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Relativistic Jets and Accretion Phenomena associated with Galactic and Extragalactic Black Holes

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More than a dozen binary star systems hosting stellar-mass black holes have been discovered in our galaxy. Some of them eject collimated relativistic jets with apparent velocities larger than the light speed. These objects have been named microquasars thanks to their similarity with the distant quasars or active nuclei of galaxies that host supermassive black holes. We have recently proposed that the large scale superluminal ejections observed in the microquasars (e.g., GRS 1915+105 source) during radio flare events are produced by violent magnetic reconnection episodes in the accretion disk that surrounds the central source, a ten-solar-mass black hole (de Gouveia Dal Pino and Lazarian 2005). The process occurs when a large-scale magnetic field is established by a turbulent dynamo in the inner disk region with a ratio between the gas+radiation and the magnetic pressures $\beta \simeq 1$. During this process, substantial angular momentum is removed from the disk by the wind generated by the vertical magnetic flux therefore increasing the disk mass accretion to a value near (but below) the critical Eddington limit. Part of the magnetic energy released by reconnection heats the coronal gas above the disk that produces a steep, soft X-ray spectrum with luminosity consistent with observations. The remaining magnetic energy released goes to accelerate the particles to relativistic velocities ($v \sim v_A \sim c$, where v_A is the Alfvén speed) in the reconnection site through first-order Fermi processes. For the first time we have examined the Fermi process within the reconnection zone and found that a power-law electron distribution is produced $N(E) \propto E^{-\alpha_E}$, with $\alpha_E = 5/2$, and a corresponding synchrotron radio power-law spectrum with a spectral index which is compatible with that observed during the flares ($S_\nu \propto \nu^{-0.75}$), though a standard Fermi process behind shocks that develop just above the reconnection site is also possible. The possibility that the ejection mechanism of relativistic blobs induced by magnetic reconnection can be applied to all classes of black hole-relativistic jet systems, from microquasars to quasars and active galactic nuclei, is addressed here.

I. INTRODUCTION

Galactic and extragalactic accretion-powered sources often exhibit quasi-periodic variability and ejection phenomena that may offer important clues to the general physical processes in the inner regions of all classes of accreting sources.

Binary star systems containing stellar-mass black holes emitting X-rays (also denominated BHXRTs) were first detected in our galaxy during the last decade. Some of them produce collimated bipolar radio jets with apparent superluminal velocities. They are, actually, scaled-down versions of the more distant extragalactic jets associated to quasars. While the extragalactic versions typically propagate for up to ~ 1 Mpc and are powered by spinning supermassive black holes with masses $M \simeq 10^8 M_\odot$, the galactic relativistic jets extend for ~ 1 pc and are powered by black holes with masses of up to $\sim 10 M_\odot$. For this reason they have been named microquasars (Mirabel & Rodriguez 1994, 1999). The most investigated example of this class, the X-ray source GRS 1915+105, which is at a distance of only 12.5 kpc and probably hosts a 10 solar-mass black hole, offers excellent tools for the investigation of black hole accretion and associated jet phenomena. In a compilation of radio and X-ray data of this microquasar, taken during several weeks, Dhawan, Mirabel & Rodriguez (2000) have distinguished two main states of the system, a plateau and a flare state. The plateau state is characterized by a flat radio spectrum coming from a compact jet of size of a few AU. During this phase, the associated (2-12 keV) soft X-ray emission is weak. On the other hand, during the flare phase, superluminal blobs are ejected up to thousands of AU

and fade after several days. The soft X-rays also flare during this phase and exhibit high variability.

