ON THE ROLE OF FAST MAGNETIC RECONNECTION IN ACCRETING BLACK HOLE SOURCES

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ABSTRACT

We attempt to explain the observed radio and gamma-ray emission produced in the surroundings of black holes by employing a magnetically dominated accretion flow model and fast magnetic reconnection triggered by turbulence. In earlier work, a standard disk model was used and we refine the model by focusing on the sub-Eddington regime to address the fundamental plane of black hole activity. The results do not change substantially with regard to previous work, ensuring that the details of accretion physics are not relevant in the magnetic reconnection process occurring in the corona. Rather, our work puts fast magnetic reconnection events as a powerful mechanism operating in the core region near the jet base of black hole sources on more solid ground. For microquasars and low-luminosity active galactic nuclei, the observed correlation between radio emission and the mass of the sources can be explained by this process. The corresponding gamma-ray emission also seems to be produced in the same core region. On the other hand, emission from blazars and gamma-ray bursts cannot be correlated to core emission based on fast reconnection.

Key words: accretion, accretion disks – magnetic reconnection

1. INTRODUCTION

Almost a decade ago, de Gouveia Dal Pino & Lazarian (2005, hereafter GL05) proposed a model for producing jet plasmons and particle acceleration by magnetic reconnection events in the surroundings of accretion disks around black holes (BHs) with magnetospheres. This model predicts that the amount of magnetic power released by reconnection may be more than sufficient to explain observed flares from BH mass sources in different scales (from microquasars to low-luminosity active galactic nuclei, LLAGNs; see de Gouveia Dal Pino et al. 2010a, 2010b, hereafter GPK10; Kadowaki et al. 2014, hereafter KGS14). Their model invokes the interactions between the field lines anchored onto the BH horizon and those onto the accretion disks around BHs.

A standard disk model (Shakura & Sunyaev 1973) was used in these works to describe the accretion flow around BHs, taking into account the near Eddington regime. At the high/soft or very high states of X-ray emission (Remillard & McClintock 2006; Fender et al. 2004, 2009) the accretion is dominantly via a standard disk extending to the innermost stable circular orbit with a weak corona above the disk. However, in the low/hard state, it is believed that the accretion flows are geometrically thick, optically thin, advection-dominated (ADAFs; Narayan & Yi 1995) with an outer geometrically thin, optically thick disk.

Recently, Qiao & Liu (2013) considered the cooling of the soft X-ray photons from the underlying accretion disk to the corona, and the bremsstrahlung, synchrotron, and corresponding self-Compton cooling of the corona itself. With the decrease of the mass accretion rate, the size of the inner disk decreases and eventually the disk vanishes completely by evaporation. Consequently, the accretion becomes dominated by an ADAF, in which the X-ray emission is produced by the Comptonization of the synchrotron and bremsstrahlung photons of the ADAF itself.

The recent simulation work by Dexter et al. (2014) on transient jets in the ADAF regime during the transition from the hard to soft state has shown that the magnetic reconnection of opposite polarity fields converts magnetic energy into kinetic and thermal energy fluxes. The transient jet power depends on the magnetic energy density and timescale over which it is dissipated, not on the BH spin (Dexter et al. 2014). Besides, Sikora & Begelman (2013) have suggested that the radio-quiet/loud dichotomy in AGNs could be due to the absence or presence of sufficient coherent magnetic fields. To include the dominant role of magnetic fields in the inner region around BHs, Meier (2005, 2012) proposed that ADAF could be replaced by a magnetically dominated advective flow (MDAF).

