PROCEEDINGS OF SCIENCE

Fast Magnetic Reconnection in the Core Region of Low Luminosity AGNs and Black Hole Binaries and the Origin of their Gamma-Ray Emission

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Fast magnetic reconnection can be a very powerful mechanism operating in the core region of black hole binaries (BHBs) and active galactic nuclei (AGNs). In earlier work, we have been suggested that the power released by fast reconnection events between the magnetic field lines lifting from the inner accretion disk region and the lines anchored into the central black hole (BH) could accelerate relativistic particles in a first-order Fermi process and produce the observed radio emission from BHBs and low luminosity AGNs (LLAGNs). Moreover, we have been proposed that the observed correlation between the radio emission and the mass of these sources, spanning 10^{10} orders of magnitude in mass, might be related to this process. Here we present our late results of the comparison of the magnetic power released by fast reconnection with the observed very high energy emission (from MeV/GeV to Tev bands) of BHBs, LLAGNs, blazars, and gamma-ray bursts (GRBs). In the case of LLAGNs and BHBs, not only the radio but also the gamma-ray emission can be due to magnetic power released by fast reconnection and follows the same trend in the luminosity-mass diagram as that of the core radio emission of these sources (tested for over 200 sources). This indicates that the very high energy emission of these sources can be produced in the core. On the other hand, the emission from blazars and GRBs does not follow the same trend, suggesting that their emission is produced outside the core, as expected.

The 34th International Cosmic Ray Conference
30 July- 6 August, 2015
The Hague, The Netherlands

∗Speaker.

†This work has been partially supported by grants from the Brazilian agencies FAPESP (2013/09065-8, 2013/10559-5), CNPq (142220/2013-2 and 306598/2009-4) and CAPES.

PoS(ICRC2015)919

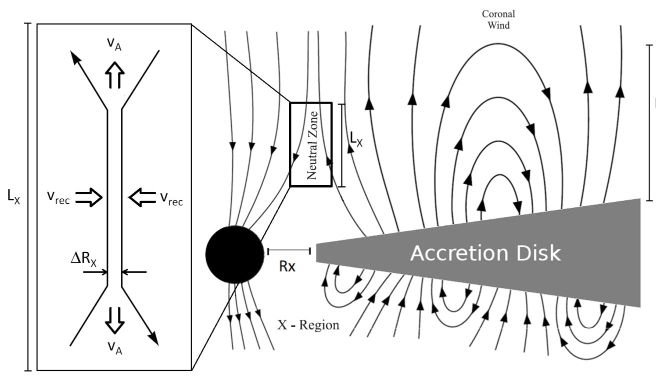

Figure 1: Schematic drawing of the magnetic field geometry in the region surrounding the BH. R_X characterizes the inner accretion disk radius. ΔR_X and L_X correspond to the width and the extension of the magnetic reconnection region, respectively. L is the height of the corona. Obtained from [11].

1. Introduction

Galactic black hole binary systems (BHBs) and active galactic nuclei (AGNs) often exhibit variability and quasi-periodic relativistic outflow ejections of matter that may offer important clues about the physical processes that occur in their inner regions, in the surroundings of the central black hole (BH).

A potential model to explain the origin of these ejections and the often associated radio flare emissions was proposed by de Gouveia Dal Pino and Lazarian (2005, hereafter GL05 [5]) for BHBs and extended to AGNs and young stellar objects by de Gouveia Dal Pino et al. (2010, hereafter GPK10 [6]). Their model invokes the interactions between the magnetosphere anchored into the central BH horizon (see [4]) and the magnetic field lines arising from the accretion disk.

In accretion episodes where the accretion rate is increased (and may even approach the critical Eddington rate), both magnetic fluxes are pushed together in the inner disk region and reconnect under finite magnetic resistivity (see Figure 1). In the presence of kinetic plasma instabilities [23], anomalous resistivity [20], or turbulence [13], reconnection becomes very efficient and fast (with reconnection velocities approaching the local Alfvén speed, which in these systems is near the light speed) and then may cause the release of large amounts of magnetic energy power. Part of this power will heat the coronal and the disk gas and part may accelerate particles to relativistic velocities by a first-order Fermi process at the magnetic discontinuity.

Employing the magnetic reconnection model above in the surrounds of BHs with an anoumalous resistivity mecanism, GPK10 found some evidence that the observed correlation between the radio luminosities and the BH source masses, spanning 10^{10} orders of magnitude in mass and 10^6 in luminosity, from BHBs to low-luminosity AGNs (LLAGNs) could be explained by the magnetic power released by fast reconnection. They also argued that this model could be related to the transition between the observed "hard" and "soft" steep-power-law (SPL) states of BHBs (e.g., [18]).

In recent years, the very high energy (VHE) from AGNs have revealed strong variability, with timescales of the order of days (e.g., M87), which points to extremely compact emission regions (corresponding to only a few Schwarzschild radii; e.g., [1]). Magnetic reconnection events occurring close to the central sources could offer appropriate conditions for producing particle acceleration and the associated VHE gamma-ray emission in these sources (via, e.g., Inverse Compton, Synchrotron self-Compton, proton-proton, or proton-photon up-scatterings).

