Magnetic layers and neutral points near a rotating black hole

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Abstract
Magnetic layers are narrow regions where the field direction changes sharply. They often occur in the association with neutral points of the magnetic field. We show that an organized field can produce these structures near a rotating black hole (BH), and we identify them as potential sites of magnetic reconnection. To that end, we study the field lines affected by the frame-dragging effect, twisting the magnetic structure and changing the position of neutral points. We consider oblique fields in vacuum. We also include the possibility of translational motion of the black hole which may be relevant when the black hole is ejected from the system. The model settings apply to the innermost regions around black holes with the ergosphere dominated by a super-equipartition magnetic field and loaded with a negligible gas content.

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(Some figures in this article are in colour only in the electronic version)

1. Introduction
Magnetic reconnection takes place while topologically distinct regions approach each other and the magnetic field lines change their connectivity (Priest and Forbes 2000, Somov 2006). The standard setup involves the violation of the ideal magneto-hydrodynamic (MHD) approximation on the boundary between neighbouring magnetic domains, where the field direction changes rapidly. The essential question is thus about the formation of antiparallel field lines and neutral points of the magnetic field. Our objective is to explore if the reconnection process can be influenced by the strong gravitational field near a black hole (BH), and whether the black-hole proximity creates conditions favourable to incite reconnection. To this end, we examine the structure of the magnetic field lines twisted by a highly curved spacetime of a rotating BH.
Astrophysical black holes do not support their own intrinsic magnetic field. Instead, the field is generated by currents in the surrounding plasma and brought down to the horizon by accretion. Most likely, the magnetic field is frozen in an equatorial accretion disc which acts as a boundary condition. The inward-directed bulk transport of plasma is often in some kind of interaction with outflows and jets (e.g., Begelman et al. (1984) and Burgarella et al. (1993)), and so the models of electromagnetic acceleration and collimation have been continuously advanced during the last decade (Fendt and Greiner 2001, Krolik et al. 2005, Komissarov et al. 2007). The presence of the central BH is essential. Observations indicate that the initial acceleration happens very near the horizon (Junor et al. 1999, Albert et al. 2008); however, the exact mechanism and the place of the particle acceleration are still a subject of investigation.

Simulations as well as theoretical considerations point to the decisive importance of the magneto-rotational instability operating in the inner regions of the accreting BH systems (Balbus and Hawley 1998, Proga and Begelman 2003). On the other hand, the origin of highly collimated outflows is easier to understand with the help of an organized magnetic field. Indeed, it has been argued that an organized magnetic field is needed to ensure the outflow collimation that is seen on larger scales, i.e., $\gtrsim 10r_g$ in some accreting BH systems (Stone and Norman 1992, McKinney and Narayan 2007). At the same time, the organized field has consequences for the turbulent dynamo mechanism (Haugen and Brandenburg 2004).

The role of an ordered component of the magnetic field and whether it may pervade down to the plunging region is a matter of debate (Koide 2004, McKinney and Narayan 2007). A distinctive feature here is the general-relativistic (GR) frame dragging by the BH rotation which, however, can be concealed by MHD effects in astrophysically realistic situations (Komissarov and McKinney 2007). Turbulent magnetic fields are thought to be limited to sub-equipartition values, so the rotating disc can indeed enter into the ergosphere. Plasma acceleration is then driven not only by the frame-dragging effect of the BH, but mainly by the differential rotation. Here, we address a related issue of the BH rotation from another perspective: we assume a magnetically dominated system. Distinguishing the impact of the two mechanisms is quite a delicate task when both are in operation.

We assume that the magnetic pressure dominates the studied region of the ergosphere and has its origin in currents flowing farther out (Koide et al. 2006, Rothstein and Lovelace 2008). Even though the assumption of an ordered field component constrains the applicability of our calculation, the model setup can still be reconciled with the recent simulations in which the magnetic field pressure outside the main flow exceeds the gas pressure (Bisnovatyi-Kogan and Lovelace 2007, Beckwith et al. 2008). Moreover, in the absence of the standard accretion disc, the system does not have to be aligned with the BH equatorial plane, and the gas chunks can arrive episodically (Coker and Melia 1997, Cuadra et al. 2008). In these circumstances, one does not expect the BH and the ordered magnetic field to have a common symmetry axis (the Bardeen–Petterson effect does not operate due to the lack of a steady accretion flow). Neither do we expect that the black hole is resting in the centre. The possibility of such misaligned accretion has been observed also in the simulations of geometrically thick accretion (Rockefeller et al. 2005), the latter computations reveal a significant part of the equatorial plane near BH to be devoid of gas although their consistency is restricted by use of the pseudo-Newtonian model. The possibility of rapid linear motion will be addressed later in the paper.

