Evidence on the origin of ergospheric disc field line topology in simulations of black hole accretion

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ABSTRACT

This Letter investigates the origin of the asymmetric magnetic field line geometry in the ergospheric disc (and the corresponding asymmetric powerful jet) in 3D perfect magnetohydrodynamic (MHD) numerical simulations of a rapidly rotating black hole accretion system reported in Punsly, Igumenshchev & Hirose. Understanding why and how these unexpected asymmetric structures form is of practical interest because an ergospheric disc jet can boost the black hole driven jet power many fold, possibly resolving a fundamental disconnect between the energy flux estimates of powerful quasar jets and simulated jet power. The new 3D simulations of Beckwith, Hawley & Krolik that were run with basically the same code that was used in the simulation discussed in Punsly et al. describe the 'coronal mechanism' of accreting poloidal magnetic flux towards the event horizon. It was determined that reconnection in the inner accretion disc is a 'necessary' component for this process. The coronal mechanism seems to naturally explain the asymmetric ergospheric disc field lines that were seen in the simulations. Using examples from the literature, it is discussed how apparently small changes in the reconnection geometry and rates can make enormous changes in the magnetospheric flux distribution and the resultant black hole driven jet power in a numerical simulation. Unfortunately, reconnection is a consequence of numerical diffusion and not a detailed (yet to be fully understood) physical mechanism in the existing suite of perfect MHD-based numerical simulations. The implication is that there is presently great uncertainty in the flux distribution of astrophysical black hole magnetospheres and the resultant jet power.

Key words: accretion, accretion discs – black hole physics – MHD – galaxies: active – galaxies: jets.

1 INTRODUCTION

The ultimate nature of the power output of a black hole magnetosphere is highly dependent on two poorly understood circumstances, the source of plasma injection on the magnetic field lines that thread the event horizon and the fate of accreted vertical magnetic flux (Punsly & Coroniti 1990a,b). In the past 8 years, the use of perfect magnetohydrodynamic (MHD) numerical simulations has been developed in the scientific community to help understand these issues. In order to establish and maintain the event horizon magnetosphere, the simulations must rely on the numerical artifice of a mass floor, local mass injection to establish a minimum density. In spite of some discussion of anecdotal mass floor examples, perfect MHD simulations are not likely to resolve the first issue since a mass floor violates rest-mass and energy–momentum conservation and necessarily contradicts the perfect MHD assumption (McKinney 2006b). However, recently MHD simulations have shed some light on the second point. The mystery of how magnetic flux was accreted to the black hole in MHD numerical simulations was revealed in Beckwith et al. (2009) through their meticulous high-resolution numerical work. In this Letter, the insight provided by Beckwith et al. (2009) is used to explain the strange ergospheric disc field topology seen in the simulations reported in Punsly et al. (2009) that resulted in powerful one-sided jets that dominate the total energy output in the jetted system with a location that changed hemispheres in different time snapshots (Punsly 2007a,b).

The fate of accreted flux is perhaps the most critical issue in understanding the power source for black hole driven jets. It was noted in Punsly & Coroniti (1990b) that if vertical, magnetic flux accretes, it is not clear where it ends up. It was argued that reconnection of vertical flux would be determinant to the final magnetic field configuration since the black hole is effectively a sink with infinite capacity for mass, but with a very limited capacity to accept magnetic flux. One possible field configuration that could result from reconnection produced a disc in the ergosphere that can drive...
powerful jets. If this happens, then the power source for the jet drastically increases in efficiency, so this configuration is of profound interest in AGN (Nemmen et al. 2007; Punsly 2011). However, there is much scientific uncertainty in the reconnection geometry and rate expected in an accretion flow near a rapidly rotating black hole, since our experimental experience is based on very different environments, the solar corona, the solar wind, the Earth magnetosphere and magnetotail, and magnetic confinement devices for thermonuclear fusion. The situation was further complicated by the argument that the existence of coherent vertical flux within the dense accreting gas is inhibited by the turbulent magnetic diffusivity of the plasma (van Ballegooijen 1989; Lubow, Papaloizou & Pringle 1994). Thus, it was not even clear if the notion of a large-scale field associated with an accretion flow was viable.

