Neutron Stars in Microquasars

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Abstract. We discuss the “basic” condition for an accreting neutron star to become a microquasar, i.e. ejecting relativistic particles orthogonal to the accretion disk instead of confining disk-material down to the magnetic poles and creating the two emitting caps typical for a X-ray pulsar. Jet creation is prevented for $B > 10^{12}$ G independent of the accretion rate. This excludes the possibility for a classic X-ray pulsar to develop a “microquasar-phase” and is consistent with the lack of radio emission from such pulsar systems. Millisecond accretion-powered pulsars, on the contrary, may show a “microquasar-phase”, where $B < 10^{7.5}$ G is valid, whereas the limit for Z sources is $B < 10^{8.2}$ G. The implication of our analysis is that the jet might be the suitable agent of angular momentum sink for millisecond accretion-powered pulsars.

1. Introduction

X-ray binaries are stellar systems formed by two stars of a very different nature: A normal star (acting as a mass donor) and a compact object (the accretor) that either can be a neutron star or a black hole. However, the classification of the X-ray binaries (XRBs) into Low Mass X-ray Binary and High Mass X-ray Binary systems leaves unspecified the nature of the accreting object and exclusively is based on the companion star (van Paradijs & McClintock 1996), for HMXRB young bright stars (O-B) or for LMXRB old stars (later than G). An accreting object (as result of a supernova explosion) close to a normal star is an extremely rare binary among stellar systems and in fact up to now only 280 X-ray binary systems of this type are known (Liu et al. 2000, 2001). The microquasars (Massi 2005) are the 17 XRB systems, where 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).

2. Magnetohydrodynamic jet production

Numerical simulations show that the launch of jets involves a weak large-scale poloidal magnetic field anchored in rapidly rotating disks/compact objects (Meier et al. 2001). The geometry of this field is analogous to that of solar coronal holes and generated by the dynamo process (Blackman & Tan 2004).

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, $P_B < P_p$, the differentially rotating disk is able to bend the magnetic field lines, resulting 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 at 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. As recently proved for the bipolar outflows from young stellar objects, these rotating plasma-flows take angular momentum away from the disk (magnetic braking): The angular momentum transport rate of the jet can be two thirds or more of the estimated rate transported through the relevant portion of the disk (Woitas et al. 2005). This loss of angular momentum slows down the disk material to sub-Keplerian rotation and therefore the disk matter can finally accrete onto the central object. The accreting material further pulls the deformed magnetic field with it in that way increasing the magnetic field compression and magnetic reconnection may occur (Matsumoto et al 1996). The stored magnetic energy is released and the field returns to the state of minimum energy (i.e. untwisted).

3. The Alfvén radius

As seen in the previous section, the “basic” condition for ejection is a weak magnetic field. But how weak? In case of neutron stars we can take observed values, which allow a quantitative estimate. In this case there is an additional stellar magnetic field together with the disk-field. Let us assume that the stellar field dominates. The stellar field will be bent in the sweeping spiral (discussed above) only if the magnetic pressure $B^2/8\pi$ is less than the hydrodynamic pressure $\rho v^2$ of the accreting material. We here show that
the existence of the above conditions can easily be verified by plotting the Alfvén radius (normalised to the stellar surface) vs accretion rate and magnetic field strength. The Alfvén radius is the radius at which the magnetic and plasma pressure balance each other. If $R_A/R_\ast < 1$, the field will be twisted ($R_\ast$ is the stellar radius).

The Alfvén radius depends on the strength, on the (bipolar or multipolar) topology of the magnetic field and on the mode of accretion (spherically symmetric or disk-like). In case of a spherically symmetric accretion, the mass accretion rate $\dot{M}$ is equal to $4\pi R^2 \rho v^2$ (Longair 1994), where $v$ is the infall velocity $v = (2GM_\ast/R)^{1/2}$. For a magnetic dipole field with a surface magnetic field $B_\ast$, $B/B_\ast = |R_\ast/R|^3$. Therefore the parameter $R_A/R_\ast$ in terms of accretion rate $\dot{M}$ and surface magnetic field $B_\ast$ is equal to:

$$R_A/R_\ast \simeq 0.87 \left(\frac{B_\ast}{10^8}\right)^{4/7} \left(\frac{\dot{M}}{10^{-8}}\right)^{-2/7}.$$  \hspace{1cm} (1)

The equation has been calculated for a neutron star with a mass and a radius of respectively $M_\ast = 1.44$ $M_\odot$ and $R_\ast = 9$ km (Titarchuk & Shaposhnikov 2002).

