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A basic condition for jet formation in accreting X-ray binaries

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Abstract. We introduce the use of a well-known parameter, the Alfvén Radius - $R_{\rm A}$, as a new tool to discern whether an X-ray binary system may undergo a microquasar phase, i.e. ejecting relativistic particles orthogonal to the accretion disk. We study what we call *the basic condition*, $R_{\rm A}/R_{*} = 1$ in its dependency with the magnetic field strength and the mass accretion rate. With this basic condition we establish under which combination of parameters any class of accreting neutron stars could become a microquasar instead of confining disk-material down to the magnetic poles and creating the two emitting caps typical for an X-ray pulsar. In the case of black-hole accreting binaries we equate the magnetic field pressure to the plasma pressure in the last stable orbit (i.e. $R_{\rm A}/R_{\rm LSO} = 1$) and we get upper limits for the magnetic field strength as a function of the mass accretion rate and the black hole mass.

Key words. Stars: magnetic fields - X-rays: binaries - Accretion, accretion disks - Galaxies: active

1. Introduction

Microquasars (MQs) are a subclass of the stellar systems called X-ray binaries (XRBs), defined as the XRB systems where either high resolution radio interferometric techniques have shown the presence of collimated jets or a flat spectrum has been observed (indirect evidence for an expanding continuous jet, Fender 2004). The nature of the compact object, neutron star (NS) or black hole (BH), is still uncertain for several MQs.

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2. Magnetohydrodynamic Jet Production

Numerical simulations show that the launch of a jet involves a weak large-scale poloidal magnetic field anchored in rapidly rotating disks or compact objects (Meier et al. 2001). The strength of the large-scale poloidal field must be low enough that the plasma pressure, $P_{\rm p}$, dominates the magnetic field pressure, $P_{\rm B}$. Only under that condition, $P_{\rm B} < P_{\rm p}$, the differentially rotating disk is able to bend the magnetic field lines in a magnetic spiral (Meier et al. 2001). Because of the increasing compression of the magnetic field lines, the magnetic pressure will grow and may become larger than the gas pressure on the surface of the accretion disk, where the density is lower. There, the magnetic field becomes "active", i.e. dynami-

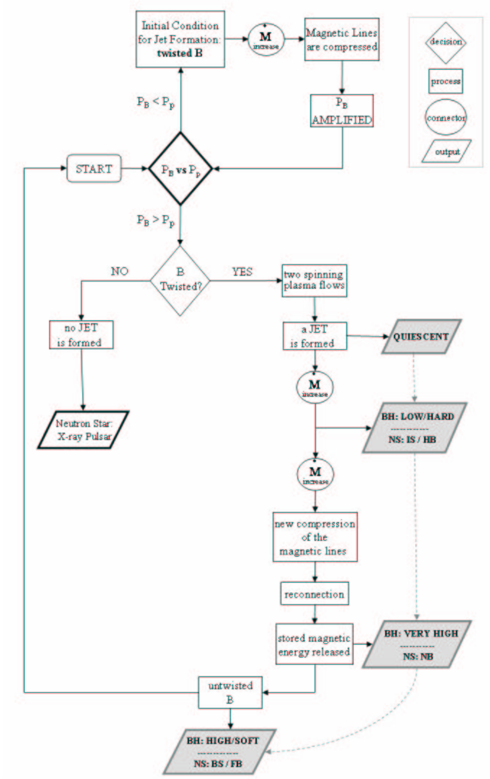

Fig. 1. Flowchart for the jet formation process. BH and NS XRBs' X-ray state names are mentioned. In the case of neutron stars the distinction between atoll- and Z-type sources is made: IS = Island State / HB = Horizontal Branch, NB = Normal Branch, BS = BS = Banana State / FB = Flaring Branch.

cally dominant, and the plasma has to follow the twisted magnetic field lines, creating two spinning-plasma flows.

The competition process between the magnetic field pressure and the plasma pressure that seems to be at the base for the formation of a jet has been summarised in a flowchart that we show in Fig. 1. The generation of jets and their presence in XRBs is coupled to the evolution of a cycle that can be observed in the X-ray states of this kind of systems (Fender et al. 2004, Ferreira et al. 2006), also shown in Fig. 1.