We demonstrate that antiparallel field lines can be brought in mutual contact by the frame dragging alone. Separatrices and the associated null points occur roughly at the innermost stable circular orbit (ISCO), where they can act as a place of particle acceleration. It is interesting to realize that even the (asymptotically) ordered magnetic field becomes so entangled by the BH gravity that the conditions for reconnection exist near the horizon. It is
also pertinent to remark that the present-day techniques almost reach the necessary resolution of the order of one gravitational radius, at least in the case of the largest on the sky black hole, i.e. Sagittarius A* (Doeleman et al 2008).

2. Stretching the magnetic lines by gravitational frame-dragging

We set up an idealized framework which maximizes the action of frame dragging due to the BH rotation, while suppressing the MHD effects caused locally due to plasma motions. The gravitational field is described by the Kerr metric

\[ ds^2 = -\frac{\Delta}{\Delta_2} dr^2 + \frac{\Delta}{\Delta_2} d\theta^2 + \frac{\Delta}{\Delta_2} d\varphi^2 + \frac{A}{\Delta} \sin^2 \theta (d\phi - \omega \, dt)^2, \]

where \( a \) denotes the specific angular momentum, \(|a| \leq 1\) (\( a = 0 \) is for a non-rotating BH, while \( a = \pm 1 \) is for the maximally co/counter-rotating one), \( \Delta = r^2 - 2Mr + a^2 \), \( \Sigma = r^2 + a^2 \mu^2 \), \( A = (r^2 + a^2)^2 - \Delta a^2 \mu^2 \) and \( \omega = 2ar/M \). \(^1\) The outer horizon, \( r \equiv r_+ \), is where \( \Delta(r) = 0 \), whereas the ISCO ranges between \( 1 \leq r_{\text{ISCO}}(a) \leq 9 \) (Bardeen et al 1972). The presence of terms \( \propto \omega \) in metric (1) indicates that the GR frame dragging operates and affects the motion of particles as well as the structure of fields (e.g., Karas and Vokrouhlický (1994), Merloni et al (1999) and Barausse et al (2007)). This influence on the accreted matter resembles a rotating viscous medium, forcing the field lines to share the rotational motion, while at the same time the electric component is generated (Punsly 2008).

We assume that the electromagnetic field does not contribute to the system gravity, which is correct for every astrophysically realistic situation. Within a limited volume around the BH, typically of the size \( \ell \approx 10 \), the magnetic field lines exhibit a structure resembling the asymptotically uniform field. The electromagnetic field is a potential one and can be written as a superposition of two parts: the aligned component (Wald 1974, King et al 1975), plus the asymptotically perpendicular field (Bičák and Janiš 1980, Aliev and Galtsov 1989). The 4-potential is

\[ A_t = B_0 a[r_S^{-1}(1 + \mu^2) - 1] + B_\perp a r S^{-1} \Psi \mu, \]
\[ A_\varphi = -B_\perp (r - 1) a \mu \sin \psi, \]
\[ A_\theta = -B_\perp [(r \sigma^2 + \mu^2)a \cos \psi + (r \mu^2 + (a^2 - r)(\mu^2 - \sigma^2)) \sin \psi], \]
\[ A_\varphi = B_\perp \frac{1}{2} [(r^2 + a^2)^2 - a^2 r S^{-1}(1 + \mu^2)] \sigma^2 - B_\perp [\Delta \cos \psi + (r^2 + a^2) \Sigma^{-1} \Psi] \mu, \]

where \( \Psi = r \cos \psi - a \sin \psi, \delta = r_+ - r \) and \( r_\pm = 1 \pm \sqrt{1 - \alpha^2} \).