### 4. Neutron star X-ray binaries

Table 1 shows the ranges, available in the literature, for accretion rate and magnetic field strength of neutron stars in X-ray binary systems. Including the classic accretion-powered pulsars the interval for $B$ ranges over more than 4 orders of magnitude: From classic accretion-powered pulsars with fields above $10^{12}$G, to the low value of $10^7$-8G of millisecond-pulsars and atoll sources. The interval for accretion rate covers several orders of magnitude, too, from less than 0.1% Eddington critical rate ($1.6 \times 10^{-8}M_\odot$ yr$^{-1}$) for millisecond-pulsars to Eddington critical rate for the Z sources (see references in Table 1).

In Fig. 1 we show a 3-D plot of the parameter $R_A/R_\ast$ as function of both, accretion rate and magnetic field strength. The value $R_A/R_\ast$ is plotted only above unity, i.e. the "white" area refers to values of $R_A/R_\ast < 1$. This is the region, where accretion rate and magnetic field strength are combined in such a way that the stellar field is nowhere dynamically important. This means the white region of Fig. 1 is the part of the parameter space where potential microquasars can exist. One can see in Fig. 1 that this region is rather small for the given large range of $B$ and $\dot{M}$.

#### 4.1. Classical accretion-powered pulsars

Classical accretion-powered pulsars have periods of the order of one second or more. In this sense they are also called "slow" accretion-powered pulsars in comparison to the milliseconds-pulsars (Sect. 4.3). Only five classic accretion-powered pulsars have been found in LMXRBs, whereas the vast majority are found in HMXRB systems (Psaltis 2004).

As one derives from Fig. 1 classic accretion-powered pulsars with magnetic fields of $10^{12}$G have $R_A/R_\ast >> 1$ even for accretion rates comparable to the Eddington critical rate. The stellar field therefore is dynamically dominant. In this case the plasma is forced to move along the...
magnetic field lines, converges onto the magnetic poles of the neutron star and there releases its energy creating two X-ray emitting caps. In the case of a misalignment between the rotation and the magnetic axis, X-ray pulses are produced (Psaltis 2004).

The value \( R_A / R_* > 1 \), therefore, excludes the formation of jets in accreting pulsars for any accretion rate. Our result agrees with the observations. A deep search for radio emission from X-ray pulsars has been performed by Fender et al. (1997) and none of the pulsar candidates has been detected. The lack of radio emission is statistically discussed by Fender et al. (1997) and they conclude that X-ray pulsations and radio emission from X-ray binaries are strongly anti-correlated. More recent observations (Fender & Hendry 2000; Migliari & Fender 2005) again confirm that none of the high-magnetic-field X-ray pulsars is a source of synchrotron radio emission.

4.2. Atoll and Z-sources

The LMXRBs with neutron stars have been divided into two subclasses called Atoll-type (the largest class) and Z-type, based on their timing and spectral properties observed by Hasinger & van der Klis (1989). The differences reflect different values of accretion rates, but also different values for the magnetic field strength (see Table 1). For each of the two types, Atoll-sources and Z-sources, the accretion rate is different in the different spectral states: For the Atoll-sources there are two states (island and banana) and for the Z-type sources there are three ones (horizontal-, flaring-, and normal-branch).

Two Z sources (Circinus X-1 and Scorpius X-1) are microquasars. Therefore, the condition \( R_A / R_* \leq 1 \), must be satisfied in them. From Fig. 4 bottom results, that this is true only if \( B \leq 10^{8.2} \) G. As a consequence, the value of \( B \sim 10^6 \) G (given in the literature) may be applied only to Z-type sources with no radio jet. Indeed, our upper limit well agrees with the estimate of Titarchuk et al. (2001) on the microquasar Scorpius X-1. These authors deriving \( B \) from magnetoacoustic oscillations in kHz QPO in three neutron stars (Scorpius X-1 one of them) determine a strength of \( 10^{7–8} \) G on the surface of the neutron star.