Besides the cycle connected with the microquasar phase, one has to consider the situation in which $P_\mathrm{B} > P_\mathrm{p}$ from the very beginning, i.e. with untwisted field. This is the case of an XRB holding a NS with a strong magnetic field. This situation corresponds to a classical X-ray Pulsar scenario. The strong magnetic field cannot be twisted. It dominates the dynamic all the time, confining the disk-material down to the magnetic poles where two emitting caps are created.

Table 1. Neutron Stars: Accretion Rate and Magnetic Field Strength

Class	$\frac{\dot{M}}{10^{-8}}$ ($\mathrm{M}_\odot$ yr^{-1})	B_* (G)
classical X-ray pulsars	---	$> 10^{12}$ (a)
ms X-ray pulsars	0.001 (b) 0.01 (c, d) 0.03 (b), 0.07 (d)	3×10^7 (c, d) 3×10^8 (c)
Atoll sources	0.01-0.9 (e)	3×10^7 (f) 10^8 (g)
Z sources	0.5 (e), ≥1 (e)	10^{7-8} (h) 3×10^8 (f) 10^9 (g)

[a] Makishima et al. 1999 [b] Chakrabarty & Morgan 1998 [c] Lamb & Yu 2005 [d] Gilfanov et al. 1998 [e] van der Klis 1996 [f] Zhang & Kojima 2006 [g] van der Klis 1994 [h] Titarchuk et al. 2001

2.1. The Alfvén Radius: a Tool for the Basic Condition

The magnetic field can be bent in a sweeping spiral only if the magnetic pressure, $P_\mathrm{B} = B^2/8\pi$, is smaller than the hydrodynamic pressure, $P_\mathrm{p} = \rho \mathrm{v}^2$, of the accreting material. The distance at which the magnetic and plasma pressure balance each other is called the Alfvén radius. Using this magnitude we define what we call *the basic condition* for jet formation, $R_\mathrm{A}/R_* = 1$ or $R_\mathrm{A}/R_\mathrm{LSO} = 1$, in the case of NS or BH XRBs respectively, with R_* the NS surface radius and R_LSO the radius of the BH last stable orbit. $R_\mathrm{A}/R_* = 1$ or $R_\mathrm{A}/R_\mathrm{LSO} = 1$ ensure that the magnetic field lines of the stellar field or of the accretion disk

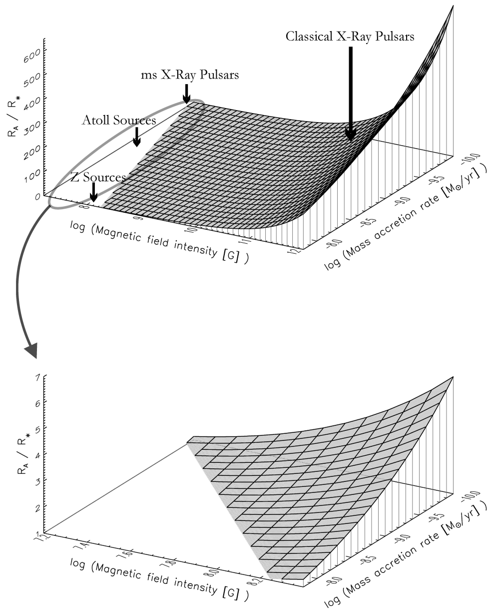

Fig. 2. 3-D plot of the Alfvén radius normalised to the stellar radius (R_A/R_*).

around a BH, will then be twisted close to the compact object.

Expressing the mass accretion rate $\dot{M}$ as $4\pi R^2 \rho \mathrm{v}$ (Longair 1994), where v is the infall velocity $\mathrm{v} = (2\mathrm{G}\mathrm{M}_*/\mathrm{R})^{1/2}$ and for a magnetic dipole field with a surface magnetic field B_*, $B/B_* = [R_*/R]^3$, we get:

$$R_\mathrm{A} = {B_*}^{4/7} {R_*}^{12/7} \, (2GM_*)^{-1/7} \, \dot{M}^{-2/7}. \quad (1)$$

Therefore the ratio R_A/R_* in terms of the accretion rate, $\dot{M}$, and the NS surface magnetic field, B_*, is equal to (Massi 2006):

$$R_\mathrm{A}/R_* \simeq 0.87 \left(\frac{B_*}{10^8\ \mathrm{G}}\right)^{4/7} \left(\frac{\dot{M}}{10^{-8}\ \frac{\mathrm{M}_\odot}{\mathrm{yr}}}\right)^{-2/7}, \quad (2)$$

for a neutron star with a mass and a radius of $M_* = 1.44\ \mathrm{M}_\odot$ and $R_* = 9$ km (Titarchuk & Shaposhnikov 2002).