In the present work (see [11]), we revisit the model of GL05 and GPK10 comparing two different fast magnetic reconnection mechanisms, namely, fast reconnection driven by anomalous resistivity and by turbulence.

2. Magnetic power produced by fast reconnection in the surrounds of a BH

To evaluate the amount of magnetic energy that can be extracted through violent magnetic reconnection, it is adopted the standard model for the radiation-dominated accretion disk by Shakura and Sunyaev (1973, [19]) and the model by Liu et al. (2002, [14]) to quantify the parameters of the corona. Also, it is assumed that the inner radius of the accretion disk corresponds two times the last stable orbit around the BH ($R_X = 6R_S$, where R_S is the Schwarzschild radius). To determine the accretion rate immediately before an event of violent magnetic reconnection, it is assumed the equilibrium between the disk gas ram pressure and the magnetic pressure of the magnetosphere anchored at the BH horizon. It is assumed further that the intensity of the BH horizon field is of the order of that of the inner disk. Under these conditions, the magnetic power released during violent fast magnetic reconnection in the surrounds of a BH for the anomalous resistivity mechanism is approximately given by

$$\dot{W}_B \simeq 2.89 \times 10^{34} \Gamma^{\frac{1}{8}} r_X^{-\frac{107}{32}} l^{\frac{17}{16}} q^{\frac{7}{2}} \dot{m}^{\frac{25}{16}} m^{\frac{1}{2}} \;\; erg/s, \tag{2.1}$$

where $r_X = R_X/R_S$ is the inner radius of the accretion disk in R_S units, $l = L/R_S$ is the normalized size of a coronal magnetic flux tube (which will also characterize the height of the corona), $\dot{m} = \dot{M}/\dot{M}_{Edd}$ is the mass accretion rate in $\dot{M}_{Edd}$ units (which corresponds to the Eddington mass accretion rate $\dot{M}_{Edd} = 1.45 \times 10^{18} m\ g/s$), $m = M/M_{\odot}$ is the BH mass in solar mass units, and $q = [1 - (3R_S/R_X)^{1/2}]^{1/4}$. In the equation (2.1), $\Gamma = [1 + (\frac{v_{A0}}{c})^2]^{-1/2}$ (see, e.g., [21]), where $v_{A0} \sim c$ is the local Alfvén speed.

Using the turbulent-driven fast reconnection mechanism, we have obtained that the magnetic reconnection power released is given by

$$\dot{W}_B \simeq 1.66 \times 10^{35} \Gamma^{-\frac{1}{2}} r_X^{-\frac{5}{8}} l^{-\frac{1}{4}} l_X q^{-2} \dot{m}^{\frac{3}{4}} m \;\; erg/s, \tag{2.2}$$

where $l_X = L_X/R_S$ is the extension of the reconnection zone as in Figure 1 in R_S units. We clearly see that the equation above results a larger value than in the case of fast reconnection driven by anomalous resistivity.

3. Comparison of $\dot{W}_B$ with the observed core radio and gamma emission

Employing the model described above, we selected a set of compact sources including blazars and GRBs (see [17]), LLAGNs (see [16], [15], [9],[10]) and galactic sources (e.g., the BHBs Cyg-X1 and Cyg-X3; see [15], [7]) with observed radio and gamma emission and compared their

