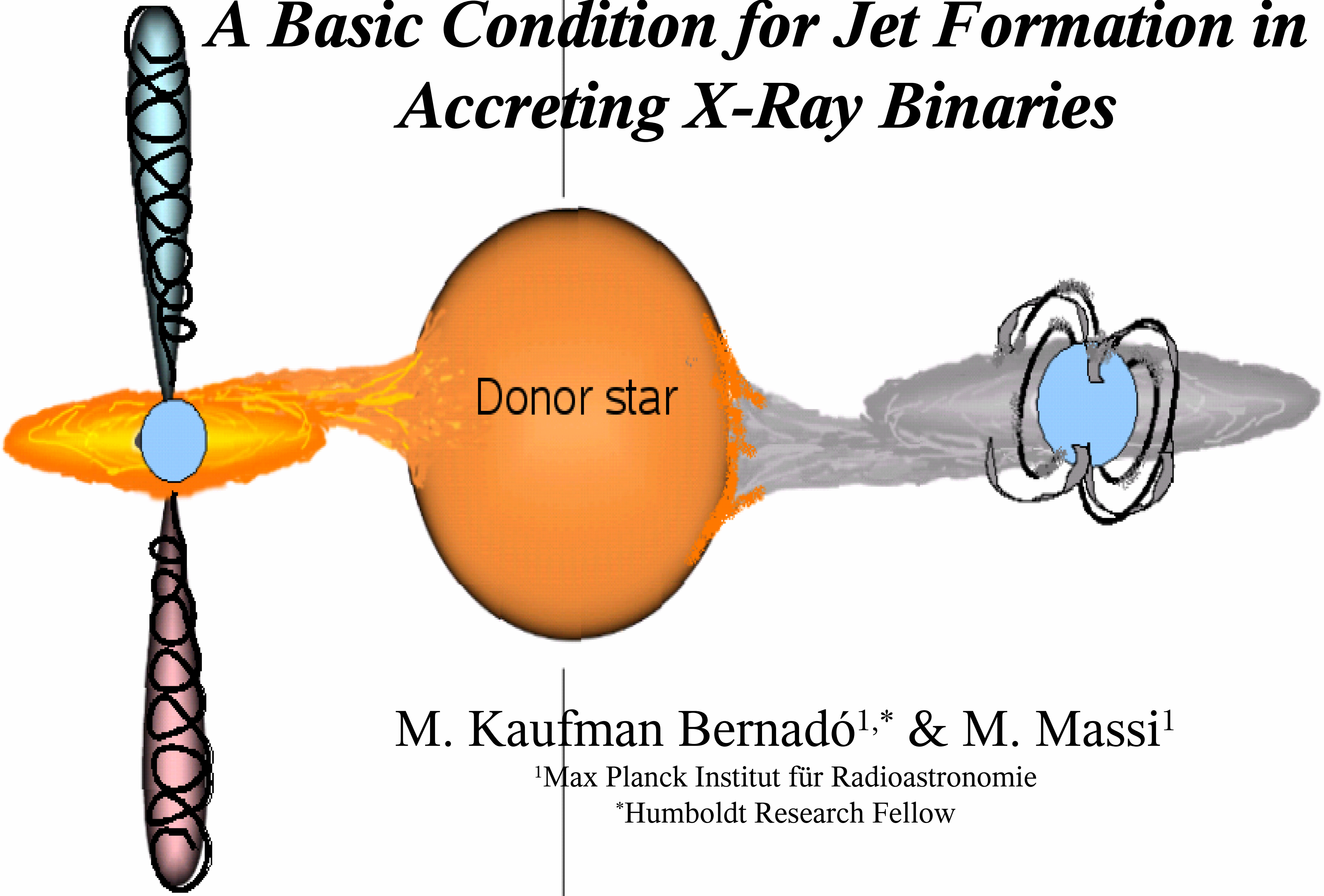
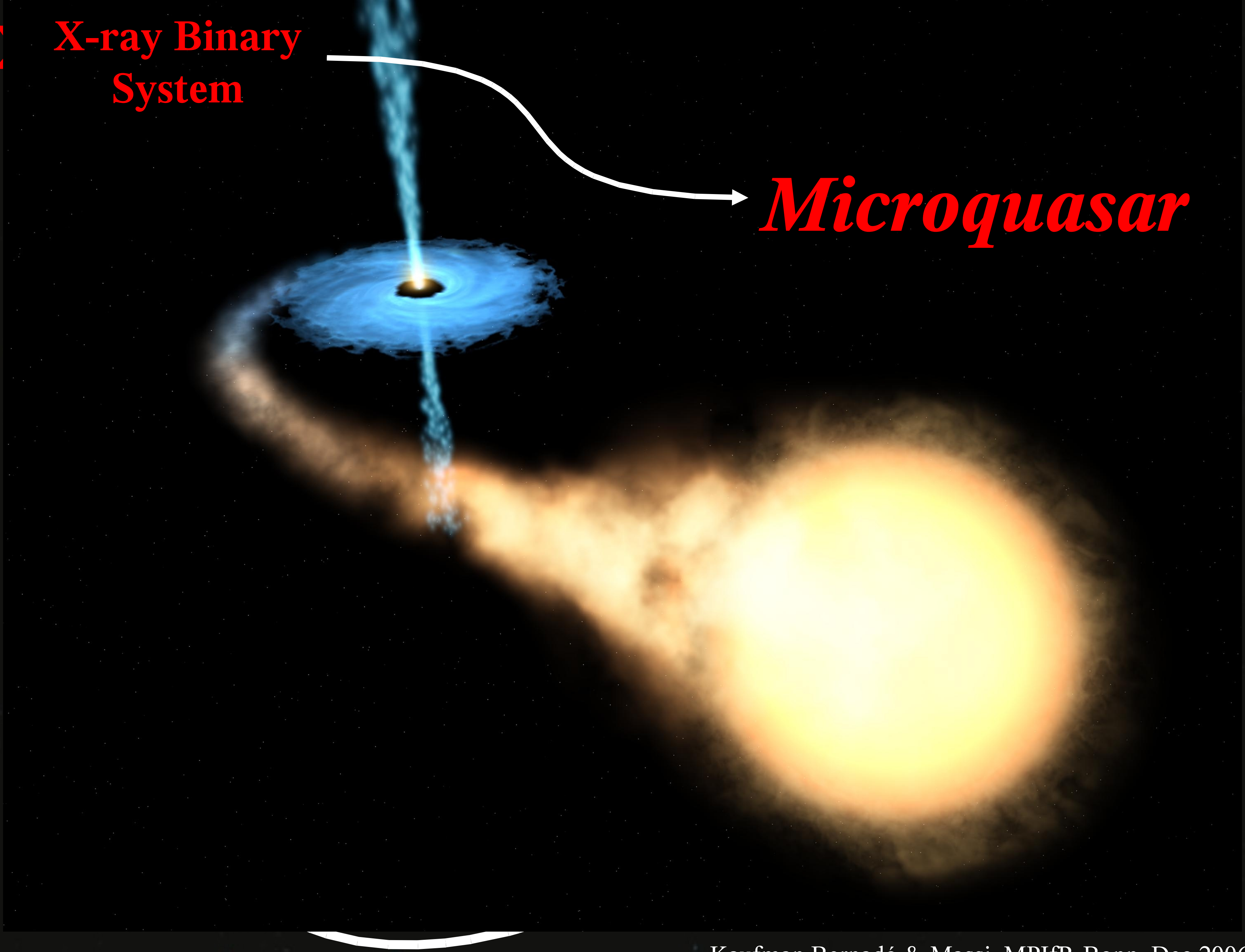
A Basic Condition for Jet Formation in Accreting X-Ray Binaries



