*High-mass X-ray Binaries: Illuminating the Passage*
*from Massive Binaries to Merging Compact Objects*
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# Superstrong magnetic fields of neutron stars in Be X-ray binaries

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**Abstract.** A few Be X-ray binaries might constitute a group of special sources because the neutron stars in them may have superstrong magnetic fields. Generally, the neutron stars have long spin periods and some emission lines are shown from the B type star, which is attributed to an equatorial disc. We re-build new dimensionless torque models and obtain the superstrong magnetic fields of the neutron stars in the Be X-ray binaries in Large Magellanic Cloud, Small Magellanic Cloud and Milky Way when the compressed magnetosphere is considered. Although our conclusions are obtained when the disk accretion mode is considered, the results may be applied the Be X-ray binaries with wind accretion mode. SXP1323 and 4U 2206+54, in which the magnetic fields of the NSs may be close to the maximum 'virial' value, are the best objects to explore superstrong magnetic field.

**Keywords.** accretion, accretion disks, stars: neutron, X-rays: binaries.

## 1. Introduction

Be X-ray binaries (BeXBs) are the most numerous sub-class of the high mass X-ray binaries and have attracted many researchers due to the possible superstrong magnetic fields of the neutron stars (NS) in them (Shi, Zhang & Li 2015). There is a $8M_\odot - 18M_\odot$ B type star with emission lines and a rotating neutron star (NS) in every BeXB, where $M_\odot$ is the mass of the Sun. Generally, BeXBs are transient due to their eccentric orbits ($e > 0.3$) and the Be stars in these systems are often surrounded by a circumstellar disk, which may originate from the ejected photospheric matter with sufficient angular momentum and energy due to the fast rotating Be stars (Knigge *et al.* 2011; Reig 2011). When the neutron star passes through the disk, the matter in the disk can be accreted through the magnetosphere. Then the variable angular momentum produced from accretion or outflow leads to a change of the NSs spin period ($P$). Therefore the changed torque can be obtained from the parameters such as the derivative of the changing spin period ($\dot{P}$).

Klus *et al.* (2014) obtained two groups of magnetic field solutions for the NSs in 42 Be X-ray binaries in the Small Magellanic Cloud (SMC). Ho *et al.* (2014) argued that higher solutions of the magnetic fields are more correct. Shi, Zhang & Li (2015) recalculated the surface magnetic fields of these NSs and expanded this recalculation to the NSs of Be X-ray binaries (BeXBs) in the Large Magellanic Cloud (LMC) and Milky Way (MW).

## 2. New dimensionless torque

The accreting matter in the accretion disk rotates around the NS and it is funneled to the two poles of the NS with a dipolar magnetic field, which is aligned to the magnetic axis and perpendicular to the Keplerian accretion disk (Ghosh & Lamb 1979). The accretion disk interacts with the neutron star by the transportation of the accretion matter in the disk. Wang (1995) obtained different results for the relation between the azimuthal magnetic field and the toroidal magnetic field in the accretion disk when reconnection takes place outside the disk and the magnetosphere is force-free. Bozzo *et al.* (2018) reviewed the implications of the case with a non-orthogonal rotator in the magnetically threaded disk model and compared the magnetospheric radius from Ghosh & Lamb (1979) with that from Wang (1995). Generally, it is believed that the spin-up state for NSs in XBs can be differentiated from the spin-down state by the corotation radius ($r_{\rm co}$). The spin-up state originates from a positive torque that is imposed on a NS and the spin-down state from a negative one.

The total torque (N) acting on the NS system is made of the material torque from the accretion matter and the magnetic torque produced by the magnetic coupling between the NS and the accretion disk. It was considered that all the angular momentum of the accreting matter is transferred to the NS and the corresponding torque is $N_{\mathtt{0}}$, i.e. $\dot{M}\sqrt{GMr_{\mathtt{i}}}$, where $G$ is gravitational constant, $M$ the mass of the NS, $\dot{M}$ the accretion rate, $r_{\mathtt{i}}$ the inner radius, which is often considered as the magnetospheric radius ($r_{\mathtt{m}}$). However, the NS and the dipolar magnetic field around the NS should be one system and the accretion disk is the other system. As a part of the accretion disk, the accreting plasma should keep the last angular momentum at the magnetospheric radius when it is controlled by the magnetosphere and corotates with the NS at the magnetospheric radius. Therefore, the torque acting on the NS system that corresponds to the lost angular moment of the plasma is $\dot{M}\sqrt{GMr_{\rm m}} - \dot{M}\Omega_{\rm s} r_{\rm m}^2$, where $\Omega_{\rm s}$ is the angular frequency of the spin. According to this hypothesis, we obtain the new dimensionless torque as follows,

$$n = \frac{N}{N_0} = \begin{cases} (1-\omega) + \frac{1}{3}\frac{\mu^2 r_{\rm m}^{-3}}{\dot{M}\sqrt{GMr_{\rm m}}}(\frac{2}{3} - 2\omega + \omega^2), \ \omega \leqslant 1, \\ (1-\omega) + \frac{1}{3}\frac{\mu^2 r_{\rm m}^{-3}}{\dot{M}\sqrt{GMr_{\rm m}}}(\frac{2}{3}\omega^{-1} - 1), \ \omega > 1. \end{cases} \tag{2.1}$$

where $\omega = (r_{\rm i}/r_{\rm co})^{3/2}$ is the fast parameter.