GL05 proposed a plausible model in which fast magnetic reconnection episodes in the corona above and below the inner region of accretion disks can explain the origin of radio flares observed in the galactic microquasar GRS 1915+105. This might happen whenever a large magnetic field arises from the inner accretion disk removing part of the angular momentum so that the accretion rate approaches the Eddington rate and pushes the disk magnetic field lines toward the BH magnetosphere. If both magnetic fluxes have opposite polarity, then, in the presence of anomalously high resistivity or turbulence, an event of fast magnetic reconnection may take place, releasing copious amounts of magnetic power that may accelerate particles to relativistic velocities in a first-order Fermi process (GL05; Kowal et al. 2011, 2012; de Gouveia Dal Pino & Kowal 2015). The model was further extended to other microquasars, AGNs, and young stellar objects (GPK10). Recently, the model was applied to a much larger sample of sources than before, including LLAGNs, blazars, microquasars, and gamma-ray bursts (GRBs; KGS14). They found evidence that the observed correlation between radio luminosities and the source masses, spanning $10^{10}$ orders of magnitude in mass and $10^6$ orders of magnitude in luminosity, in microquasars and LLAGNs (Merloni et al. 2003; Nagar et al. 2005; Fender et al. 2004) could be naturally explained by this fast magnetic reconnection model. Moreover, they found that the observed gamma-ray emission in these sources could be also produced in the same core region. They also argued that the proposed mechanism could be associated with the transition from the low/hard to the high/soft states.

Here we revisit a similar scenario related to violent fast reconnection episodes between the field lines of the inner disk corona and those that are anchored in the BH, taking into account a sub-Eddington flow. We study the same mechanism that comes...
and accretion rates in Eddington units
\[ \dot{M} = \dot{m} \dot{M}_{\text{Edd}}, \]
where \( \dot{M}_{\text{Edd}} = 1.39 \times 10^{18} \text{g s}^{-1} \).

It is further assumed that, at some radius \( R_0 = 7.3 \times 10^4 \text{m} \theta^{-1} \text{cm} \), the ion temperature, \( T_i \), will saturate to a finite multiple of \( \theta \) of the electron temperature, \( T_e \),
\[ \theta = \frac{T_i}{T_e} \geq 1. \]  

The value of \( \theta \) can lie between 1 and 820 (Meier 2012). In other words, an MDAF exists somewhere outside the ISCO and inside the two-temperature ADAF.

Also, as shown in Figure 1, the location of the reconnection region \( R_X = R_1 \) where \( R_1 = \alpha^{2/3} R_0 \) is given by
\[ R_X = R_1 = 7.3 \times 10^8 \alpha^{2/3} m \theta^{-1} \text{cm}, \]
with \( \alpha \) being the viscosity parameter. As in GL05, GPK10, and KGS14, the magnetic field in the inner region can be evaluated from the momentum flux balance between the accretion flow and the magnetic pressure around the BH. In an MDAF-like corona, this condition implies magnetic fields in the \( Z \) and \( R \) directions that depend on \( m, \dot{m}, \theta, \) and \( \alpha \), and are expressed as (Meier 2012)
\[ B_Z = 3.34 \times 10^4 m^{-1/2} \dot{m}^{1/2} \theta^{5/4} \text{G}, \]
\[ B_R = 3.84 \times 10^4 \alpha^{-5/3} m^{-1/2} \dot{m}^{1/2} \theta^{5/4} \text{G}. \]  

The corresponding poloidal field strength is determined as
\[ B_p = 10^4(11.15 + 14.89 \alpha^{-10/3} \dot{m}^{-1/2} \dot{m}^{1/2} \theta^{5/4}) \text{G}. \]  

Other MDAF coronal parameters such as density, ion temperature, and height are, respectively, given by
\[ \rho = 8.9 \times 10^{-10} \alpha^{-2} m^{-1} \dot{m}^{3/2} \text{g cm}^{-3}, \]
\[ T_i = 10^9 \theta \text{K}, \]
\[ H = 6.29 \times 10^9 \alpha m \theta^{-1} \text{cm}. \]

2.2. Magnetic Energy Release by Fast Magnetic Reconnection

Let us assume that the magnetic field anchored into the BH is of the same order of the poloidal magnetic field in the corona above and below the disk in the inner edge of the disk (GL05). This is a reasonable assumption since the BH magnetosphere is built by the dragging of magnetic field lines from the accretion disk (MacDonald et al. 1986; Neronov & Aharonian 2007; GL05). Furthermore, to allow for reconnection, let us assume that the new flux of lines that rise in the MDAF disk corona have opposite polarity to those deposited earlier in the BH magnetosphere (which is possible if dynamo processes occur in the accretion disk; GL05; KGS14 and references therein). As mentioned, in order to extract as much magnetic power as possible to accelerate particles, magnetic reconnection has to be fast. The presence of anomalous resistivity (Parker 1979; Biskamp et al. 1997; Shay et al. 2004) or turbulence (Lazarian & Vishniac 1999; Kowal et al. 2009) can speed up the reconnection rate to values near the Alfvén velocity \( (v_A) \). As described in GL05 and KGS14, the rate of magnetic energy that

\[ M = m M_\odot \]  

