Magnetic Fields of Black Holes and the Variability Plane

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Abstract

We estimated the magnetic field strength at the horizon radius of black holes, that is derived by the magnetic coupling process and depended on the black hole mass $M_{BH}$ and the accretion rate $\dot{M}$. Our estimation is based on the use of the fundamental variability plane for stellar mass black holes, AGNs and QSOs. The typical values of magnetic field strength on the black hole horizon are appeared at the level of $B_{BH} \sim 10^6 \text{G}$ for stellar mass black holes and $B_{BH} \sim 10^4 \text{G}$ for the supermassive black holes. We have obtained the relation $p_{\perp} \sim \nu_b^{-1/2}$ between the intrinsic polarization of the accretion disk radiation and the characteristic frequency of the black hole X-ray variability.

1 Introduction

Recently, the strong evidence has been obtained that active galactic nuclei and soft-state black hole X-ray binaries populate a plane in the space defined by the black hole mass, accretion rate and characteristic frequency of their X-ray variability (McHardy et al., 2006; Körding et al., 2007; Casella et al., 2008). It should be noted that there exist and other relations between the basic physical parameters of central engines supported the general idea about similarity between X-ray binaries (XRBs) and active galactic nuclei (AGNs). First, the so-called, fundamental plane of accreting black holes connects XRBs and AGNs through a plane in the black hole mass, radio and X-ray luminosity space (Merloni, Heinz & Di Matteo, 2003; Falcke, Körding & Markoff, 2004). The space defined by the accretion rate, the black hole mass and a characteristic time scale of the X-ray variability suggests that all black holes can be unified by taking the accretion rate as well as the black hole mass into account.

The new idea developed by us in this paper is to show based on taking into account the effect of Faraday rotation plane at multiple scattering of accretion disk radiation has been developed in series of papers by Gnedin and Silant’ev and their co-authors (Gnedin & Silant’ev, 1994; 1997; Dolginov, Gnedin & Silant’ev, 1995; Gnedin, Silant’ev & Shternin, 2002; Silant’ev, 2002; 2003 and also in papers by Agol & Blaes, 1996; Agol, Blaes & Ionescu-Zanetti, 1998; Shternin, Gnedin & Silant’ev, 2003).

The power spectral density (PSD) is usually described by a number of Lorentzians (Psaltis et al., 1999; Belloni et al., 2007). Each Lorentzian is described by their characteristic frequency, i.e. the frequency of the maximum of the Lorentzian in the frequency times power plot.

The measured shapes of AGN PSDs are similar to those of soft-state stellar black holes, but time scales for AGNs are several orders of magnitudes longer. It means that characteristic frequency $\nu_B$ for AGNs is, as a rule, less that its value in the case of stellar black holes. Nevertheless, the dependence of the variability properties on accretion rate and mass of a black hole takes similar forms both for stellar black holes, and for AGN.

2 The Variability Plane

McHardy et al. (2006) have shown that galactic black holes in their soft-state and AGNs populate a plane in the parameter space of the black hole mass, accretion rate and characteristic frequency in PSD (Körding et al., 2007) recently presented evidence for this variability plane to extend to the hard-states BHs. At last, Casella et al. (2008) extended this plane to the black holes in ultraluminous X-ray sources. For two ULXs M82 X-1 and NGC 5408 X-1 they estimate a black hole mass in the range $100 \div 1300 M_\odot$. This result gives a definite evidence that ULX sources may be considered as intermediate mass black holes (IMBH).

The variability plane can be presented in the following form (Körding et al., 2007; Casella et al., 2008):

$$\log \nu_b = \log \dot{M} - 2 \log M - 14.7 - 0.9 \theta,$$

where $\dot{M}$ is the accretion rate in g/s, $M = M_{BH}/M_\odot$ (here and below) is the black hole mass in $M_\odot$ and $\theta$ goes from 0 for the soft-state stellar black holes to 1 for hard-state BHs, $\nu_b$ is the break frequency in Hz. For AGNs the value $\theta = 0$ can be accepted.

