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MAGNETIC RECONNECTION PROCESS IN ACCRETION DISK SYSTEMS

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RESUMEN

En este estudio investigamos el papel de la reconexión magnética en tres diferentes sistemas astrofísicos: objetos estelar jóvenes (YSOs), microcuasares y núcleos activos de galaxias (AGNs). En el caso de microcuasares y AGNs, episodios de reconexión violentos entre las líneas de campo magnético de la región interna del disco (que son establecidas por un dínamo tubulento) y aquellas ancladas en el hoyo negro, son capaces de calentar el gas coronal y del disco y acelerar partículas a velocidades relativistas a través de un proceso difusivo de primer orden tipo Fermi dentro del sitio de reconexión, que producirán grumos relativistas. El calentamiento del gas coronal y del disco es capaz de producir un espectro empinado de rayos X con una luminosidad que es consistente con las observaciones la cual argumentamos que es producida principalmente en la base de la zona de reconexión, mientras que el proceso de aceleración tipo Fermi dentro del sitio de reconexión resulta en una distribución de electrones de ley de potencia con $N(E) \propto E^{-\alpha}$, con $\alpha = 5/2$, y un espectro de radio de ley de potencia correspondiente, con un índice espectral que es compatible con el observado en ráfagas de radio en microcuasares ($S_\nu \propto \nu^{-0.75}$). Las leyes de escalamiento que derivamos para AGNs indican que el mismo mecanismo puede estar ocurriendo ahí. Finalmente, en el caso de YSOs, una configuración magnética similar puede ser alcanzada. La cantidad de energía magnética que puede ser extraida de la región interna del disco puede calentar el gas coronal a temperaturas del orden de 10^8 K y podría explicar las emisión de ráfaga de rayos X observada.

ABSTRACT

At the present study, we investigate the role of magnetic reconnection in three different astrophysical systems, namely young stellar objects (YSO's), microquasars, and active galactic nuclei (AGN's). In the case of microquasars and AGN's, violent reconnection episodes between the magnetic field lines of the inner disk region (which are established by a turbulent dynamo) and those anchored into the black hole are able to heat the coronal/disk gas and accelerate particles to relativistic velocities through a diffusive first-order Fermi-like process within the reconnection site that will produce relativistic blobs. The heating of the coronal/disk gas is able to produce a steep X-ray spectrum with a luminosity that is consistent with the observations and we argue that it is being produced mainly at the foot of the reconnection zone, while the Fermi-like acceleration process within the reconnection site results a power-law electron distribution with $N(E) \propto E^{-\alpha}$, with $\alpha = 5/2$, and a corresponding synchrotron radio power-law spectrum with a spectral index that is compatible with that observed during the radio flares in microquasars ($S_\nu \propto \nu^{-0.75}$). The scaling laws that we derive for AGN's indicate that the same mechanism may be occurring there. Finally, in the case of the YSO's, a similar magnetic configuration can be reached. The amount of magnetic energy that can be extracted from the inner disk region can heat the coronal gas to temperatures of the order of 10^8 K and could explain the observed X-ray flaring emission.

Key Words: acceleration of particles — accretion, accretion disks — magnetic fields

1. INTRODUCTION

Highly collimated supersonic jets and less collimated outflows are observed to emerge from a wide variety of astrophysical objects. They are seen in young stellar objects (YSOs), compact objects (such as galactic black holes or microquasars), and in the nuclei of active galaxies (AGNs). Despite their different physical scales (in size, velocity, and amount of energy transported), they have strong morphological similarities suggesting a common mechanism for their origin.

The currently most accepted model for jet production is based on the magneto-centrifugal acceleration out off a magnetized accretion disk that surrounds the central source (Blandford & Payne 1982; see also Spruit 1996; de Gouveia Dal Pino 2005 for reviews). Nonetheless, within this scenario, there is

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a number of questions that are still not fully understood, such as the quasi-periodic ejection phenomenum that is often associated to these sources.

For example, the X-ray source GRS1915+105 was the first galactic object to show evidence of large scale superluminal radio ejection (Mirabel & Rodriguez 1994, 1999) which is normally interpreted as due to relativistic jets. In a compilation of (VLBA) radio and (RXTE and BATSE) X-ray data, taken during several weeks, Dhawan et al. (2000, hereafter DMR) have distinguished two main states of the system, a plateau and a flare state. The plateau state is characterized by a flat radio spectrum ($S_\nu \propto \nu^0$) coming from a compact region of size of a few AU, and flux density 1–100 mJy. During this phase, the associated RXTE (2–12 keV) soft X-ray emission is weak, while the BATSE (20–100 keV) hard X-rays are strong.