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\[ M = m M_\odot \]  

\[ \dot{M} = \dot{m} \dot{M}_{\text{Edd}}, \]
can be extracted from the magnetic contact discontinuity in the corona through reconnection is given by (see the rectangular zone in the lower panel of Figure 1)

$$\dot{W} = \frac{B_{\rho}^2}{8\pi} v_{\text{rec}}(4\pi R_X L_X) = \frac{B_{\rho}^2}{8\pi} v_{\text{rec}}(4\pi R_X A H). \quad (10)$$

Here, $0 < \lambda \leq 1$. In the case of fast reconnection driven by turbulence (Lazarian & Vishniac 1999), we can derive the magnetic reconnection power in a similar way as explained in KGS14. The presence of weak turbulence causes the magnetic field lines to wander and induces fast reconnection (see also Kowal et al. 2009, 2012). Assuming that the injection scale of the turbulence ($L_{\text{inj}}$) is of the order of the size of the reconnection zone ($L_X$), the reconnection rate is

$$v_{\text{rec}} \approx v_A M_A^2,$$

$$v_A = \frac{v_{A0}}{(1 + \frac{v_{\text{th}}^2}{c^2})^{1/2}} = \Gamma v_{A0},$$

$$v_{A0} = \frac{B_{\rho}}{(4\pi \rho)^{1/2}}, \quad (12)$$

where $M_A = v_{\text{inj}}/v_A$ is the Alfvénic Mach number of the turbulence and $v_{\text{inj}}$ the turbulence velocity at the injection scale. Based on the expression of the turbulence velocity in the transitional layer between ADAF and MDAF, we have (Meier 2012)

$$v_{\text{inj}} = 3.7 \times 10^8 \alpha^{1/2} \theta^{1/2} \text{cm s}^{-1}. \quad (13)$$

Substituting Equations (4), (6)–(9), and (11)–(13) into Equation (10), the magnetic reconnection power released by turbulent fast reconnection in the surroundings of the BH is given by (GL05)

$$\dot{W} = 3.34 \times 10^{34} \dot{m} \theta A \Gamma^{-1}(11.15\alpha^{10/3} + 14.89)^{1/2} \text{erg s}^{-1}. \quad (14)$$

We note that $\dot{W} \propto \dot{m}$, which has the same dependence on $\dot{m}$ as that for a standard accretion disk model (Equation (15) from KGS14). The dependence on $\dot{m}$ on the other hand, is stronger in this case ($W \propto \dot{m}^{3/4}$).

3. RESULTS

As stressed in KGS14, the magnetic reconnection power that is produced in an anomalous resistivity model does not cover most of the observed radio and gamma-ray emissions of the sources, so we only consider the turbulent-driven fast reconnection model in the following. Besides, the MDAF scenario naturally drives turbulence in the corona, as remarked.

Figure 2 compares the calculated fast magnetic reconnection power driven by turbulence as derived in this work (range of free parameters $1 \leq m \leq 10^{10}, 5 \times 10^{-4} \leq \dot{m} \leq 0.05, 0.003 \leq \alpha \leq 0.3, 0.01 \leq A \leq 1, 1 \leq \theta \leq 46$) with the calculated power in KGS14 employing the standard accretion model rather than MDAF. We find that, in spite of the inherent differences in the assumptions and parameterization (the parametric space in KGS14 spans $R_X/R_S = 6, 1 \leq m \leq 10^{10}, 5 \times 10^{-4} \leq \dot{m} \leq 1, 0.05 \leq \alpha \leq 0.5$, and $0.06 R_s < L_X < 17.5 R_s$), both models produce very similar ranges of values for the magnetic reconnection power, therefore confirming the earlier prediction in GPK10 that the details of the accretion model should not have much affect on the results regarding the fast reconnection power extracted from the coronal regions around BHs. The models are also compared with the observed correlations between the core radio luminosity and the BH mass found for microquasars and LLAGNs by Nagar et al. (2002, 2005) and Merloni et al. (2003). We see that the slope dependence of the magnetic power released by turbulent reconnection with the source mass is very similar to the observed radio luminosity–source mass correlations for these sources.