M. Kaufman Bernadó[1,*] & M. Massi[1]
[1]Max Planck Institut für Radioastronomie
[*]Humboldt Research Fellow

December 2006 - MPIfR



X-ray Binary System

→

Microquasar

Kaufman Bernadó & Massi, MPIfR-Bonn, Dec 2006

JET FORMATION

$$P_B < P_p$$

Quantification of the Magnetic Field

Magnetic Field Upper Limit

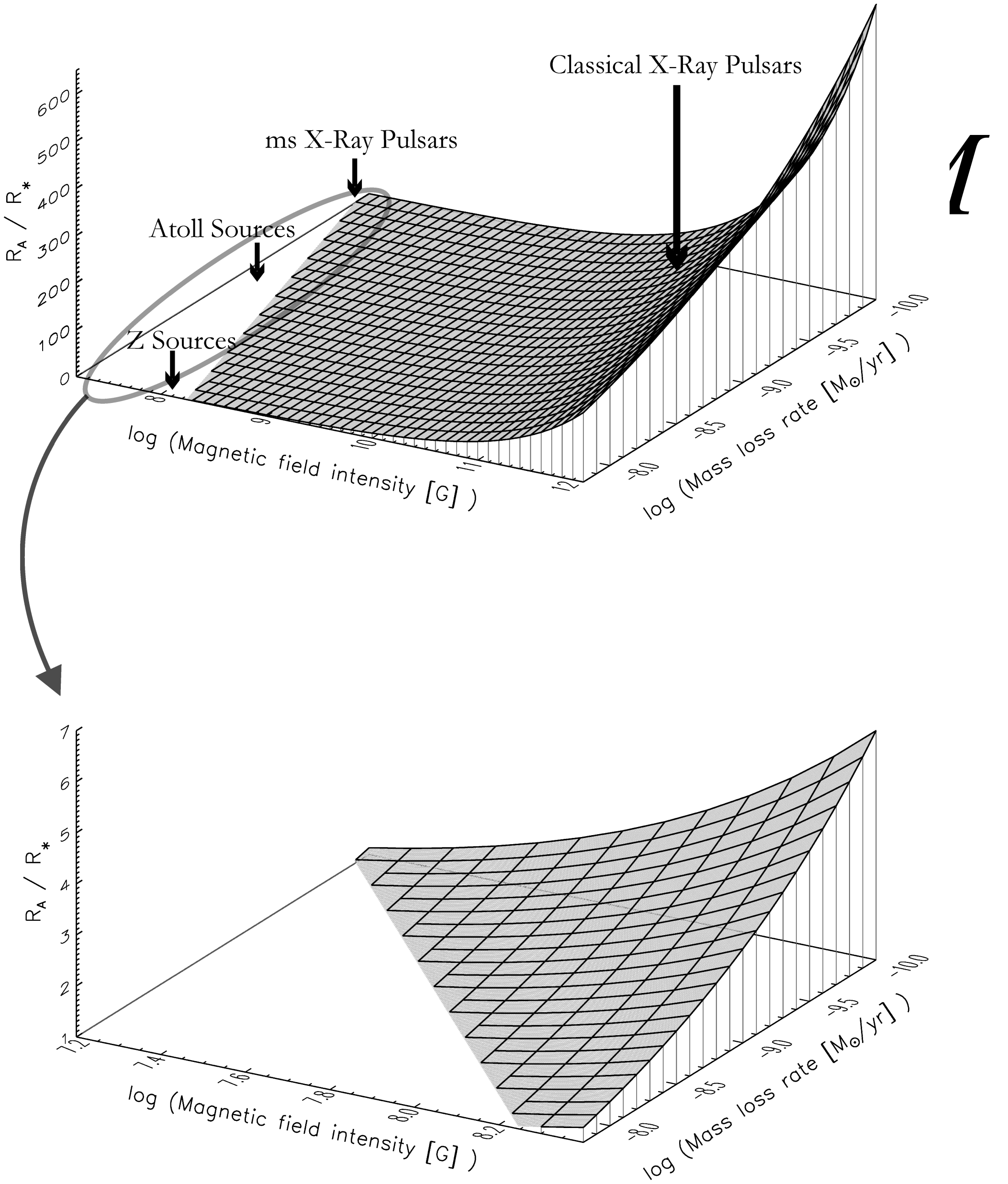
Alfvén Radius

$$R_A / R_* = 1$$

Neutron Star Surface Radius

The Basic Condition

R l



Kaufman Bernadó & Massi, MPIfR-Bonn, Dec 2006

A Basic Condition for Jet Formation in Accreting X-Ray Binaries

M. Kaufman Bernadó[1,*] and M. Massi[1]

[1] Max-Plamck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany
[*] Humboldt Research Fellow