4.3. Millisecond accretion-powered pulsars

Millisecond accretion-powered pulsars also have a weak magnetic field \( B \sim 10^8 \) G together with the main characteristic of a rapidly spinning neutron star. They are very few and all of them in the class of LMXRBs. As one can derive from the values given in Table 1, the millisecond X-ray pulsars are extreme Atoll sources. The prolonged, sustained accretion of matter on the neutron star from the long-living companion, carrying angular momentum, is thought to be responsible for the acceleration to milliseconds. Less clear is the cause for the decay of \( B \) (Cumming et al. 2001; Chakrabarty 2005; Psaltis 2004).

As shown in Fig. 1 the obstacle for jet production in millisecond accretion-powered pulsars is their low accretion rate. For the average \( B \sim 10^8 \) G, assumed in the literature, the condition \( R_A / R_* < 1 \) would be fulfilled only for accretion rates of \( \geq 6 \times 10^{-9} M_\odot \) yr\(^{-1} \) whereas the maximum observed accretion rate nearly is one order of magnitude lower, i.e \( \dot{M} \leq 0.7 \times 10^{-9} M_\odot \) yr\(^{-1} \) (Table 2). On the contrary, if \( \dot{M} = 0.7 \times 10^{-9} M_\odot \) yr\(^{-1} \), the condition \( R_A / R_* < 1 \) would be fulfilled for \( B = 10^{7.5} \) G, a value compatible with observations (Table 1).

In the accreting millisecond X-ray pulsar SAX J1808.4-3658, the long-term mean mass transfer rate is \( \dot{M} \approx 1 \times 10^{-13} M_\odot \) yr\(^{-1} \) (Chakrabarty & Morgan 1998). During bright states peak values of \( \dot{M} \sim 0.3 - 0.7 \times 10^{-9} M_\odot \) yr\(^{-1} \) (Chakrabarty & Morgan 1998; Gilfanov et al. 1998) have been measured and the upper limit on the magnetic field strength is \( B \lesssim \text{a few times} \ 10^7 \) G (Gilfanov et al. 1998). As a matter of fact, in this source hints for a radio jet have been found. It is one of the two accreting millisecond X-ray pulsars, SAX J1808.4-3658 (Gaensler et al. 1999) and IGR J00291+5934 (Pooley 2004), that have shown transient radio emission related to X-ray outbursts. Especially interesting is the fact that the size of the radio emitting region of SAX J1808.4-3658 is much larger than the separation of the binary system, which is what would be expected for expanding material ejected from the system (Gaensler et al. 1999; Migliari & Fender 2006). In other words, SAX J1808.4-3658, which normally behaves like a pulsar, could switch to a microquasar state at maximum accretion rate. While future high resolution radio observations can probe or rule out the presence of a radio jet, at the moment theory and observations give positive indications for one.

5. Discussion and conclusions

The results of our analysis are:

1. It is excluded that X-ray accreting-pulsars or in general neutron stars with strong (i.e. \( B \sim 10^{12} \) G) magnetic fields may be associated with a jet, even if accreting at the Eddington critical rate.

2. It is known that Z-sources, “low” magnetic field neutron stars accreting at the Eddington critical rate, may develop a jet. In this paper we quantify the magnetic field strength to \( B \lesssim 10^{8.2} \).

3. It is not ruled out that a millisecond pulsar could develop a jet, at least for those sources where \( B \lesssim 10^{7.5} \) G. In this case the millisecond pulsar, could switch to a microquasar phase during maximum accretion rate. The millisecond source SAX J1808.4-3658 with such a low \( B \), shows hints for a radio jet.

One of the major open issues concerning millisecond pulsars is the absence (and possible non-existence) of sub-millisecond pulsars. The spin distribution sharply cuts off well before the breakup spin rate for neutron stars. The
physics setting that limit is unclear (Chakrabarty 2005). If the jet hypothesis will be proved, the jet might be the suitable agent of angular momentum sink, as in the bipolar outflows from young stellar objects. The transport rate of angular momentum by the jet can be two thirds or more of the estimated rate transported through the relevant portion of the disk (Woitas et al. 2005).

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