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NEUTRON STARS IN X-RAY PULSARS AND THEIR MAGNETIC FIELDS

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Abstract

Estimates of the magnetic field of neutron stars in X-ray pulsars are obtained using the hypothesis of the equilibrium period for disk and wind accretion and also from the BATSE data on timing of X-ray pulsars using the observed maximum spin-down rate. Cyclotron lines at energies ≥ 100 keV in several Be-transient are predicted for future observations.
We suggest a new method of estimating distances to X-ray pulsars and their magnetic fields. Using observations of fluxes and period variations in the model of disk accretion one can estimate the magnetic momentum of a neutron star and the distance to X-ray pulsar. As an illustration the method is applied to the system GROJ1008-57.

1 Introduction

Among all astrophysical objects neutron stars (NSs) attract most attention of physicists. Now we know more than 1000 NSs as radiopulsars and more than 100 NSs emiting X-rays, but the Galactic population of these objects is about $10^8 - 10^9$. So only a tiny fraction of one of the most fascinating astrophysical objects is observed at present.

NSs can appear as sources of different nature: as isolated objects and as binary companions, powered by wind or disk accretion from a secondary companion. X-ray pulsars are probably one of the most prominent among binary sources, because there important parameters of NSs can be determined.

Now we know more than 40 X-ray pulsars (see e.g. Bildsten et al.[1)], Borkus[2)]). Observations of optical counterparts of X-ray sources give an opportunity to determine distances to these objects and other parameters with relatively high precision, and with hyroline detections one can obtain the value of magnetic field, B, of a NS. But lines are not detected in all sources of that type and magnetic field can be estimated from period measurements (see e.g. Lipunov[4)]). Precise distance measurements usually are not available immediately after X-ray discovery (especially, if localization error boxes are large and X-ray sources have transient nature). In that sense methods of simultaneous determination of field and distance basing only on X-ray observations can be useful, and several of them were suggested by different authors previously.

Here we try to obtain estimates of the magnetic fields (and distances) of NSs in X-ray pulsars from their period (and flux) variations.

2 Estimates of the magnetic field

Magnetic fields of accreting NSs can be estimated using period variations or using the hypothesis of the equilibrium period (see Lipunov[4]). We use both of these methods.

For estimating of magnetic momentum of NSs using observed values of maximum spin-down we use the following main equation:

$$\frac{dI\omega}{dt} = -k_t \frac{\mu^2}{R_{co}^3},$$

where I – NS's momentum of inertia, $\omega = \frac{2\pi}{p}$ – spin frequency, μ – magnetic momentum, $R_{co} = \left(\frac{GM}{\omega^2}\right)^{1/3}$– corotation radius. We used $k_t = 1/3$, $I = 10^{45}$ g cm^2, $M = 1.4 M_\odot$.

We used graphs from (Bildsten et al.[1]) to derive spin-up and spin-down rates and flux changes measurements. Data on these graphs is shown with one day time resolution.

Equilibrium period can be written in different forms for disk and wind-fed systems. For the first case we used the following equation:

$$p_{eq.disk} = 2.7\, \mu_{30}^{6/7} L_{37}^{-3/7}\ s. \tag{1}$$

For wind-accreting systems we have:

$$p_{eq.wind} = 10.4\, L_{37}^{-1} T_{10}^{-1/6} \mu_{30}\ s. \tag{2}$$

Here L_{37} – luminosity in units 10^{37} erg s^{-1}, T_{10} – orbital period in units 10 days, μ_{30} – magnetic momentum in units 10^{30} G cm^3.

Estimates of the magnetic momentum, μ, obtained with different assumptions are shown in the table 1. Three values are shown: an estimate from spin-down obtained from the BATSE data (Bildsten et al.[1]); an estimate from the equilibrium period for wind-fed systems (eq. (2)); an estimate for disk-accreting systems (eq. (1)). Less probable values are marked with asterix.

In table 1 we use the following notation: LMXRB- Low Mass X-Ray Binary; HMSG - High Mass SuperGiant; BeTR- Be-transient source. Values, which were used for estimates with the hypothesis of the equilibrium period: spin period, mean luminosity in units 10^{37} erg s^{-1}, orbital period in units 10 days can be found on the Web: **http://xray.sai.msu.ru/~ polar**.

More precise estimates can be made by fitting all observed values of spin-up and spin-down rate together with flux measurements. When the distance to the source is know only the value of the magnetic field should be fitted. And on the figure 1 we show such estimates for Her X-1.