On the other hand, during the flare phase, optically thin ejecta are superluminally expelled up to thousands of AU with fluxes up to 1 Jy at $\lambda\,13\,$cm ($S_\nu \propto \nu^{0.6}$) with rise time less than one day and which fade after several days. The soft X-rays also flare during this phase eand exhibit high variability, while the hard X-rays fade for a few days before recovering (see Figures 1 and 4 of DMR). The radio imaging over a range of wavelengths (13, 3.6, 2.0, and 0.7 cm) resolves the nucleus as a compact jet of length $\sim 10\lambda_{\rm cm}$ AU. This nuclear jet varies on time scales of $\sim 30\,$min during minor X-ray/radio bursts and reestablishes within $\sim 18\,$h after a major outburst.

de Gouveia Dal Pino & Lazarian (2005, hereafter GDPL), in the context of the MHD scenarios, have proposed that these large scale superluminal ejections observed during radio flare events are produced by violent magnetic reconnection episodes. In § 2, we will briefly present their model and in § 3 and § 4 we will extend it to other sources of jets, like AGNs and quasars and YSOs. Finally, in § 5 we present our conclusions.

2. THE MAGNETIC RECONNETION MODEL: MICROQUASARS

A detailed description of the model and its formulation is given in GDPL. To understand the proposed model, let's consider a magnetized accretion disk around a rotating (Kerr) black hole (BH). The magnetic field lines originally frozen in the disk plasma will deposit along with accreting gas onto the BH horizon, therefore developing an ordered magnetosphere around the horizon (MacDonald et al. 1986). Though not a necessary condition, we will assume,

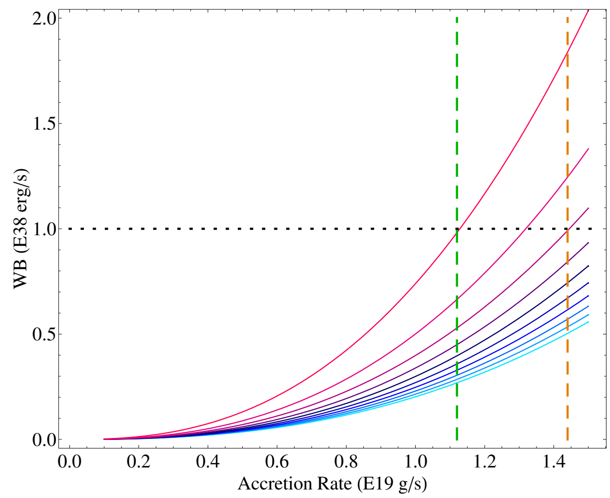

Fig. 1. Magnetic power released as function of mass accretion rate for different values of β (from blue to pink, $\beta = 10-1$). The black dotted line corresponds to the observed X-ray luminosity of GRS1915+105 microquasar. The green and orange vertical lines represent accretion rates of 80% and 100% the Eddington ones.

for simplicity, 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, thus significantly increasing the accretion rate (possibly at a rate greater than that 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 very violent when enough magnetic energy is stored in the corona. GDPL showed that this occurs when $\beta \sim 1$ and the accretion rate approaches the critical value.

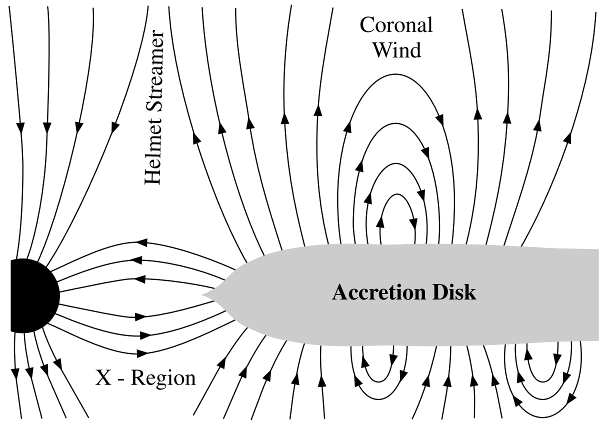

Fig. 2. Schematic drawing of the magnetic field geometry in the inner disk region at R_X. The acceleration occurs in the magnetic reconnection site at the Y type neutral zone (extracted from de Gouveia Dal Pino & Lazarian 2005; see the text).

This can be seen in Figure 1. As the dynamo amplify the poloidal magnetic field, β decreases and the energy that is extracted by reconnection increases.

Considering the assumptions above, the resulting structure of the magnetosphere of the hole and the accretion disk must be like that shown in Figure 2. In the inner disk region (of radius R_X), there is a site that 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 2, 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 Amperes law, large electric currents must flow out of the plane shown in Figure 2, 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.

