High-mass X-ray Binaries: Illuminating the Passage from Massive Binaries to Merging Compact Objects
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Statistical study of magnetic reconnection in accretion disks systems around HMXBs

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Abstract. Highly magnetized accretion disks are present in high-mass X-ray binaries (HMXBs). A potential mechanism to explain the transition between the High/Soft and Low/Hard states observed in HMXBs can be attributed to fast magnetic reconnection induced in the turbulent corona. In this work, we present results of global general relativistic MHD (GRMHD) simulations of accretion disks around black holes that show that fast reconnection events can naturally arise in the coronal region of these systems in presence of turbulence triggered by MHD instabilities, indicating that such events can be a potential mechanism to explain the transient non-thermal emission in HMXBs. To find the zones of fast reconnection, we have employed an algorithm to identify the presence of current sheets in the turbulent regions and computed statistically the magnetic reconnection rates in these locations obtaining average reconnection rates consistent with the predictions of the theory of turbulence-induced fast reconnection.

Keywords. accretion disks, magnetohydrodynamics (MHD), instabilities, turbulence, magnetic reconnection

1. Introduction

Accretion disks systems are believed to be very common structures in the Universe (for reviews, see, e.g., Pringle 1981; Balbus & Hawley 1998; Abramowicz & Fragile 2013). These systems are associated with Black Hole Binaries (BHBs), Active Galactic Nuclei (AGNs) and Young Stellar Objects (YSOs). In particular, high-energy (HE) and very-high-energy (VHE) emissions are frequently observed in BHBs and AGNs. For instance, the X-ray transitions observed in BHBs (see, e.g., Fender *et al.* 2004; Belloni *et al.* 2005; Remillard & McClintock 2006; Kylafis & Belloni 2015) are characterized by a high/soft state attributed to the thermal emission of a geometrically thin, optically thick accretion disk (Shakura & Sunyaev 1973), and a low/hard state attributed to inverse Compton of soft X-ray photons by relativistic particles in a geometrically thick, optically thin accretion flow (see Esin *et al.* 1997, 1998, 2001; Narayan & McClintock 2008). Besides, a fast transient state (of the order of a few days; see Remillard & McClintock 2006) is identified between these two states. VHE emission (gamma-rays in GeV and TeV band) has also been observed in BHBs, such as Cgy-X1 (Albert *et al.* 2007) and Cgy-X3 (Aleksić *et al.* 2010). In particular, the origin of the latter is uncertain due to the poor resolution of current gamma-ray detectors. Kadowaki *et al.* (2015) and Singh *et al.* (2015) found that turbulent fast magnetic reconnection (Lazarian & Vishiniac 1999) operating at the coronal region of accretion disks can explain the gamma-ray emission as coming from the core region of BHBs. According to this model, reconnection events between the magnetic field lines lifting from the accretion disk corona and those anchored into the horizon of black hole could accelerate relativistic particles in a first-order Fermi process (see, de Gouveia Dal Pino & Lazarian 2005; de Gouveia Dal Pino *et al.* 2010a; Kowal *et al.* 2012; del Valle *et al.* 2016). These particles, interacting with the density, magnetic and radiation fields are able to produce gamma-ray emission. Recently, Khiali *et al.* (2015) considered the power released by turbulent fast magnetic reconnection events to develop an analytical, single zone scenario to produce leptons and hadrons to obtain the SEDs of Cgy-X1 and Cgy-X3. The comparison with the observed SEDs shows that this core model assuming magnetic reconnection as a source of acceleration of the particles explains very well the VHE emission of the BHBs (see also Ramirez-Rodriguez, de Gouveia Dal Pino & Alves-Batista, in these proceedings).

Despite these studies, numerical simulations are still required to probe the viability of turbulent fast magnetic reconnection events in BHBs and AGNs core regions. In this work, we have performed global general relativistic MHD (GRMHD) simulations of accretion disks around black holes and evaluated the presence of turbulent fast reconnection driven by MHD instabilities, such as the magnetorotational instability (MRI; Chandrasekhar 1960; Balbus & Hawley 1991; Hawley *et al.* 1995). To find the zones of fast reconnection, we have employed an algorithm to identify the presence of current sheets in the turbulent regions (see, Zhdankin *et al.* 2013; Kadowaki *et al.* 2018) and computed statistically the magnetic reconnection rates in these locations (see, Kadowaki *et al.* 2018; for an application in shearing-box simulations).

2. Global GRMHD simulations

We have used the ATHENA++ code (White *et al.* 2016) to perform global GRMHD simulations of a torus (thick disk, see, Fishbone & Moncrief 1976) around a rotating black hole in a two-dimensional domain with 512 cells in the radial direction and 512 in the polar direction (in Kerr-Schild coordinates). We have assumed a black hole with mass $M = 1$, spin $a/M = 0.95$, and adiabatic index $\Gamma = 13/9$. The grid was set between 0.98 times the outer horizon radius $M + \sqrt{M^2 - a^2}$ and $r = 20$ in the radial direction, and between $\theta = 0$ and $\theta = \pi$ in the polar direction. We have imposed outflow conditions in the radial boundaries and reflecting conditions in the polar boundaries. An LLF (local LaxFriedrichs) Riemann solver was used.