Equations (2)–(5) describe the electromagnetic field in vacuum. They were originally derived in the above-mentioned papers and further explored in various follow-ups (e.g., Karas (1989)). Even if the vacuum fields are obviously a simplification as far as the realistic systems are concerned, they may actually capture some important aspects of the field outside dense plasma distributions, i.e., away from the main body of the accretion flow. These properties are likely to persist as long as the magnetic field is dragged at a (slightly) different pace than the plasma itself (the case of resistive magneto-hydrodynamics), although a detailed form of the realistic solution will be different. One can argue and note in the simulations that whereas the currents in plasma do create a turbulent field structure in their immediate neighbourhood,

\(^1\) Hereafter, we use geometrical units, \( c = G = 1 \), and scale all quantities by the BH mass \( M \) (Misner et al 1973). The gravitational radius is \( r_g = c^2 G M \approx 4 \times 10^{-7} M_7 \) pc, and the corresponding light-crossing timescale \( t_8 = c^5 G M \approx 49 M_7 \) sec, where \( M_7 = M/(10^7 M_\odot) \). We use spheroidal coordinates with \( \mu = \cos \theta, \sigma = \sin \theta \).
as soon as one looks outside the plasma flow, the field structure becomes simpler and organized on larger scales.

Most important for our arguments is the fact that solutions (2)–(5) include the interaction of the BH strong gravity with the electromagnetic field, including the influence of the frame dragging. A question arises of whether the ordered field configuration can efficiently accelerate the particles from the vicinity of the horizon. Magnetic reconnection assisted by the gravitational frame dragging could help to solve this puzzle.

The magnetic field is directed in a general angle with respect to the BH rotation axis. Only a few aspects of these misaligned magnetic fields have been explored so far (see Tomimatsu (2000) and Neronov and Aharonian (2007)). The transversal component is wound up around the horizon, and it is not expelled out of the horizon (i.e., the transversal magnetic flux across the horizon does not vanish even in the extremely rotating case, Bičák et al 2007). On the other hand, the behaviour of the aligned component is simpler, the field being gradually expelled out of the horizon as the BH rotation increases (King et al 1975). Conductivity of the medium changes this property (McKinney and Gammie 2004, Komissarov and McKinney 2007), and so non-vacuum fields are more complicated.

To obtain the physical components of the electromagnetic tensor, \( F = 2dA \), we project \( F \) onto the local tetrad, \( e^{(a)} \). The appropriate choice of the projection tetrad is the one attached to a frame in Keplerian orbital motion, which exists for \( r \geq r_{\text{isco}}(a) \). Below \( r_{\text{isco}}(a) \), the circular motion is unstable and the matter has to spiral downwards while maintaining constant angular momentum of \( l \equiv l(r_{\text{isco}}) \). Only in the extremely rotating case is the circular motion possible all the way down to \( r_{\text{isco}} = 1 \). The electric and magnetic intensities, measured by a physical observer, are \( E^{(a)} = e^{(a)}_{\mu} F^{\mu\nu} u^\nu, B^{(a)} = e^{(a)}_{\mu} F^{* \mu\nu} u^\nu \), where \( u^\nu = e^{(a)}_{(\nu)} \) is the observer’s 4-velocity (the remaining three basis vectors can be chosen as spacelike, mutually perpendicular vectors). The dependence of the electromagnetic components on the \( \psi \) angle indicates the ever increasing effect of the frame dragging near the horizon.

Assuming an ordered magnetic field is obviously a crude starting point, but a sensible one. It approximates the field generated by sources distant from the BH. The magnetic intensity of the organized component in real systems is quite uncertain (e.g., McKinney 2005). By analogy (see Markoff et al (2001), Morris (2006) and Eckart et al (2008)), we can expect \( \simeq 10 \) Gauss acting on length scales of \( \simeq 10–20 \) gravitational radii near the Galactic centre supermassive BH. This allows us to estimate the maximum energy to which a particle can be accelerated by an equipartition electric field acting along the distance \( \ell, E_{\text{max}} \simeq 10^{18} q_e (B/10\text{G}) (\ell/r_g) \text{ eV} \), where \( q_e \) is in units of the elementary charge. Naturally, this qualitative estimate is exceeded if a non-stationary field governs the acceleration process.

### 3. Magnetic layers and null points

Figure 1 shows the typical structure of the field lines representing an asymptotically transverse field \( (B_\parallel = 0) \). Albeit we have fixed the boundary condition corresponding to the homogeneous field outside the ergosphere, its near-horizon structure is much more dramatic. In fact, it is sensitive to the direction of the field with respect to the rotation axis. Formation of the layers in the ergospheric region is an interesting feature of the rotating spacetime. Two critical points can be seen occurring at radii up to \( r \simeq 1.7 \) for \( a = 1 \). Figure 1 shows two plots that differ from each other only by the sense of the BH rotation.