It is generally believed that the X-ray emission of galactic black holes and active galactic nuclei (quasars) arises from the hot gas accreting onto the central source and the radio emission from the relativistic jet. During the plateau phase, the observed 30-minute soft X-ray variability and the nuclear jet have been explained in terms of periodic evacuation and refilling of the inner disk region on time scales of seconds as a result of thermal viscosity in the accretion disk (Belloni et al. 1997). In contrast, the large superluminal radio flares observed at the 500 AU scales cannot be explained by the same viscous disk instability model because they eject an order of magnitude more mass than the AU-scale jet and require a much larger evacuation radius well beyond that where the instability is expected to occur. Recently, different groups have proposed alternative scenarios to explain the variability of the GRS 1915+105 microquasar. Livio, Pringle & King (2003; see also Tagger et al. 2004), for example, have suggested that the inner region of the accretion disk would switch between two states. In one of them, the accretion energy would be dissipated locally by thermal viscosity to produce the observed disk luminosity, and in the other the accretion energy would be converted into magnetic energy and emitted in the form of a relativistic jet. They have attributed the transition between the two states to dynamo generation of a global poloidal magnetic field.

Contemporaneously, we have proposed that the large scale superluminal ejections observed in GRS 1915+105 during the radio flare events could be produced by violent magnetic re-

connection episodes in the corona just above the inner edge of the magnetized accretion disk that surrounds the central 10 solar-mass black hole (de Gouveia Dal Pino & Lazarian 2005; see Figure 1). The process occurs when a large scale magnetic field is established by turbulent dynamo in the inner disk region with a ratio between the gas+radiation and the magnetic pressures $\beta \sim 1$.

We draw the potential scenario for flare production and the superluminal ejecta in the next sections.

II. OUR SCENARIO

A detailed description of the model and its formulation is given in de Gouveia Dal Pino & Lazarian (2005). Magnetized accretion disks around rotating (Kerr) black holes (BHs) are frequently invoked to explain the high energy radiation and jet production and collimation both in quasars and microquasars. The magnetic field lines originally frozen in the disk plasma will deposit along with accreting gas onto the BH horizon, therefore developing a magnetosphere around the horizon. Near the horizon, no matter how chaotic the field threading the disk, the field through the hole will become ordered. If the disk tries to deposit a chaotic field on the hole, the field's closed loops will destroy themselves on a time scale $t \simeq R_H/c \sim 10^{-4} s M_{10}$, leaving the field ordered. If on the other hand, magnetic pressure from field lines threading the disk temporarily push the hole's field into a clumped configuration, it will spring back on this same time scale and make itself more uniform (MacDonald et al. 1986).

Though not a necessary condition, we will assume, for simplicity, in the present study that the BH and the inner disk edge are nearly co-rotating so that no significant angular momentum and energy transfer is occurring between them.

Also, we will assume that during the *plateau* state that precedes a radio flare, a large scale poloidal field is progressively built in the disk by a turbulent dynamo process. The action of buoyancy forces will also make the disk unstable against the Parker-Rayleigh-Taylor instability and horizontal magnetic field lines will raise from the disk forming large scale loops in the rarified hot corona. We further assume that once the dynamo process establishes a global poloidal field over a substantial region of the disk, it will be able to maintain that field for a period of time.

The vertical field flux will give rise to a wind that will remove angular momentum from the disk, therefore significantly increasing the accretion rate (possibly at a rate greater than the rate due to the disk viscosity). Also, with the accumulation of vertical flux in the inner regions the ratio between the gas+radiation pressure to the magnetic field pressure (β) will soon decrease to one. Under these conditions, events of reconnection of magnetic field lines with opposite polarization will be inevitable, and in the innermost regions this process may become eventually very violent when enough magnetic energy is stored in the corona. We show below that this occurs when $\beta \sim 1$ and the accretion rate approaches the critical value. We argue that this could explain the large scale radio flares in GRS 1915+105 and then extend the mechanism to all

classes of black hole-relativistic jet systems, with ejection of the observed relativistic blobs from the innermost regions.

Considering the assumptions above, the resulting structure of the magnetosphere of the hole and the accretion disk must be like that shown in Figure 1. In the inner disk region (of radius R_X), there is a site which is appropriate for violent magnetic reconnection. Surfaces of null poloidal field lines mediate the geometry of the open field lines anchored into the BH horizon with the opened lines of the disk wind and those connecting the disk with the BH horizon. Labeled as "Y neutral zone" in Figure 1, these magnetic null surfaces begin or end on Y points. Across each null surface, the poloidal field suffers a sharp reversal of direction. According to Ampère's law, large electric currents must flow out of the plane shown in Figure 1, along the null surfaces, and in the presence of finite electric resistivity, dissipation of these currents will lead to reconnection of the oppositely-directed field lines. We here investigate the possibility that the magnetic energy released by reconnection near the Y point region is able to accelerate the plasma to relativistic velocities and produce the synchrotron radio flares (see below).