We have adapted the algorithm used in Zhdankin *et al.* (2013) and Kadowaki *et al.* (2018) to measure the magnetic reconnection rate (see, Kowal *et al.* 2009) in a General Relativistic approach (see also Ball *et al.* 2018). Figure 1 shows the magnetic reconnection rate ($V_{rec} = V_{in}/V_A$)† measured by an observer in the coordinate frame (top diagram) and the profiles of the magnetic field intensity and the current density (bottom diagram). This model corresponds to a torus with an initial weak poloidal magnetic field (represented by closed loops inside the torus) with the ratio of maximum gas pressure to maximum magnetic pressure equal 100 (see, White *et al.* 2016). The bottom diagram of Figure 1 shows the formation of turbulent structures due to the MRI, allowing the accretion process and the development of magnetic reconnection sites (filled circle symbols). The black symbols correspond to the local maxima current density identified by the algorithm, and the white symbols correspond to the confirmed magnetic reconnection sites (see more details in Kadowaki *et al.* 2018). The top diagram of Figure 1 shows the time evolution of the averaged values of V_{rec} evaluated in the confirmed magnetic reconnection sites (white symbols in the bottom diagram). We have obtained averaged values between 0.01 and

† We have evaluated the magnetic reconnection (V_{rec}) rate in a similar way to the method used by Kowal *et al.* (2009), where we averaged the ratio between the inflow velocity (V_{in}) of the opposite magnetic fluxes and the Alfvén speed (V_A) at the reconnection site.

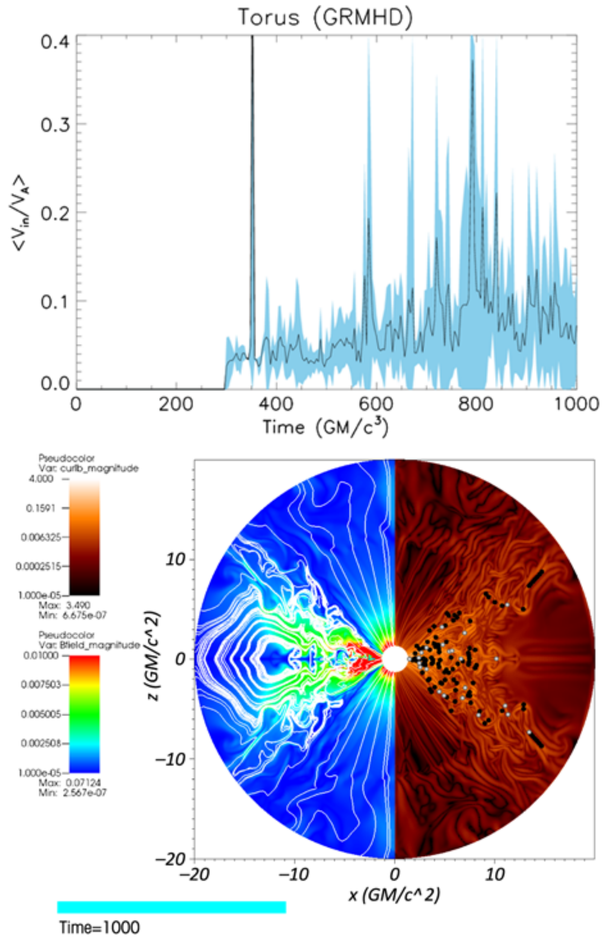

Figure 1. The top diagram shows the time evolution of the magnetic reconnection measured by an observer in the coordinate frame. The bottom diagram shows the system at $t = 1000$ (in units of GM/c^3). As time goes by the MRI sets in, allowing the accretion process and the formation of a turbulent environment. The black symbols correspond to the local maxima identified by the algorithm and the white symbols correspond to the confirmed magnetic reconnection sites.

0.7 consistent with the predictions of the theory of turbulence-induced fast reconnection (Lazarian & Vishiniac 1999).

3. Conclusions

In this work, we have employed an algorithm to identify the presence of current sheets in the turbulent regions of a torus around a black hole and computed statistically the magnetic reconnection rates in these locations. Preliminary results of our GRMHD simulations have revealed the development of turbulence due to the MRI and we have detected the presence of fast reconnection events, obtaining average reconnection velocities in Alfvén speed units of the order of 0.01 and 0.7, as predicted by the theory of turbulence-induced fast reconnection (Lazarian & Vishiniac 1999). This result strengthens the scenario where turbulent fast magnetic reconnection can take place in the core region of BHBs (de Gouveia Dal Pino & Lazarian 2005; de Gouveia Dal Pino *et al.* 2010a; Kadowaki *et al.* 2015; Singh *et al.* 2015; see also Ramirez-Rodriguez et al., in these proceedings), where the magnetic energy released by these events can accelerate relativistic

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particles by a first-order Fermi process and produce HE and VHE emissions observed in these sources.

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