However, recent numerical simulations have shown that vertical flux accretion can occur, but not by diffusing through the disc, but by a two-step process called the ‘coronal mechanism’. The first step is the transport towards the black hole of an inwardly stretched, disc-anchored, poloidal loop through the low-turbulence, coronal layer just above the disc, the ‘hairpin’ field in Beckwith et al. (2009). This coronal transport is similar to the mechanism proposed in Rothstein & Lovelace (2008), but see Beckwith et al. (2009) for some dynamical differences. Then loops of magnetic field in the inner accretion flow reconnect with the half of the ‘hairpin’ at mid-latitudes, allowing it to contract into the black hole, leading to one sign of field threading the black hole (see Section 3). Reconnection is apparently ‘necessary’ for vertical flux accretion in all the numerical simulations of this family (Hawley & Krolik 2006; Beckwith et al. 2009; McKinney & Blandford 2009), but the geometry of the reconnection site is very different than what was described in Punsly & Coroniti (1990b). In spite of this geometric difference, an ergospheric disc does form in some simulations. In the following, the coronal mechanism is shown to naturally explain the asymmetric magnetic field observed in 3D simulations of the ergospheric disc (Punsly et al. 2009).

This work derives from a family of simulations based on a constrained transport MHD code on the Kerr space–time background that has been described numerous times in the literature, so this is not reproduced here (De Villiers & Hawley 2003; De Villiers, Hawley & Krolik 2003; Hirose et al. 2004; De Villiers et al. 2005; Krolik, Hawley & Hirose 2005; Hawley & Krolik 2006; Beckwith, Hawley & Krolik 2008). The particular simulation, KDJ, discussed in Punsly et al. (2009) was described in detail in Krolik et al. (2005) and Hawley & Krolik (2006), which the reader should consult for particulars. KDJ simulates accretion on to a rapidly rotating black hole with an angular momentum per unit mass of $a = 0.99\, M$ in geometrized units. This Letter focuses on the very complicated twisted topologies that are involved in the reconnection events in the simulation.

### 2 FIELD LINE TOPOLOGY IN THE ERGOSPHERIC DISC

A surprising feature of 3D MHD numerical simulations is that the ergospheric disc was threaded mainly by the type I field lines instead of type III field lines in the nomenclature introduced in Punsly et al. (2009). In the left-hand panel of Fig. 1, the type I vertical magnetic field lines emerge from the inner equatorial accretion flow. The false colour plot is a contour map of a 2D cross-section of the density in Boyer–Lindquist coordinates expressed in code units. The interior of the inner calculation boundary (just outside of the event horizon) is greyish white. These field lines are distinguished by connecting to the Poynting jet in one hemisphere only, with the other end spiralling around within the accreting gas in the opposite hemisphere. Another distinguishing feature of a type I field line is that the azimuthal direction of the magnetic field changes direction as the field line crosses the mid-plane of the accretion flow. It was expected in Punsly & Coroniti (1990b) that the direct advection of magnetic flux would produce the type III field topology depicted in the right-hand frame of Fig. 1. However, these were rare in the 3D simulation reported in Punsly et al. (2009). Unlike the type I field lines, the type III field lines connect to both sides of the bipolar jet.

One should consult fig. 3 of Punsly et al. (2009) to appreciate the physical significance of the one-sided type I field lines from the ergospheric disc. These field lines directly equate to a powerful jet of Poynting flux. When this jet forms, it swamps the power output.
from the event horizon (Punsly 2007a,b). In fact, it even suppresses the event horizon jet power to some degree (Punsly 2011).