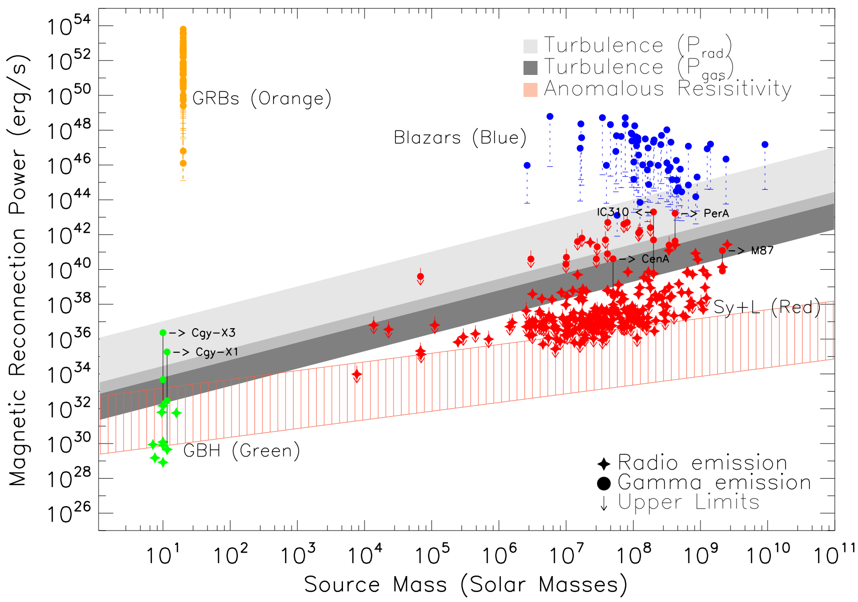

Figure 2: Magnetic power released by fast reconnection driven by anomalous resistivity (in red) and by turbulence (gray colors) as a function of the BH mass. The light and dark gray band correspond to a radiation-pressure and gas-pressure dominated disk, respectively. In a few cases for which there is observed gamma-ray luminosity from MeV/GeV to TeV ranges, we plotted the maximum and minimum values linking both circles with a vertical black line that extends down to the radio emission of each source.The arrows associated to some sources indicate that the gamma-ray emission is an upper limit only. Adapted from [11].

luminosities with the calculated magnetic reconnection power as a function of their masses (see Figure 2).

Figure 2 shows the magnetic power ($\dot{W}_B$) released by fast reconnection driven by anomalous resistivity (in red) and by turbulence (gray colors) as a function of the BH mass. The upper part of the diagram of the turbulent driven reconnection power (light gray) corresponds to a radiation-pressure dominated disk with larger accretion rates ($0.05 \leq \dot{m} \leq 1$), while the lower part of the diagram (dark gray) stands for a gas-pressure dominated disk with $\dot{m} \simeq 5 \times 10^{-4}$; and the intermediate gray region is the overlap between both regimes. The diagram of the magnetic reconnection power driven by anomalous resistivity also corresponds to a radiation-pressure dominated disk. The other free parameters in the diagrams span $1 \leq l \lesssim 18$; and $0.06l \lesssim l_X \leq l$ (assuming $R_X = 6R_S$) for both mechanisms.

We clearly see in Figure 2 that the observed radio luminosity of LLAGNs and BHBs (red and green diamonds symbols) can be explained by the magnetic power released by fast reconnection driven by turbulence in the core region of these sources. Furthermore, the turbulent-driven fast reconnection model is able to reproduce better the observed emission than the anomalous resistivity model. The gamma-ray emission, which is produced from the interaction of the accelerated relativistic electrons and protons with the surrounding photon and density fields (through inverse Compton, and/or pp inelastic collisions and photon-meson decay) can in principle be also associated with the same emission zone in the surroundings of the core of LLAGNs and BHBs (red and green circle symbols).

The blazars and the GRBs (blue and orange symbols) clearly do not have their radio or gamma emission correlated with the magnetic reconnection power released at the core regions. This result confirms the previous findings of GPK10 and Nemmen et al. (2012, [17]) which suggested that the gamma and radio emission observed in such sources is originated further out at the relativistic jet associated to these sources (as the nuclear emission is being screened by the surrounding strong photon and density fields).

4. Conclusions

The results of the present work indicate that in the case of BHBs and LLAGNs, the power released by fast magnetic reconnection driven by turbulence in the surrounds of the BH is able to explain the observed core radio and gamma-ray emission of these sources, therefore indicating that the surrounds of the BHs (as sketched in Figure 1) can be the acceleration region in these cases. Also, according to our results, fast reconnection induced by anomalous resistivity is clearly less efficient to provide the appropriate magnetic power for most of the sources of the sample, therefore, fast reconnection induced by turbulence (as described in [13]) is clearly more appropriate and besides, it results nearly the same trend (slope) of the observed luminosity distributions for these sources. On the other hand, in the case of blazars (and GRBs), our results show that the magnetic power released by fast reconnection (either driven by turbulence or anomalous resistivity) in the surrounds of the central source is clearly not sufficient to explain both the observed radio and gamma-ray radiation for most of these sources (Figure 2). This is probably due to the fact that these sources have their jets pointing to our line of sight and therefore, the core emission is screened by the jet. So that what is effectively observed is emission coming from further out - from the jet, as generally expected for these sources.

The results above connecting both the radio and gamma-ray emission from low-luminosity compact sources to magnetically dominated reconnection processes are very promising as they suggest a unifying single process of relativistic particle acceleration in the core region which may naturally help with the interpretation of the observed correlations of LLAGNs and BHBs, as remarked, and also with clues for existing unification AGN theories, providing important predictions for the coming new generation of VHE observatories with much larger sensitivity and energy range to perform emission and variability studies, such as the Cherenkov Telescope Array (CTA; see [2], [3], [22]). Also, multi-frequency observation (as, e.g., [8]) will be crucial to better constrain the location of the gamma-ray emission and the acceleration mechanisms.

Finally, we should note that in this work we have focussed on the total power released by magnetic reconnection in the core region of the sources, without examining the radiation mechanisms by which this energy can be transformed into radio or gamma-ray emission. In a companion work we have explored the acceleration mechanism above operating in the core region of the BHBs Cyg X-1 and Cyg X-3 (see Figure 2) and have reproduced their entire observed non-thermal spectral energy distribution (SED), from the radio to the gamma-ray flux profile (see [12]).

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