## 3. Superstrong magnetic field

As a rotating system, the NS is sped up due to the total interactional torque and thus we can obtain the relation $-\dot{P} = NP^2/2\pi I_{\rm eff}$, where $I_{\rm eff}$ is the effective moment of inertia of the NS. If equation (2.1) is substituted into the above equation and the magnetospheric radius is obtained, we can obtain an estimate for the surface magnetic field of the NS in BeXB. Finally, the surface magnetic field can be expressed as a relation, $B \propto PL^{\alpha}$, where $\alpha$ is a constant that reflects the amount of compression. As discussed by Shi, Zhang & Li (2014, 2015), the calculated surface magnetic field of a NS in BeXB for the compressed magnetosphere is much higher than the one for the uncompressed magnetosphere.

Besides the results for the magnetic field in the non-equilibrium state of a BeXB ($r_m < r_{\rm co}$), we can also estimate the magnetic field for the equilibrium state ($r_{\rm co} = r_m$). In fact, most BeXBs are close to spin equilibrium. The effect of a compression of the dipolar magnetic field for the spin equilibrium can be found in Figure 1. Three types of magnetospheric radii are considered in Figure 1, i.e. $r_{\rm m1}$ for the uncompressed magnetosphere, $r_{\rm m2}$ for the compressed magnetosphere in the plane of an accretion disk, $r_{\rm m3}$ for the compressed magnetosphere that comes from Kulkarni & Romanova (2013).

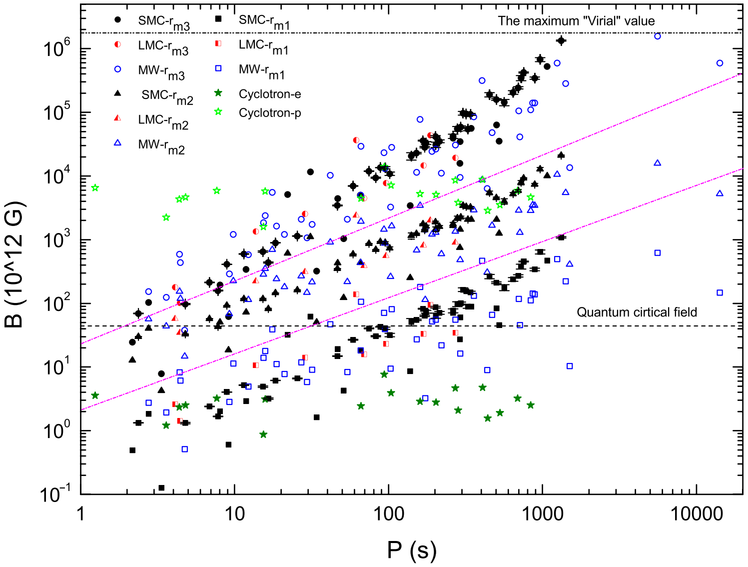

**Figure 1.** Relation between the spin period of NSs and the surface magnetic fields of NSs in BeXBs. The square points indicate for rm1, the triangle points for rm2, the circle points the solutions for rm3, the open points indicate sources for the MW, the half-filled points for LMC, and the solid points the solutions for the SMC as well. The stars show the magnetic field inferred from the observed cyclotron line sources (the solid points for electrons and the hollow for protons).

The whole compression from Kulkarni & Romanova (2013) leads to the calculated maximum magnetic field, which is close to the maximum 'virial' value, especially for the sources SXP1323 and 4U 2206+54. Most magnetic fields of NSs in BeXBs are shown to be higher than the quantum critical field (44.14 TG), which means that BeXBs are a kind of accreting magnetars. The surface magnetic field obtained from the observed cyclotron lines can be expressed as $B_{12} = 0.863 * E_{10\mathrm{kev}}$ for the electrons in the ground state, but $B_{12} = 1585 * E_{10\mathrm{kev}}$ for the protons, where $E_{10\mathrm{kev}}$ expresses the energy of the cyclotron absorption line in units of 10 keV, $B_{12}$ the surface magnetic field of NSs in BeXBs in units of $10^{12}$ G. The data for protons are in the range of the upper solutions discussed above. It seems as if the discussed cyclotron lines may be indeed produced by protons.

## 4. Discussion and conclusion

BeXBs with a high luminosity always include a long period NS, which may have a superstrong magnetic field. However, some ultraluminous X-ray sources (ULXs) whose distance is still unclear are found to be BeXBs. When the real surface magnetic field of the NS in a ULX is equally strong to the value estimated according to our calculations for the compressed magnetosphere, the derived distance from the Earth would be smaller and then the ULXs may not be found to be ultraluminous, i.e. some of these ULXs may be normal BeXBs. The relation between ULXs and BeXBs need to be explored further.

The magnetic field of a NS in some BeXB is found to be superstrong. However, supergiant X-ray binaries (SGXRs) might also be characterized by a similar accretion disk. Expanding our calculation to SGXRs, it might also be concluded that the magnetic fields of NSs in some SGXRs could be superstrong. A NS being formed from the terminal contraction of a dying massive star may keep the original magnetic flux and then end up obtaining a superstrong magnetic field. Many physical mechanisms in extreme conditions in BeXBs need to be explored.

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