.J.Lett., v.555, L107, L113, L117; 2001, Nuovo Cim., v.116B, p.99.

[26] Ruffini R., Vitagliano L., 2002, astro-ph/0209072

[27] Ruffini R., Wheeler J.A., 1971, Relativistic Cosmology from Space Platforms, in Proc. Conf on Space Phys, eds. Hardy V. and Moore H., E.S.R.O., Paris.

[28] Shakura N.I., Synayev R.A., 1973, Astron. Astrophys., V.24, p.337.

[29] Shatsky A.A., 2001, Zh.Eksp.Teor.Fiz., v.93, p.920 (gr-qc/0202068).

[30] Shatsky A.A., 2003, astro-ph/0301535.

[31] Shatsky A.A., Kardashev N.S., 2002, Astron.Zh., v.46, p.639, astro-ph/0209465.

[32] Silant’ev N.A., 2002, Astron.Astrophys., v.283, p.326.
Spectropolarimetry of Cyg X-1.
Spectroscopy of Cyg X-1.