As in KGS14, in Figure 3 we compare the calculated fast magnetic reconnection power driven by turbulence (Equation (14)) with the observed nuclear radio and gamma-ray luminosities of a large sample (of more than 270 sources) including microquasars (or galactic black hole binaries (GBHs)), LLAGNs, blazars, and GRBs (see KGS14 and references therein for a detailed description of this sample). The radio emission is rep-

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1. We note that the adopted range of values for $\theta$ and $\lambda$ ensure the nearly collisionality condition required by the MHD equations and the fast reconnection driven by turbulence (see more details in KGS14). With this parametric space $L_X = \lambda H$ spans between $0.02 R_S$ and $\sim 44 R_S$ and $R_X$ between $1.1 R_S$ and $\sim 186 R_S$, where $R_S = 2.95 \times 10^3 \text{cm}$ is the Schwarzschild radius.
are powered by the same acceleration mechanism. Figure 3 also likely to be produced in the same core region around the BH and as that of the radio emission and that both seem to be correlated. seen with certainty is that this emission follows the same trend to also produce the gamma-ray emission; however, what can be calculated magnetic energy power appears to be sufficient enough to explain the observed radio emission for most of them both in the core region (Figure 3). Furthermore, as argued in GPK10 and KGS14, since fast magnetic reconnection and the associated emission flares are strongly dissipative phenomena that lead to partial destruction of the equilibrium configuration in the inner accretion disk/corona region, this mechanism could be related to the transition from the hard or low/hard to the high/soft X-ray state (see also Huang et al. 2014).

The observed gamma-ray emission of these sources is also well correlated with the radio luminosity, and the calculated fast magnetic reconnection power is large enough to produce them both in the core region (Figure 3). Furthermore, as mentioned in KGS14, the results here do indicate that the fast reconnection is relatively insensitive to the accretion disk model. The similarity between the results here produced with MDAF accretion and those of KGS14 with standard disk accretion is striking (Figure 2). The only difference is that in order for magnetic reconnection to produce both emissions, the sources in general require accretion rates $\dot{m} > 0.5$ in the MDAF case and $\dot{m} > 0.05$ in the standard accretion case (KGS14). This difference is due to the inherent physical assumptions of each model as described.

Finally, our work further supports the observed correlation between GRBs and blazars (Nemmen et al. 2012) and suggests that the gamma-ray and radio emission from such sources cannot be produced by fast magnetic reconnection in the core region. It is rather originated further out in the jet.

4. DISCUSSION AND CONCLUDING REMARKS

We have extended the earlier works by GL05, GPK10, and KGS14 investigating the conditions for fast reconnection between the magnetic field lines that rise from the accretion disk and the lines anchored into the BH horizon. Distinct from previous works that adopted the standard thin, optically thick model of disk accretion, in this study we considered MDAF accretion in the inner region around the BH, which includes the dominant role of the magnetic field and is suitable for sub-Eddington sources (Meier 2005, 2012). This model produces results that are similar to those obtained in earlier works. The calculated magnetic power released by fast reconnection driven by turbulence versus source mass is consistent with the observed correlation between radio emission and source mass for microquasars and LLAGNs. This may be useful for the interpretation of the fundamental plane of BH activity which correlates the radio and X-ray emission of these sources with their BH mass (Merloni et al. 2003; Falcke et al. 2004; Huang et al. 2014). The investigation of the X-ray emission, which is directly related to emission processes in the accretion disk, is beyond of the scope of this work which focused on coronal emission. Nevertheless, our model suggests a simple interpretation for the existence of these empirical correlations.
To conclude, the results above mainly connect the radio and gamma-ray emission from low-luminosity compact sources to magnetically dominated reconnection process in the nuclear region of these sources whether the accretion flow model is standard disk corona (KGS14) or MDAF (this work). As a further step, more general analytical and numerical studies will be needed to more realistically explore the scenario presented here. Also, the reproduction of observed non-thermal spectral energy distributions of different sources employing the acceleration mechanism above will help to further test it (see attempts in this direction in Khiali et al. 2014).

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