We introduce the use of a well-known parameter, the Alfvén Radius - R_A, as a new tool to discern whether an X-ray binary (XRB) system may undergo a microquasar phase, i.e. ejecting relativistic particles orthogonal to the accretion disk. X-ray binaries with either a neutron star (NS) or a black hole (BH) as the compact object and low- or high-mass stellar companions are considered. We study what we call *the basic condition*, $R_A/R_* = 1$ or $R_A/R_{LSO} = 1$, in its dependency with the magnetic field strength and the mass accretion rate and analyse these results in a 3-D and 2-D plot.

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 consider the evolution of the magnetic field strength and the mass accretion rate under the basic condition for different values of the compact object mass. Our analysis has an important implication for the case of High-Mass X-ray Binaries: if a jet is observed in such a system one must exclude as the compact engine a neutron star with either a low magnetic field (because of lifetime considerations) or with a strong magnetic field (because of violation of the basic condition, $R_A/R_* = 1$). If a High-Mass X-ray Binary (HMXB) is associated with a microquasar, the accretor must therefore be a black hole.

The strength of the large-scale poloidal field must be low enough, that the plasma pressure, P_p, dominates the magnetic field pressure, P_B. Only under that condition, $\mathbf{P_B < P_p}$, 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. dynamically dominant) and the plasma has to follow the twisted magnetic field lines, creating two spinning-plasma flows.

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, $R_A/R_* = 1$ or $R_A/R_{LSO} = 1$, 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. Imposing this condition we can guarantee that $P_B < P_p$ is valid all over the disk not only from a certain distance onwards. $R_A/R_* = 1$ or $R_A/R_{LSO} = 1$ ensure that the magnetic field lines will then be twisted close to the compact object.

The Alfvén radius depends on the strength of the magnetic field, on its (bipolar or multipolar) topology and on the mode of accretion (spherically symmetric or disk-like). We will studied this dependency of the basic condition with the magnetic field and the mass accretion rate. This allowed us to establish under which combination of these parameters NS and BH XRBs may undergo a microquasar phase.

NEUTRON STAR X-RAY BINARIES

Equating the magnetic pressure, $B^2/8\pi$, with the plasma pressure, ρv^2, one can deduce an expression for the Alfvén Radius.

$$R_A = B^{4/7} R_*^{12/7} (2GM_*)^{-1/7} \dot{M}^{-2/7}$$

and then:

$$R_A / R_* \simeq 0.87 \left(\frac{B_*}{10^8 G}\right)^{4/7} \left(\frac{\dot{M}}{10^{-8} \frac{M_\odot}{yr}}\right)^{-2/7}$$

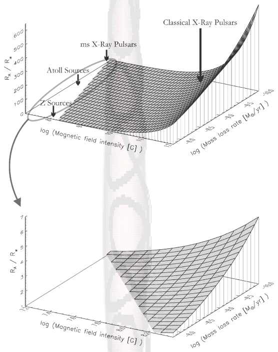
for a NS with $M_* = 1.44 M_\odot$ and $R_* = 9$km (Titarchuk & Shaposhnikov 2002)

Neutron Stars: Accretion Rate and Magnetic Field Strength

Class	$\frac{\dot{M}}{10^{-8}}(M_\odot yr^{-1})$	$B_*(G)$
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)

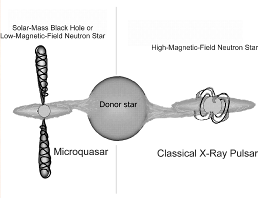
[a] Makishima et al. 1999 [b] Chakrabarty & Morgan 1998 [c] Lamb & Yu 2005
[d] Gilfanov et al. 1998 [e] van der Klis 1996 [f] Zhang & Kojima 2006
[g] van der Klis 1994 [h] Titarchuk et al. 2001

Inserting the values of the Table into the above equation we obtain a 3-D plot of the parameter R_A/R_* as function of both, the accretion rate and the magnetic field strength:

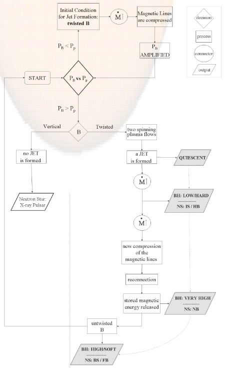


The "white" area refers to values of $R_A/R_* = 1$. This is the region, where the accretion rate and the magnetic field strength are combined in such a way that the stellar field is nowhere dynamically important.
This means that the white region is the part of the parameter space where potential microquasars can exist. One can see that this region is rather small for the given large range of magnetic field strength and mass accretion rate.