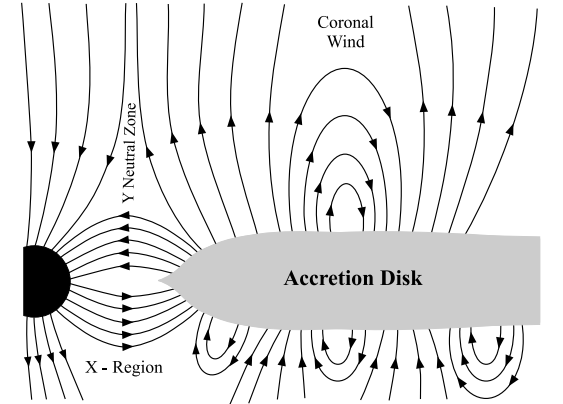


Figure 1. Schematic drawing of the magnetic field geometry in the inner disk region at R_X . The acceleration occurs in the magnetic reconnection site at the Y type neutral zone (de Gouveia Dal Pino & Lazarian 2005; see the text).

We notice that after reconnection, the partial destruction of the magnetic flux in the inner disk will make β increase and make the disk return to the less magnetized condition of the plateau state with most of the energy being dissipated locally within the disk instead of in the outflow.

III. THE RELATIVISTIC EJECTIONS DURING THE FLARES

We adopt the field geometry of the magnetized accretion disk/corona as described in the previous section (Fig. 1). For a BH with mass $M_* = 10M_\odot = M_{10}$ and Schwarzschild radius $R_* = 2GM_*/c^2 = 2.96 \times 10^6 M_{10}$ cm, let us assume that the inner radius of the accretion disk (R_X) corresponds approximately to the last stable orbit of the BH, $R_X \simeq 3R_* \simeq 10^7$ cm, and that the accretion rate $\dot{M} \lesssim \dot{M}_{Edd}$, where $\dot{M}_{Edd} =$

$1.9 \times 10^{19} M_{10} \text{ g s}^{-1}$ is the Eddington critical accretion rate (Shakura & Sunyaev 1973).

As remarked before, the violent magnetic reconnection events that may generate large scale relativistic ejections are expected to occur when the large scale magnetic field in the inner disk region, which is generated by dynamo process, attains an intensity as large as $B_d^2/8\pi \simeq P_d$, where P_d is the disk pressure which is dominated by the radiation pressure, i.e., when $\beta \simeq 1$, giving

$$B_d \simeq 6.9 \times 10^8 \text{ G } \alpha_{0.1}^{-1/2} M_{10}^{1/4} R_{X,7}^{-3/4} \quad (1)$$

Where $\alpha_{0.1}$ is the Shakura-Sunyaev (1973) viscous coefficient in units of 0.1, and $R_{X,7}$ is R_X in units of 10^7 cm. Let us assume that the poloidal magnetic field that rises in the corona just above the inner disk region (B_X) is of the order of the local disk magnetic field, B_d (eq. 1). In this case, we have demonstrated that the rate of magnetic energy that is extracted from the Y-zone in the corona (above and below the disk) through reconnection is (de Gouveia Dal Pino & Lazarian 2005):

$$\dot{W}_B \simeq 2.4 \times 10^{39} \text{ erg s}^{-1} \alpha_{0.1}^{-0.33} \beta_1^{0.94} M_{10}^{1.73} \times R_{X,7}^{-4.18} \dot{M}_{19}^{2.5} l_8^{0.69} \quad (2)$$

and the corresponding reconnection time is

$$t_{\text{rec}} \simeq \frac{R_X}{\xi v_A} \simeq 3.3 \times 10^{-4} \text{ s}^{-1} \xi^{-1} R_{X,7} \quad (3)$$