GDPL 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, in $\mathrm{erg\,s^{-1}}$,

$$\dot{W}_B \cong 7.5 \times 10^{37} \alpha_{0.1}^{-1} M_{10}^{1/2} R_{X,7}^{1/2} \left(\frac{\Delta R_X / R_X}{0.0026} \right), \quad (1)$$

and the corresponding reconnection time, in s, is

$$t_{\rm rec} \cong \frac{R_X}{\xi v_A} \cong 3.3 \times 10^{-4} \xi^{-1} R_{X,7}, \quad (2)$$

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} $\mathrm{g\,s^{-1}}$, l_8 is the scale height of the Y neutral zone in the corona in units of 10^8 cm, $\xi = v_{\rm rec}/v_A$ is the reconnection efficiency factor, with $v_{\rm rec}$ being the reconnection velocity, $v_A = B_X/(4\pi n_c m_p)^{1/2}$ the coronal Alfven speed, m_p the hydrogen mass, and n_c the coronal density. They found that $v_A \sim c$ for the inner radius disk conditions. Equation (1) gives the total expected amount of magnetic energy released by fast reconnection in the Y-zone during the flare of GRS1915+105. Part of this energy will heat the coronal gas ($T_c \sim 5 \times 10^8$ K) that may produce a steep, soft X-ray spectrum with luminosity 10^{38} 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 GDPL 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.

They noticed 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 sub-critical disk mass accretion, instead of in the outflow.

3. AGNS AND QUASARS

AGNs/quasars and microquasars are systems morphologically very similar (Mirabel & Rodriguez 1998). For this reason, the model above can be extended to the much larger relativistic jets produced by supermassive black holes from active galactic nuclei (AGNs). These jets are also observed to produce relativistic components that produce synchrotron power law spectrum with similar spectral indices, as above.

The amount of magnetic energy that can be extracted by magnetic reconnection in this case is (de

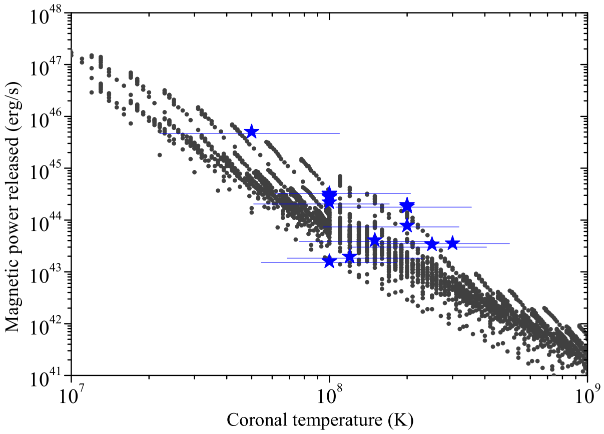

Fig. 3. Comparison between theoretical prediction and the observed X-ray luminosities for 14 quasars (blue stars.)

Gouveia Dal Pino 2005, 2006), in erg s^{-1},

$$\dot{W}_B \cong 2.1 \times 10^{43} \alpha_{0.1}^{-1} M_8^{1/2} R_{X,14}^{1/2} \left(\frac{\Delta R_X / R_X}{7.2 \times 10^{-5}} \right). \quad (3)$$

In Figure 3, there is a comparison between the theoretical prediction and the observed x-ray luminosities for 14 quasars (blue stars). This comparison suggests that the energy rate released by reconnetion is compatible with the observed luminosities of the extragalactic jets and their superluminal components, so 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 supermassive black hole.

4. YOUNG STELLAR OBJECTS

YSOs are systems that differ in many aspects from the microquasars and AGNs. For example, while the inner disk regions of these are dominated by radiation pressure, the inner disk regions of YSOs are dominated by gas pressure. The opacity law is also different and the corona model assumed for microquasars is not adequate for the YSOs corona. Taking these differences into account, we estimated the maximum energy that could be extracted by magnetic reconnection from the neighborhood of YSO accretion disks assuming initial conditions which are appropriate to T-Tauri systems (Piovezan & de Gouveia Dal Pino, in prep.; see also Shu et al. 1997),

$$\dot{W}_B \cong 1,4 \times 10^{31} \, (\delta B_*)_{5000}^{-16/7} \, M_1^{11/7} \dot{M}_{\rm max}^{22/7} \times \times R_2^{-48/7} n_{11}^{-3/2} T_8^{-1/2} \quad (4)$$