As mentioned above, we construct the field lines with respect to the frame, orbiting freely in the equatorial plane. The two panels shown in figure 1 are not merely a symmetrical inversions of each other, but this asymmetry is indeed due to the frame motion, which is oriented in the same (positive) sense in both examples. Nonetheless, the alternating direction...
Figure 1. The magnetic field lines in the equatorial plane $x-y$, perpendicular to the rotation axis of an extremely rotating BH (coordinates are scaled in units of $r_g$). The black hole is resting at the origin; its horizon is denoted by the circle. An asymptotically uniform magnetic field is directed along the $x$-axis at large radii and plotted with respect to the physical frame in the Keplerian orbital motion. Left: the case of a co-rotating frame with respect to the BH ($a = 1$). Right: the counter-rotating case ($a = -1$).

of the field lines arises in both cases. We note that the gravito-magnetically induced electric field does not vanish along the magnetic lines, and it is thus capable of accelerating the charged particles.

In the outlined model, we have imagined the origin of the magnetic field by amplification in the accreted plasma. However, recent studies in numerical relativity point to another possibility, namely, that a supermassive BH receives a high-kick velocity. Recently, Campanelli et al. (2007) and González et al. (2007) arrived at the conclusion that a black hole could gain a recoil velocity up to $\approx 0.5\%$ of the speed of light, as a result of an anisotropic emission of gravitational waves during the merger process. The merged BH is then ejected from the nucleus of a host galaxy (Kornreich and Lovelace 2008, Komossa and Merritt 2008). On its way out, the BH encounters regions where the interstellar magnetic field is enhanced (the evidence for the localized magnetic field enhancements has been discussed e.g. in the case of Galaxy centre BH magnetosphere; (Morris 2006)). In order to describe the interacting magnetic field in such circumstances, one needs to take the BH linear velocity into account.

So far, we neglected any translational motion of the BH. However, a fast-moving BH can be included by generalizing equations (2)–(5) in a straightforward manner, allowing us to construct the magnetic field lines of the misaligned field near a BH in uniform motion. This motion can be taken into account by the Lorentz boost of the field intensities $E_{\lambda}(a), B_{\lambda}(a)$. To this end, we note that the Lorentz transform, when applied in the asymptotically distant region, has two consequences on the field components: (i) it turns the direction of the uniform magnetic field, and (ii) it generates a new electric component.

The electromagnetic test field near a moving black hole, $F_{\gamma \rightarrow \infty} = A_{\beta} F A_{\beta}$, is obtained as a superposition of two parts combined together in the due ratio, i.e. the asymptotically uniform magnetic field rotated into the desired direction, and the solution for the asymptotically uniform electric field ($A_{\lambda}$ denotes the matrix of Lorentz boost to the desired velocity $\beta \equiv v/c$). The form of the latter is found by applying the dual transform to Wald’s field, which interchanges the role of magnetic and electric terms. Albeit these are lengthy expressions, the field components with respect to the moving frame and the tetrad components $e_{\nu \mu}(a)$ can be written in the explicit
Figure 2. The magnetic lines for a maximally rotating BH in uniform translational motion in the $y$ direction. Left: the same magnetic field as in figure 1 ($a = 1$), but with the linear velocity of the black hole, turning the asymptotic direction of the field lines far from the black hole. The motion also affects the field structure near the horizon. Right: the same case as in the left panel, but for the counter-rotating BH ($a = -1$).

Figure 3. The layered structure of the field lines near the horizon. Left: a detail of the magnetic field from the left panel of figure 1. Right: a detail of the right panel of figure 2. The separatrix curve is clearly revealed around the magnetic null point.

form. We include the BH linear motion in figure 2. In order to show the effect clearly, we choose high velocity, $\beta_y = -0.99$. Let us note that the tightly layered structure of the magnetic field lines becomes quite confusing very near the horizon. Alternatively, it can be plotted in terms of a new radial variable, $r^* = 1 - 1/r$. It allows us to stretch the complicated structure caused by the frame dragging just above the horizon, as the latter is brought to the coordinate system origin (for these plots and for the explicit form of the field components, see Kopáček (2008)).

Figure 3 shows a detail of the magnetic structure. As one proceeds towards the horizon, the magnetic layers become progressively narrow and eventually develop a magnetic null point.