which indicates that the release of magnetic energy is very fast. In the equations above: $\beta_1 = \beta/1$, \dot{M}_{19} is \dot{M} in units of 10^{19} g s^{-1} , l_8 is the scale height of the Y neutral zone in the corona in units of 10^8 cm, $\xi = v_{\text{rec}}/v_A$ is the reconnection efficiency factor, with v_{rec} being the reconnection velocity, $v_A = B_X/(4\pi n_c m_p)^{1/2}$ the coronal Alfvén speed, m_p the hydrogen mass, and n_c the coronal density. We find that $v_A \simeq c$ for the inner radius disk conditions (de Gouveia Dal Pino & Lazarian 2005).

Eq. (2) gives the total expected amount of magnetic energy released by fast reconnection in the Y-zone during the flare of GRS 1915+105. Part of this energy will heat the coronal gas ($T_c \simeq 5 \times 10^8$ K) that may produce a steep, soft X-ray spectrum with luminosity $10^{39} \text{ erg s}^{-1}$, in consistency with the observations. The remaining released energy will accelerate the charged particles to relativistic velocities producing violent radio ejecta.

As stressed by de Gouveia Dal Pino & Lazarian (2001), the particular mechanism of particle acceleration during reconnection events is still unclear, but we have envisioned a first-order Fermi process within the reconnection site and shown that it may produce a power-law electron distribution $N(E) \propto E^{-5/2}$, and a synchrotron radio power-law spectrum ($S_\nu \propto \nu^{-0.75}$). This mechanism does not remove the possibility that the relativistic fluid may be also produced behind

shocks which are formed by magnetic plasmoids that erupt from the reconnection zone. Behind these shocks a standard first-order Fermi acceleration may occur with a particle power-law spectrum $N(E) \propto E^{-2}$ and a synchrotron spectrum $S_\nu \propto \nu^{-0.5}$. Both radio spectral indices are consistent with the observed spectral range during the flares.

After each violent reconnection event, the system must resume a sub-critical disk mass accretion with smaller magnetic field intensity and a slower reconnection rate, thus recovering the more quiescent plateau state, as described before.

IV. GENERALIZING THE MAGNETIC RECONNECTION FLARE MODEL

We have investigated above the origin of the large scale superluminal ejections observed in galactic microquasars, particularly focusing on the GRS 1915+105 source, during radio flare events and proposed a simple model in which they could be due to violent magnetic reconnection episodes in the corona just above the inner edge of the magnetized accretion disk that surrounds the central stellar mass black hole. But the model above can be extended to the much larger relativistic jets produced by supermassive black holes from active galactic nuclei. These jets are also observed to produce relativistic components that produce synchrotron power law spectrum with similar spectral indices as above.

For a typical supermassive black hole with $\sim 10^8 M_\odot$, a disk inner radius near the last scattering surface $R_X \simeq 10^{14}$ cm, an accretion rate $\dot{M} \lesssim \dot{M}_{\text{Edd}}$, $\dot{M} = 10^{26} \text{ g s}^{-1}$, and $l \simeq 10^{15}$ cm, we notice that the physical parameters above (which are scaled by the BH mass) are seven orders of magnitude larger than those of the stellar black hole. Replacing these values into the previous equations, we find that for $\beta \simeq 1$ and $\alpha \simeq 0.1$, the magnetic field intensity $B_X \simeq 2 \times 10^5$ G, and the magnetic energy released during violent reconnection episodes is $\dot{W}_B \sim 3.6 \times 10^{44} \text{ erg s}^{-1}$. This energy rate is compatible with the observed luminosities of the extragalactic jets and their superluminal components, and therefore suggests that the mechanism above is also plausible to explain the origin of the relativistic blobs in extragalactic jets from violent episodic magnetic reconnection in the inner regions of the magnetized accretion disk around the BH.

Finally, we notice that the mechanism investigated here for relativistic blobs production is compatible with the proposed unified scenario for astrophysical jet production based on the magneto-centrifugal scenario (e.g., Blandford & Payne 1982) and as such provides an extra support for it.

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