3 RELEVANT ASPECTS OF THE CORONAL MECHANISM

In this section, the coronal mechanism is reviewed and asymmetric variations in the process that are relevant to the following are noted. The coronal mechanism was detailed in fig. 11 of Beckwith et al. (2009). Some important geometric simplifications that greatly improved the clarity of presentation were implemented in Beckwith et al. (2009). In that paper, the primary focus was on detailed discussions of symmetric pairs of ‘hairpin’ field lines, where one approaches from just above the accretion disc from the north and a matching ‘hairpin’ field line approaches from the south. Furthermore, a non-rotating black hole was chosen so there is minimal azimuthal twisting near the event horizon. Ostensibly, for the sake of simplicity of presentation, all the 3D data were averaged over azimuth in Beckwith et al. (2009), so there were simple field line topologies like closed 2D poloidal loops in the accretion disc (see their fig. 11).

After the leading edge of the hairpins has penetrated the event horizon, reconnection occurs in the equatorial portion of the hairpin with a closed 2D loop. This leads to an increase in the magnetic flux in the accretion flow vortex, or ‘funnel’, in the polar region beyond the event horizon radius in both hemispheres.

It is noted here that there are two intriguing aspects of the field line evolution presented in Beckwith et al. (2009) that should be relevant to 3D field line reconnection in the Kerr geometry.

(i) There is not always symmetry in the hairpin accretion between the Northern and Southern hemispheres. A cluster of field lines in a ‘hairpin’ configuration often approach from one hemisphere at a time. This is manifested in the online animation for Beckwith et al. (2009), especially around 23 s, where one sees an excess of organized flux in the funnel, in the Southern hemisphere of the event horizon. This asymmetry also appears to a much lesser degree in fig. 11 of Beckwith et al. (2009). Note that the animation that accompanies the 2D simulation around a rapidly spinning Kerr black hole in Beckwith et al. (2008) also shows asymmetric hairpin accretion. This supports the notion that asymmetric hairpin field line accretion is not dependent on spin. This does not mean that reconnection will proceed similarly in 2D and 3D and independent of spin. Instead, the simulations show only that the potential pre-reconnection field configuration of asymmetric accretion of hairpin field lines seems to occur in either 2D or 3D and for high spin and low spin.

(ii) Some of the hairpins can actually be buoyant near the horizon and move away from the black hole, never penetrating the horizon (e.g. the hairpin $\approx 30^\circ$ below the equator in fig. 11 of Beckwith et al. (2009) moves outwards between $t = 14 600$ and $14 640 M$).

4 RECONNECTION GEOMETRY IN THE 3D ACCRETION NEAR RAPIDLY ROTATING BLACK HOLES

The reconnection aspect of the ‘coronal mechanism’ described in Beckwith et al. (2009) relies on the topology of poloidal loops in the inner accretion disc. However, in the case of interest here, 3D around a rapidly spinning black hole, almost all the flux in the inner accretion flow is twisted up into toroidal coils (Hirose et al. 2004; Punsly et al. 2009). There are no simple poloidal loops in 3D like there were in the azimuthally averaged data in fig. 11 of Beckwith et al. (2009). Since topology is critical to reconnection, the 2D expediency is not implemented here for the sake of accuracy and the expense of complexity. The analogue of a 2D poloidal loop in the Schwarzschild geometry in the 3D Kerr (rotating black hole) geometry would seem to be one of the many twisted coils that permeate the accretion flow (Hirose et al. 2004; Punsly et al. 2009). The ‘loop’ from $t = 9840 M$ (in geometrized units) of KDJ that is plotted in white in the left-hand frame of Fig. 2 is typical of most of the field lines in the inner accretion disc for high-spin black holes. It spirals near the black hole, then as it expands vertically, it leaves the disc and penetrates the corona. The twisted loop connects to large distances through the corona, presumably closing far away. There are variations of this topology in which one end of the coil stays in the disc, while the other end permeates the corona or event horizon (Punsly et al. 2009).

There are no fine time resolution snapshots of the simulation KDJ (the data are sampled every 80 M), so we cannot see the asymmetric type I field lines of Fig. 1 forming. There is only circumstantial evidence as to the chain of events.

(i) Most of the disc field lines in KDJ are twisted coils near the event horizon that can have significant random inflections due to turbulence and never leave the disc or corona (Hirose et al. 2004; Punsly et al. 2009).