Just note that this approach ignores any back reaction that the electromagnetic field may exercise on the black hole motion and rotation. However, this higher order effect acts on very long timescales (Galtsov et al 1984), so we can neglect it.
point. The most interesting case is shown in the right panel, where we capture a separatrix curve, distinguishing the location of the null point well above the horizon. For the latter plot, we again set a constant velocity directed along the $y$-axis. The null point arises just above ISCO, located at $x^2 + y^2 = 1$ for $a = 1$. Translational velocity helps us to stretch the magnetic lines further out from the horizon. We find that the null point can be as far as one gravitational radius from the horizon. The offset increases with $a$ and is also influenced by the black hole motion.

The electric field is induced by the magnetic component, and in this sense the solution is self-consistent. Particles are accelerated very efficiently by the electric field that remains non-vanishing across the neutral point. We do not show the associated electric field just because its lines do not reside in a single plane, and so the structure of the electric field is more difficult to visualize (see Kopáček (2008)).

We expect reconnection to occur intermittently, as more plasma is injected into the dissipation region or created via the pair-cascades and two-photon reactions. The presumed source of additional material is the accretion disc truncated above the ISCO, or passing stars that are damaged by tidal forces. On the other hand, the physical origin of dissipation is a matter of long-lasting debate. Under the conditions of a magnetically dominated collisionless medium, the anomalous reconnection is a promising scenario (van Hoven 1976, Birn and Priest 2007). Reconnection has been observed also in the simulations of convection dominated flows of Igumenshchev et al (2003). However, in the latter work, the MHD effects on the sheared plasma motion dominate the system evolution, while the approximation of pseudo-Newtonian gravity does not permit us to capture the frame-dragging effects.

Very recently, Koide and Arai (2008) suggested that the magnetic reconnection may indeed be a relevant mechanism for the energy extraction from the ergosphere. Nevertheless, Koide and Arai restrict their discussion to the special-relativistic MHD framework. The formalism of resistive MHD has been applied to the BH accretion (e.g., Kudoh and Kaburaki (1996)), and in this case an interplay between MHD and gravitational effects should have a significant role. The regime of the intermittent reconnection from the almost evacuated ergosphere, as envisaged here in our paper, represents a complementary situation.

4. Conclusions

We considered an interesting possibility that the immediate neighbourhood of a rotating BH may be threaded by an organized component of the magnetic field, the origin of which is in currents flowing outside the black hole. Albeit more challenging to recognize than BHs in a standard accretion regime, the diluted gas in black hole ergospheres is an interesting possibility in which the turbulent motions are suppressed by the ordered field. Hence, they could represent a suitable system to study the relativistic effects in a resistive plasma near the horizon, such as the Meissner expulsion of the magnetic flux with the increasing angular momentum. Even if we adopted an idealized system, we have seen that the magnetic structure becomes very rich just by pure interaction with the gravito-magnetic field.

We examined the influence of BH rotation acting on the ordered magnetic field in the physical frame of matter orbiting a black hole, or plunging down to it. If rotation is fast enough, the magnetic layers and the corresponding null points exist just above the ISCO. Although we prescribed a special configuration of the magnetic field, the process of warping the field lines is a general feature that should operate also in more complicated settings. The layered structure of the magnetic field lines with neutral points suggests that this should become a site of particle acceleration.
The essential ingredients of the model are the rotating black hole and the oblique magnetic field in which the BH is embedded. The interaction region is very near the horizon, representing, to our knowledge, the acceleration site nearest to the BH horizon among the variety of mechanisms proposed so far. For a rapidly rotating black hole, the magnetic null point occurs above ISCO. Our results demonstrate that the gravitational field of a rotating BH creates by itself a very complicated structure near the horizon.

The assumed electrovacuum solutions (2)–(5) capture the essential physical ingredients of our investigation, i.e. the organized field near a rotation black hole. However, it should be quite obvious that the realistic field structure must differ from the one described in our paper. Perfectly vacuum black holes are unlikely in any astrophysical system, as the horizon neighbourhood is expected to be continuously supplied with electron–positron pairs.

We concentrated on the equatorial plane in which the transverse magnetic field lines reside, so they can be readily plotted, but this constraint was imposed only to keep the graphs as clean as possible. In spite of simplified geometry, the processes taking place so close to the horizon are clearly difficult to investigate observationally. Plasma motions near the BH are currently inaccessible to direct imaging, but could be resolved by interferometric techniques in future. With a planned accuracy of 10 micro-arcseconds, GRAVITY will have a capability to carry out such type of observation in the near infrared domain.

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