The magnetic field strength is derived in a result of the magnetic coupling (MC) process. We remind that the MC
process is responsible for interaction between a rotating black hole and its surrounding accretion disk. This process is commonly accepted as a variant of the famous Blandford and Znajek (BZ) process (Blandford & Znajek 1977). [L92] 2002; [Wang et al. 2002, 2003; Aloiso 2005; Uzdensky 2005; Zhang et al. 2005; Gan et al. 2009]. In this process energy and angular momentum are transferred from a rotating BH to its surrounding disk. It can also depress accretion via transfer of angular momentum from a rotating BH to the inner disk. It is important that MC is responsible for generating the outflows and jets from the BH binaries and AGNs.

The MC process provides the relation between the magnetic field strength at the horizon of BH $B_H$ and its mass $M$ and the accretion rate $\dot{M}$. This relation is based upon the balance between the pressure of the magnetic field at the horizon and the accreted matter pressure of the innermost part of an accretion flow:

$$B_H = \frac{1}{R_H} \sqrt{2k_m M c}, \quad (2)$$

where the radius of the BH horizon $R_H$ is

$$R_H = \frac{GM_\odot}{c^2} M \left[1 + \sqrt{1 - a^2_*}\right]. \quad (3)$$

Here $a_*$ is the dimensionless Kerr parameter (spin). For a Schwarzschild BH $a_* = 0$. $k_m$ is a magnetization parameter indicating the relative power of the MC process with respect to the disk accretion. If the MC process dominates over the disk accretion, $k_m > 1$, and if it is dominated by latter, $k_m < 1$. The case $k_m \approx 1$ corresponds to equipartition between these two processes.

At logarithm scaling, Eq.(2) corresponds to

$$2 \log B_H = \log \dot{M} - 2 \log M + 2 \log f(a_*, k_m), \quad (4)$$

where

$$f(a_*, k_m) = \frac{e^{2\sqrt{2k_m c}}} {GM_\odot \left[1 + \sqrt{1 - a^2_*}\right]} \approx \frac{1.66 \sqrt{k_m}}{1 + \sqrt{1 - a^2_*}}. \quad (5)$$

Eqs.(4) and (5) gave together:

$$B_H = [\nu_b f^2(a_*, k_m)]^{1/2} \times 10^{7.35 + 0.45 \theta}. \quad (6)$$

Here we shall use the value $\theta \approx 0$ (McHardy et al. 2006).

### 3 Magnetic Field Strength of Stellar Black Hole from their X-ray Timing

We are starting with estimates of magnetic field strength at the horizon of black hole from X-ray binaries.

Recently McHardy et al. (2006) have demonstrated that the break frequency $\nu_b$ is determined by both the black hole mass $M_{BH}$ and the accretion rate $\dot{m}_{Edd} = \dot{M}/M_{Edd}$ as follows:

$$\nu_b = 0.029 \varepsilon \dot{m}_{Edd}(10^6 M_\odot / M_{BH}), \quad (7)$$

where $\varepsilon$ is the efficiency of the mass to energy conversion (usually one assumes $\varepsilon = 0.1$). For Cyg X-1 with $\dot{m}_{Edd} = 0.1$ and $M_{BH} = 10 M_\odot$ the value $\nu_b = 29$Hz and $B_H \approx 1.2 \times 10^8 G$. This magnetic field magnitude corresponds quite well to the results of polarimetric observations (Gnedin, Silant’ev & Shternin 2006; Karitskaya et al. 2009a,b). For other stellar mass black holes the typical value of the break frequency lies into the interval $160 \div 300$Hz (Tomsick et al. 2009). Then, using the estimate by Eq.(6), we obtain the following value of the magnetic field strength at the horizon radius of Kerr black hole: $B_H \approx 4 \times 10^8 G$ for the equipartition condition, i.e. $k_m = 1$. The numerical calculations for the specific stellar mass black holes are presented in Table 1.

Recently McClintock et al. (2009) have fitted the thermal continuum X-ray spectra of black hole X-ray binaries using the Novikov-Thorne thin disk model. As a result they have extracted the dimensionless spin parameter $a_*$ for some X-ray binary black holes. They have obtained $a_* = 0.65 \div 0.75$ for J1665-40 and $a_* = 0.98 \div 1$ for GRS 1915+105. Supposing $a_* = 0.7$, we obtain the following estimation of magnetic field $B_H = 3 \times 10^8 G$ for J1665-40.

### 4 Magnetic Field Strength of AGNs from their Quasiperiodic Oscillations

For SMBH (AGNs) the typical values of the break frequency lie in the ranges $\nu_b = 10^{-5} \div 10^{-7}$Hz. It allows to estimate the typical magnetic field strength for Kerr black hole ($a_* = 0.998$) $B_H \approx 10^4 \div 10^5 G$.