(ii) In KDJ, large vertical flux bundles are entrapped in the inner regions of the accretion flow tending to be far more pronounced in one hemisphere (Punsly et al. 2009).

Figure 2. A potential reconnection site in KDJ is displayed in the left-hand frame. The red field line is the accreting, slightly twisted coronal hairpin. The white field line is a typical twisted structure that is the 3D equivalent of a poloidal loop in a 2D Schwarzschild representation. The inner calculational boundary is blue. The post reconnection topology is depicted in the right-hand frame. The red curve is a buoyant hairpin. The white curve is a type I field line that threads the ergospheric disc as in Fig. 1.
(iii) In KDJ, the ergospheric disc flux shows no tendency for a preferred hemisphere. They can be in either hemisphere or in both hemispheres in an individual time snapshot (Punsly et al. 2009).

(iv) The animations of simulations show that significant poloidal flux can accrete to the inner regions of the accretion flow through the corona in the form of hairpins in an episodic fashion (Beckwith et al. 2008, 2009).

(v) These hairpins can arrive at the inner edge of the flow in asymmetric north/south configurations (Beckwith et al. 2008, 2009).

(vi) The topology of the poloidal flux near the event horizon was shown to be determined by reconnection with simple poloidal loops in 2D azimuthally averaged data (Beckwith et al. 2009).

(vii) Fig. 11 of Beckwith et al. (2009) not only shows the asymmetric accretion of hairpins to the event horizon, but also that some hairpins near the black hole can actually become buoyant and move away from the black hole.

These seven facts can be used to consider the time evolution in the twisted geometry of KDJ that results in the type I field line topology in Fig. 1. Fig. 2 simulates the most plausible scenario based on these seven results which is used as a surrogate for actual fine time-scale data sampling. The left-hand frame shows a typical twisted accretion disc coil in white being approached by a coronal hairpin in red near the black hole. Note that the coronal hairpin is azimuthally twisted in KDJ. Reconnection is very complicated in a twisted 3D environment and is not well understood (Pontin 2011). However, the configuration as drawn forms a natural reconnection site (an X-point). We expect both types of field lines in Fig. 2 to exist from points (i), (iv) and (v) above. The elements required for the pre-reconnection geometry in the left-hand frame of Fig. 2 commonly occur in this family of simulations. Thus, it is reasonable to expect that these field configurations coexist in proximity at various times, and these potential reconnection sites should not be rare. However, the reconnection rate in such a complicated geometry that does not proceed by a physical mechanism, but through numerical diffusion, is very uncertain. By points (ii), (iii) and (vi) above, reconnection must have occurred in KDJ as depicted in the right-hand frame of Fig. 2. The white curve in the right-hand frame is poloidal flux through the equatorial plane of the ergosphere in one hemisphere in analogy to the left-hand frame of Fig. 1, and the red curve would be a buoyant hairpin field line that moves out in the corona consistent with point (vii).

A significant difference between the topology resulting from the reconnection in Fig. 2 compared to that in fig. 11 of Beckwith et al. (2009) is that in Fig. 2 the reconnection is happening before the hairpin penetrates the event horizon, while in fig. 11 of Beckwith et al. (2009) it occurs after the hairpin penetrates the horizon. This indicates that the coherent flux transport rate combined with the reconnection rate and twisted 3D field line geometry (which affects the reconnection rate) might determine if a field line penetrates the event horizon or the inner accretion flow when and if reconnection occurs. The final field line topology depends on the balancing of reaction rates (reconnection and transport) as well as internal dynamics (that affect field line shape) that are determined by the numerical simulation.

5 DISCUSSION

This Letter shows that the ‘coronal mechanism’ for flux transport in simulations of black hole accretion provides a plausible explanation for the one-sided ergospheric disc field lines in the high-spin 3D simulation KDJ. It therefore explains the strange phenomenon observed in KDJ that the black hole driven jet Poynting flux was very one sided, jumping from side to side and emanating primarily from the ergospheric disc.