Inserting the values of Table 1 into Eq. 2 we obtain a 3-D plot of the parameter R_A/R_* as function of both, the accretion rate and the

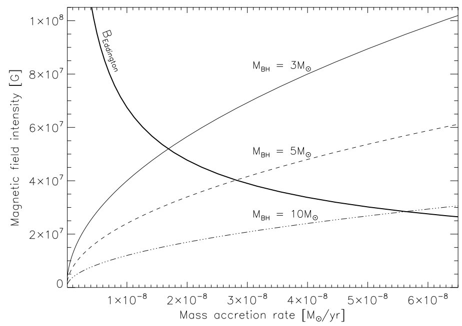

Fig. 3. BH XRBs: magnetic field strength at the last stable orbit vs mass accretion rate for different values of the BH mass. The curve "$B_\mathrm{Eddington}$" corresponds to the magnetic field strength for a mass accretion rate equal to the Eddington critical rate.

magnetic field strength, that we show in Fig 2. The "white area" refers to values of $R_A/R_* = 1$. Therefore this white region corresponds to the range of values in the parameter space where potential MQs exist.

3. Black Hole X-Ray Binaries

For the case of a BH XRBs we equate the magnetic field pressure to the plasma pressure in the last stable orbit ($R_\mathrm{A}/R_\mathrm{LSO} = 1$). Using Eq. 1, where we replace R_* by R_LSO, we get the magnetic field strength as a function of the mass accretion rate and the BH mass ($M_\bullet$):

$$B = \left(\frac{3}{c^2}\right)^{-5/4} (2G)^{-1} \left(\frac{\dot{M}}{M_\bullet^2}\right)^{1/2}$$
$$\simeq 12 \times 10^7 \left(\frac{\mathrm{M}_\odot}{M_\bullet}\right) \left(\frac{\dot{M}}{10^{-8}\ \frac{\mathrm{M}_\odot}{\mathrm{yr}}}\right)^{1/2} \mathrm{G}. \quad (3)$$

In Fig. 3 we show the result for different values of stellar-mass BHs.

4. Discussion and Conclusions

The basic condition for jet formation leads us to quantify an upper limit for the magnetic field strength as a function of the mass accretion rate. In this context, we studied each of the possible accreting XRB systems and we reached the following results:

1. The association of a classical X-ray pulsar (i.e. $B \sim 10^{12}$ G) with jets is excluded even if they accrete at the Eddington critical rate, in agreement with the systematic search of radio emission in this kind of sources with so far negative result (Fender et al. 1997, Fender & Hendry 2000; Migliari & Fender 2006).
2. It is known that Z-sources, “low” magnetic field neutron stars accreting at the Eddington critical rate, may develop jets. In this work we quantify the magnetic field strength to be $B \leq 10^{8.2}$ G in order to make possible the generation of jets in this kind of sources. This upper limit fits the observational estimation of Titarchuk et al. (2001) for Scorpius X-1.
3. Although jets have not been observed in any Atoll-sources they are potential sources for jets to be generated if $B \leq 10^{7.7}$ G.
4. It is not ruled out that a millisecond X-ray pulsar could develop jets, at least for those sources where $B \leq 10^{7.5}$ G. In this case the millisecond X-ray pulsar, could switch to a microquasar phase during maximum accretion rate. The millisecond source SAX J1808.4-3658 with such a low B shows in fact hints for a radio jet (Gaensler et al. 1999).
5. In the case of BH XRBs the upper limit of the magnetic field strength for the whole range of stellar-mass BHs, taking into account an Eddington mass accretion rate, is $B < 5 \times 10^7$G.

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