Let us consider now the specific targets.

For the radio-loud active galactic nucleus 3C 390.3 the break frequency values is $\nu_b = 2.7 \times 10^{-7}$ (Gliozzi et al. 2004). For the horizon magnetic field strength one obtains $B_H = 10^5 G$ for the Schwarzschild black hole ($a_* = 0$) and $B_H = 2 \times 10^4 G$ for the Kerr type black hole. PSD studies of the blazars Mrk 421, Mrk 501 and PKS 2155-304 with jet-dominated accretion disks suggest the presence of PSD breaks at frequencies that are nearly 2 orders of magnitude higher that the break found in 3C 390.3 i.e. at $\nu_b \approx 10^{-5}$Hz (Gliozzi et al. 2004). For these targets the horizon magnetic field strength $B_H = 5.8 \times 10^4 G$ in the case of the Schwarzschild black hole and is twice higher for the Kerr black hole with $a_* \approx 1$. 

| Source       | $\nu_b$(Hz) | $B_H$(G) $\ (a_*=0)$ | $B_H$(G) $\ (a_*=0.998)$ |
|--------------|-------------|-----------------------|---------------------------|
| GRO J1665-40 | 300         | $3.2 \times 10^8$     | $6.4 \times 10^8$         |
| H 1743-322   | 241         | $2.9 \times 10^8$     | $5.8 \times 10^8$         |
| XTE 1550-64  | 276         | $3.1 \times 10^8$     | $6.2 \times 10^8$         |
| GRS 1915+105 | 168         | $2.4 \times 10^8$     | $4.8 \times 10^8$         |
| 4U 1630-47   | 164         | $2.38 \times 10^8$    | $4.76 \times 10^8$        |
| XTE J1650-500 | 250          | $2.9 \times 10^8$     | $5.8 \times 10^8$         |
| XTE 1859+228 | 190         | $2.6 \times 10^8$     | $5.2 \times 10^8$         |
The magnetic field in an accretion disk has a strong influence on the Faraday depolarization parameter,
\[ a = 0.8 \left( \frac{\lambda_{\text{rest}}}{1 \mu \text{m}} \right)^2 \left( \frac{B}{1 \mu \text{G}} \right), \]
\[ b = 0.8 \left( \frac{\lambda_{\text{rest}}}{1 \mu \text{m}} \right)^2 \left( \frac{B}{1 \mu \text{G}} \right) \sqrt{1 - \mu^2}. \]  

Here, \( B \) is the component directed along the normal to the accretion disk surface, \( B_\perp \) is the superposition of the azimuthal and radial component of the magnetic field in the accretion disk. \( \mu = \cos i \), where \( i \) is the inclination angle.

Eqs. (9)–(11) allow to get the relation between \( \nu_b \) and polarization parameters \( P_l \) and \( \chi \). Using these Eqs. and Eq. (6), one can obtain the following relations in the asymptotic case when the depolarization parameters \( a, b \gtrsim 1 \):

\[ P_l(B, \mu) \sim 1/\sqrt{\nu_b}, \tan 2\chi \sim \sqrt{\nu_b} \text{ for } B_\perp \gg B_z \]  
\[ P_l(B, \mu) \sim 1/\sqrt{\nu_b}, \chi \approx 0 \text{ for } B_\perp \gg B_z \]

6 Conclusions

We show that the plane in the space defined by the black hole mass, accretion rate and characteristic frequency of their X-ray variability, which is populated by active galactic nuclei and soft-state black hole X-ray binaries, allows to estimate the magnetic field strength near the event horizon of black holes. The typical values of magnetic field strength at the black hole horizon are \( \sim 10^8 \)G for the stellar mass black holes and \( \sim 10^4 \)G for the supermassive black holes. The value \( B_\perp \sim 10^4 \)G does not contradict estimates made by Robertson & Leiter (2003) from extremely other point of view. They claimed existence instead of black holes the original type of objects which were called Magnetospheric Eternally Collapsing Objects (MECO). They predicted the existence of intrinsic magnetic moments of \( \sim 4 \times 10^{29} \)Gcm\(^3\) in these objects.

The magnetic field magnitudes estimated for the stellar mass black holes correspond quite well to the observation data (Karitskaya et al., 2009).%

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