An otherwise almost identical simulation to KDJ that includes additional artificial diffusion terms in the equations of continuity, energy conservation and momentum conservation (as described in De Villiers 2006) does not show these one-sided ergospheric disc structures Punsly (2011). This seems to indicate a change in the reconnection process that is driven either directly or indirectly by the numerical diffusion. In support of this interpretation, the force-free simulations of an initially uniform field in Komissarov (2004) show magnetic flux threading the ergospheric equatorial plane near the black hole, yet the same initial state that is time evolved in a different force-free code with a slower ansatz for the reconnection rate shows no magnetic flux threading the equatorial plane near the black hole (McKinney 2006a). The implication is that the global topology of the black hole magnetosphere is highly dependent on the time evolution driven by reconnection. This is not a trivial circumstance because in MHD simulations reconnection is dependent on numerical diffusion. The situation is rendered even more ambiguous by the complicated twisted magnetic field line geometries in 3D simulations around rapidly rotating black holes (e.g. Fig. 2). The complications of far less intricate 3D field line topology have been recognized in solar and planetary physics (Wilmut-Smith, Pontin & Hornig 2010; Pontin 2011). Similarly, some detailed numerical modelling has shown the need for 3D to properly describe reconnection (Kowal et al. 2009; Kulpa-Dybel et al. 2010). Furthermore, in high-energy environments, radiation effects might also be crucial for a proper treatment (Uzdensky 2011). This might be relevant because radiation is not formally considered in these MHD codes. In summary, there are many potential sources of uncertainty in the reconnection-induced topology in these simulations.

It should be noted that, in principle, the choice of coordinates (e.g. Boyer-Lindquist, as in the simulations discussed here, or Kerr–Schild) should be irrelevant to the results obtained. What is likely more relevant is the grid scale and sources of numerical diffusion in the solution methodology. A very basic consideration is that once a field line that is frozen-in to the plasma is accreted through the event horizon (technically, the inner calculational boundary that is just outside the event horizon in Boyer–Lindquist coordinates), it should be unable to migrate out of the horizon by moving outwards into the equatorial plane if causality is maintained by the frozen-in plasma inside the horizon. Field lines can only be extracted from the horizon by local reconnection, not diffusion back into the equatorial plane. As such, a black hole saturated with magnetic flux is a non-trivial ‘boundary condition’ for further magnetic flux accretion of the same orientation. For example, what happens when there is repeated injection of magnetic flux as in the simulations of Igumenshchev (2008)? The suite of simulations considered here have a finite amount of flux (either vertical or the leading edge of accreting loops) that accretes towards the black hole and a boundary condition that flux cannot leave or enter through the outer boundary. However, if that boundary condition is changed to be one of continuous injection of flux, then the magnetic topology might change near the black hole. In particular, Beckwith et al. (2009) suggest that the funnel and horizon field strength is set by the gas and magnetic pressure in the disc, and Tchekhovskoy, Narayan & McKinney (2010) claim that it is set by the ram pressure in the disc. Once this very finite value is achieved, what happens when more flux is injected into the accretion stream and approaches the horizon? Does this preferentially move the reconnection sites out to near the mid-plane of the ergosphere? This might raise the power level to be consistent with
the more powerful radio-loud AGN (Nemmen et al. 2007; Punsly 2011).

In the absence of more robust treatments of reconnection, this study suggests two new simulations that are achievable with the present numerical codes. One would be to rerun KDJ with the original code, but with high-density time sampling for a portion of the run so that we can see how the ergospheric disc flux gets established. It would also be an interesting simulation to explore the possibility of continuous vertical flux injection from the outer boundary around rapidly rotating black holes to see if the pattern of reconnection changes and if the magnetospheric distribution of flux changes, possibly enhancing the ergospheric disc. In the future, more realistic reconnection in the presence of resistivity needs to be modelled near black holes as in Palenzuela et al. (2009). One might also find environments suitable for reconnection in the ergospheres of other simulation geometries that can produce relativistic jets. For example, the collisions of black holes as discussed in Palenzuela, Lehner & Liebling (2010) or the inner regions of a tilted accretion disc as modelled in Fragile et al. (2007) are fertile areas to pursue.

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