Magnetic field estimates for accreting neutron stars in massive binary systems and comparison with magnetic field decay models

ANNA CHASHKINA AND SERGEI POPOV

Sternberg Astronomical Institute

Abstract

Some modern models of neutron star evolution predict that initially large magnetic fields rapidly decay down to some saturation value few$\times 10^{13}$ G. Lower magnetic fields do not decay significantly [Aguilera et al., 2008]. It is difficult to check predictions of the model for initially highly magnetized objects on the time scale of few million years. We propose to use Be/X-ray binaries for this purpose. We use several different methods to estimate magnetic fields of neutron stars in these accreting systems using the data obtained by the RXTE satellite [Galache et al., 2008]. Only using the most modern approach proposed by Shakura et al. [2011] we are able to obtain a field distribution compatible with predictions of the theoretical model of field decay: even neutron stars with the longest spin periods then have magnetic fields $<$ few10^{13} G.

Method

In our work we used data [Galache et al., 2008] on 40 Be/X-ray binaries in the Small Magellanic Cloud observed by the RXTE satellite. We estimated magnetic fields of these objects with several different methods. Only using the most modern approach proposed by Shakura et al. [2011] we are able to obtain reasonable results.

In [Shakura et al., 2011] the authors develop model for quasi-spherical accretion and apply it to calculate the magnetic fields of several well known X-ray sources (GX 301-2, Vela X-1 and GX 1+4). We assume that systems that we consider rapidly evolve toward the equilibrium state when the sum of the torques acting on the neutron star is zero. Magnetic moment in the units of $10^{30}\,\mathrm{G\,cm^3}$ can be written as follows:

$$\mu_{30} = 0.12 \left(\frac{\delta^2 \varpi \xi^{-12/33}}{1 - z/Z}\right)^{11/12} \left(\frac{P_s/100\mathrm{s}}{P_{orb}/10\mathrm{d}}\right)^{11/12} \dot{M}_{16}^{1/3} v_8^{-11/3} \qquad (1)$$

Here numerical coefficients in the brackets are of order of unity, P_s and P_{orb} is spin and orbital periods correspondingly. $\dot{M}_{16}$ is accretion rate in $10^{16}\,\mathrm{g\,s^{-1}}$ units and v_8 is the total velocity in $10^8\,\mathrm{cm\,s^{-1}}$ units .

We apply this model only to objects with spin periods $P_s > 50$ s. For short-period objects ($P_s < 50$ s) we make calculations with the equilibrium period hypothesis in the framework of standard disc accretion [Lipunov, 1992]:

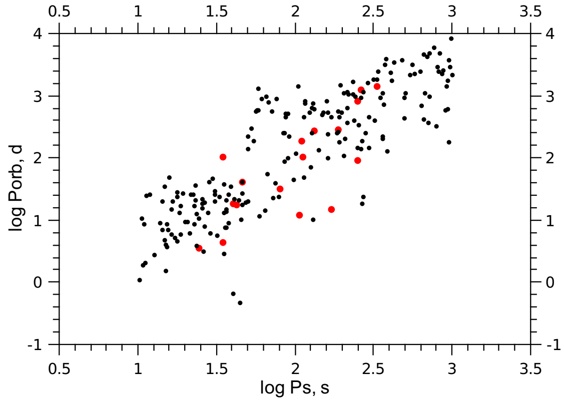
$$\mu_{30} = 0.12 P_s^{7/6} \dot{M}_{16}^{1/2} \qquad (2)$$

Below we refer to this approach as hybrid model.

Corbet diagram

Additional consistency check for magnetic field estimates can be made using the Corbet diagram [Corbet, 1984]. Using Monte-Carlo approach we simulate the distribution of Be/X-ray systems. The values of spin periods calculated due to hybrid model. Simulated results are shown in Fig. 1 by black dotted. We plot the observational data [Reig, 2011] as red circles in this figure. One can see good correlation between theoretical and observational data.

Fig. 1



Corbet diagram for the observed data (red circles) and for the hybrid model (black dots).

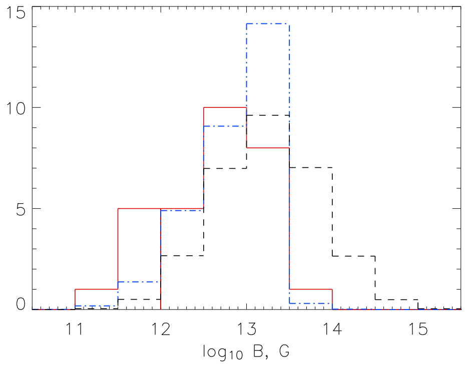
Comparison with magnetic field decay models

During a neutron star evolution its magnetic field decays. Here we compare our estimates with predictions of the model by Aguilera et al. [2008]. According to this model the evolution of magnetic field is well approximated by the following equation:

$$B(t) = B_{\min} + (B_0 - B_{\min}) \frac{\exp(-t/\tau_{Ohm})}{1 + \tau_{Ohm}/\tau_{Hall}(1 - \exp(-t/\tau_{Ohm}))}. \qquad (3)$$

Here B_0 is the initial magnetic field and $B_{min} = \min[\mathrm{B}_0/2\,, 2 \times 10^{13}]$ G. τ_{ohm} – ohmic time, τ_{hall} – Hall time, which depends on the initial field as $\tau_{hall} \propto 1/B_0$. In Fig. 2 we show magnetic field distributions. The theoretical distribution for the initial magnetic fields are plotted by a black dashed line (according to [Popov et al., 2010]). The evolved field are calculated according to eq. (3) using the values: $\tau_{Hall} = 10^4 (B_0/10^{15}\mathrm{G})^{-1}$ yrs and $\tau_{Ohm} = 10^6$ yrs are plotted by a blue dash-dotted line. Fields base on hybrid model are shown with a red solid line.

Fig. 2



Magnetic field distributions.

References

D. N. Aguilera, J. A. Pons, and J. A. Miralles. The Impact of Magnetic Field on the Thermal Evolution of Neutron Stars. ApJL, 673:L167–L170, Feb. 2008. doi: 10.1086/527547.

R. H. D. Corbet. Be/neutron star binaries - A relationship between orbital period and neutron star spin period. A&A, 141:91–93, Dec. 1984.

J. L. Galache, R. H. D. Corbet, M. J. Coe, S. Laycock, M. P. E. Schurch, C. Markwardt, F. E. Marshall, and J. Lochner. A Long Look at the Be/X-Ray Binaries of the Small Magellanic Cloud. ApJ Supp., 177:189–215, July 2008. doi: 10.1086/587743.

V. M. Lipunov. Astrophysics of Neutron Stars. 1992.

S. B. Popov, J. A. Pons, J. A. Miralles, P. A. Boldin, and B. Posselt. Population synthesis studies of isolated neutron stars with magnetic field decay. MNRAS, 401:2675–2686, Feb. 2010. doi: 10.1111/j.1365-2966.2009.15850.x.

P. Reig. Be/X-ray binaries. Ap&SS, 332:1–29, Mar. 2011. doi: 10.1007/s10509-010-0575.

N. Shakura, K. Postnov, A. Kochetkova, and L. Hjalmarsdotter. Theory of quasi-spherical accretion in X-ray pulsars. MNRAS submitted, 2011.