Left: The basic components of a **microquasar**: an accreting compact object (a neutron star or a solar-mass black hole), a donor star and radio emitting relativistic jets. Right: The basic components of a **classical (slow) X-ray pulsar**: an accreting neutron star with a very strong magnetic field (≥ 10^{12} G) emitting X-rays at the polar cups. Figure not drawn to scale.



Flowchart for the jet formation process and its parallel X-ray state cicle. Both, black holes (BH) and neutron stars (NS) X-ray state names, are mentioned. In the case of neutron stars the distinction between atoll- and Z-type is made: IS = Island State / HB = Horizontal Branch, NB = Normal Branch, BS = BS = Banana State / FB = Flaring Branch.



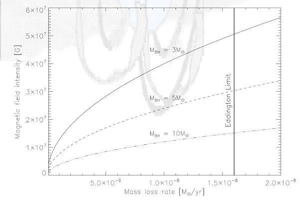
BLACK HOLES X-RAY BINARIES

$R_{LSO} = \xi R_A$ taking $\xi = 1$

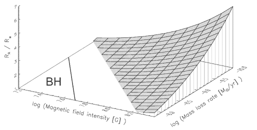
and using $R_A = B^{4/7} R_{LSO}^{12/7} (2GM_\bullet)^{-1/7} \dot{M}^{-2/7} = R_{LSO}$

we get $B = \left(\frac{3}{c^2}\right)^{-5/4} (2GM_\bullet)^{-1} \dot{M}^{1/2}$

We evaluate this relation for different values of the mass of stellar-mass BHs, $M_\bullet$, and we get the following 2-D plot:



Including the information of this 2-D plot in the NS XRBs 3-D plot, we can realise that BHs XRBs fit completely in the so called "white" area where potential microquasars can exist:



CONCLUSIONS & IMPLICATIONS

We have analysed the possibility for an XRB to undergo a MQ phase, i.e. to generate a jet. The relation between the P_B and the P_p was studied using the R_A/R_* ratio. We reached the following results:

- The association of a classical X-ray pulsar or any neutron star with a strong magnetic field (i.e. $B \sim 10^{12}$G) with a jet is excluded even if they accrete at the Eddington critical rate.
- It is known that Z-sources, "low" magnetic field neutron stars accreting at the Eddington critical rate, may develop a jet. We quantified the magnetic field strength to $B \lesssim 10^{8.2}$G.
- Although jets have not been observed in any Atoll-sources, they are potential sources for a jet to be generated for $B \lesssim 10^{7.7}$G.
- It is not ruled out that a millisecond X-ray pulsar could develop a jet, at least for those sources where $B \sim 10^{7.5}$ 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.
- Stellar-mass BHs XRBs are completely included in the so called "white area" of our 3-D plot where potential microquasars can exist.

This analysis has two further implications:

- The first refers to the nature of the accretor in HMXBs microquasars.

The decay time of the magnetic field strength of a NS is above 10^8yr and, thus, much longer than the lifetime of the massive companion star. Therefore, any NS in a HMXB system has an unevolved, strong magnetic field. Following our conclusions, a neutron star with a strong magnetic field cannot produce a jet.
This implies that all the HMXBs where a jet is detected must be black hole powered.

- The second implication of our analysis refers to the possibility of jets in ms X-ray pulsars. One of the major open issues concerning millisecond pulsars is the absence (and possible non-existence) of sub-millisecond pulsars. If the jet hypothesis is finally proven, then the jet might be the suitable agent of angular momentum sink as it happens in the bipolar outflows from young stellar objects where the transport rate of angular momentum by the jet can be two thirds or more of the estimated transport rate through the relevant portion of the disk (Woitas et al. 2005).