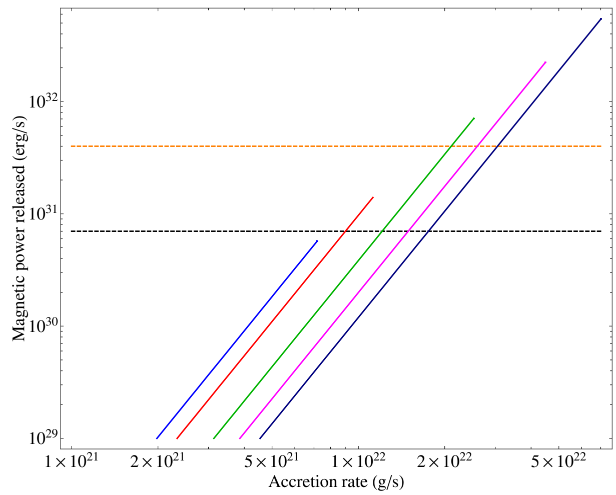

Fig. 4. $\dot{W}_B$ as function of $\dot{M}$ for different values of (δB_*) (from left to right: 4, 5, 7.5, 10, 12,5 kG). For comparison, the luminosity of two COUP souces with similar radii are indicated by dotted lines (COUP597 and COUP848 as black and orange lines).

The COUP sources in Figure 4 correspond to observed x-ray flares, possibly in an extreme case where the large magnetic structures that confine the flaring plasma can be interpreted as linking the stellar photosphere with the inner rim of the circumstellar disk (Favata et al. 2005). If this interpretation is correct, these observations correspond exactly to the phenomena we are describing.

Each solid line in Figure 4 corresponds to a fixed value of the product between the magnetic field at the surface of the star and the parameter (δ) which accounts for deformations in the dipole geometry of the magnetic field at the inner radius of the accretion disk. For $\delta \sim 2$ (the magnetic geometry is very similar to a dipole), we find that surface fields of ~ 2500 G are enough to release 10^{31}erg s^{-1}, which is consistent with the observations, if the disk accretion rate is of the order of 8×10^{22}g s^{-1}. This is an indication that the mechanism proposed can explain these flares and provide disk-coronal heating at observed temperatures ($T \sim 10^{7-8}$ G).

5. CONCLUSIONS

Table 1 summarizes the results for the three systems studied. In the case of the microquasars, violent reconnection episodes are able to heat the coronal/disk gas and accelerate particles to relativistic velocities through a diffusive first-order Fermi like process within the reconnection that will produce relativistic blobs. The heating of the coronal/disk gas is able to produce a steep X-ray spectrum with a

TABLE 1

MAIN RESULTS FOR THE THREE SYSTEMS STUDIED

	Micro	AGNs	YSOs
M^{a}	10	10^{8}	1
${R_X}^{b}$	1	10^{7}	2
$\dot{M}^{c}$	10^{19}	10^{26}	10^{21}
${B_X}^{d}$	10^{8}	10^{5}	10^{3}
$\frac{\Delta R_X}{R_X}^{e}$	10^{-3}	10^{-4}	10^{-7}
${\dot{W}_B}^{f}$	10^{39}	10^{44}	10^{32}

[a]Mass in units of solar mass.

[b]Inner disk radius in units of solar radius.

[c]Mass accretion rate in units of $\mathrm{g\,cm^{-3}}$.

[d]Magnetic field in the reconnection zone in units of G.

[e]Relative width of the reconnection zone.

[f]Rate of energy released in units of $\mathrm{erg\,s^{-1}}$.

luminosity that is consistent with the observations, while the Fermi-like acceleration process within the reconnection site results a power-law electron distribution with $N(E) \propto E^{-\alpha}$, with $\alpha = 5/2$, and a corresponding synchrotron radio power-law spectrum with a spectral index that is compatible with that observed during the radio flares in microquasars.

The mechanism proposed for microquasars can in principle be extended to other classes of systems: AGNS/quasars, and YSOS. For quasars and AGNs, the amount of magnetic energy that can be extracted by magnetic reconnection is about $10^{43}\,\mathrm{erg\,s^{-1}}$ witch is compatible with the observed luminosities of the extragalactic jets and their superluminal components. Furthermore, it is compatible with the proposed unified scenario for astrophysical jet production based on the magneto-centrifugal scenario and as such, provides an extra support for it.

In the case of the YSOs, the amount of magnetic energy that can be extracted by magnetic reconnection from the inner disk region is about $10^{32}\,\mathrm{erg\,s^{-1}}$. This can heat the coronal gas to temperatures of the order of $10^{8}\,\mathrm{K}$ and could, in principle, explain the X-ray emission of extreme flares. This issue is further explored in Piovezan & de Gouveia Dal Pino (in preparation).

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