We plot spin-up and spin-down rates as a function of the parameter, which is a combination of the spin period and source's luminosity. Spin-up and spin-down values derived from the BATSE data (Bildsten et al.[1]) are plotted as black dots, and theoretical curves for different values of the magnetic momentum are also shown. In ideal the best curve for the magnetic momentum should exist, which fits all observational points. In reality points have some errors, distance to the source in also know with some uncertainty, and simple model of spin-up and spin-down can be only the first approximation.

3 Discussion and conclusions

We made estimates of the magnetic field of NSs in X-ray pulsars. Estimates which were made with an assumption that $p = p_{eq}$ are rather rough. Obtained values depend (except

Table 1: Spin-down and magnetic momentum estimates

X-RAY PULSAR	maximum dp/dt observ. (spin-down)	Source Type	Magnetic momentum (spin-down), 10^{30} G cm^3	Magnetic momentum (wind), 10^{30} G cm^3	Magnetic momentum (disk), 10^{30} G cm^3
GRO 1744-28		BeTR		0.93^*	0.58
HER X-1	$9.3 \cdot 10^{-13}$	LMXRB	0.3		0.18
4U 0115+63	$3.0 \cdot 10^{-10}$	BeTR	5.17	0.32^*	1.26
CEN X-3	$7.5 \cdot 10^{-12}$	HMSG	0.82	1.8	4.42
4U 1627-67	$4.1 \cdot 10^{-11}$	LMXBR	1.9		2.82
2S 1417-624		BeTR		8.64^*	17.82
GRO 1948+32	$5.4 \cdot 10^{-9}$	BeTR	22.0		
OAO 1657-415	$1.5 \cdot 10^{-7}$	HMSG	115.1	0.15	4.33
EXO 2030+375		BeTR		0.1	3.45
GRO 1008-57	$3.2 \cdot 10^{-8}$	BeTR	53.3		
A 0535+26		BeTR		30.24^*	101.23
GX 1+4	$6.4 \cdot 10^{-8}$	LMXRB	75.5		167.3
VELA X-1	$3.8 \cdot 10^{-9}$	HMSG	18.5	4.03	88.15
4U 1145-61	$3.3 \cdot 10^{-7}$	BeTR	172.1	0.23^*	16.7
A 1118-616	$5.1 \cdot 10^{-7}$	BeTR	212.8		245.5
4U 1535-52	$3.6 \cdot 10^{-7}$	HMSG	56.4	17.37	299.3
GX 301-2	$8.9 \cdot 10^{-6}$	HMSG	281.9	8.34	200.5

uncertainties connected with the method itself) on unknown parameters of NSs, such as masses, radii, moments of inertia. All of them were accepted to have "standard" values, and of course it is only the first approximation. For example, our estimate for the source GRO 1744-28 is $\mu \sim 10^{30}$ G cm^3, and it is smaller than the estimate shown in (Borkus[2)]), which is $B \sim (2-5) \cdot 10^{12}$ G (we mark, that the estimate obtained by Joss & Rappaport[3)] is significantly lower than both: Borkus and our estimates). But if one take "non-standard" value for R, these estimates of μ and B can be in good correspondence.

We show several examples in table 2. NSs radii are calculated from the following simple formula:

$$R = (2\mu/B)^{1/3}.$$

Here μ are taken from table 1, and values of B are taken from Nagase[5)], Borkus[2)] and Wang[8)]. As one can see from the table for several sources measured B are not in correspondence with our calculated μ, and radii of NSs are too big. Mostly these cases are long period wind-fed pulsars like GX 301-2, where formation of temporal reverse disk is possible for the cases of fast spin-down, so there maximum spin-down can be not the best field estimate, and estimates from the equilibrium period for wind-accretion case are in better correspondence with observations.

In more clear cases (Her X-1, GRO 1744-28), where we are sure, that accretion is of the disk type, our estimates from maximum spin-down are in good correspondence with observations. And we predict for the cases of Be-transients, where disk accretion is working for sure, that in 2S 1417-624, GRO 1948+32, GRO 1008-57, A 1118-616 and 4U 1145-61 observations of cyclotron lines at energies ≥ 100 keV are possible in future.

Observations of period and flux variations can be used also for simultaneous determination of magnetic field of a NS and distance to the X-ray source (Popov[6)]).

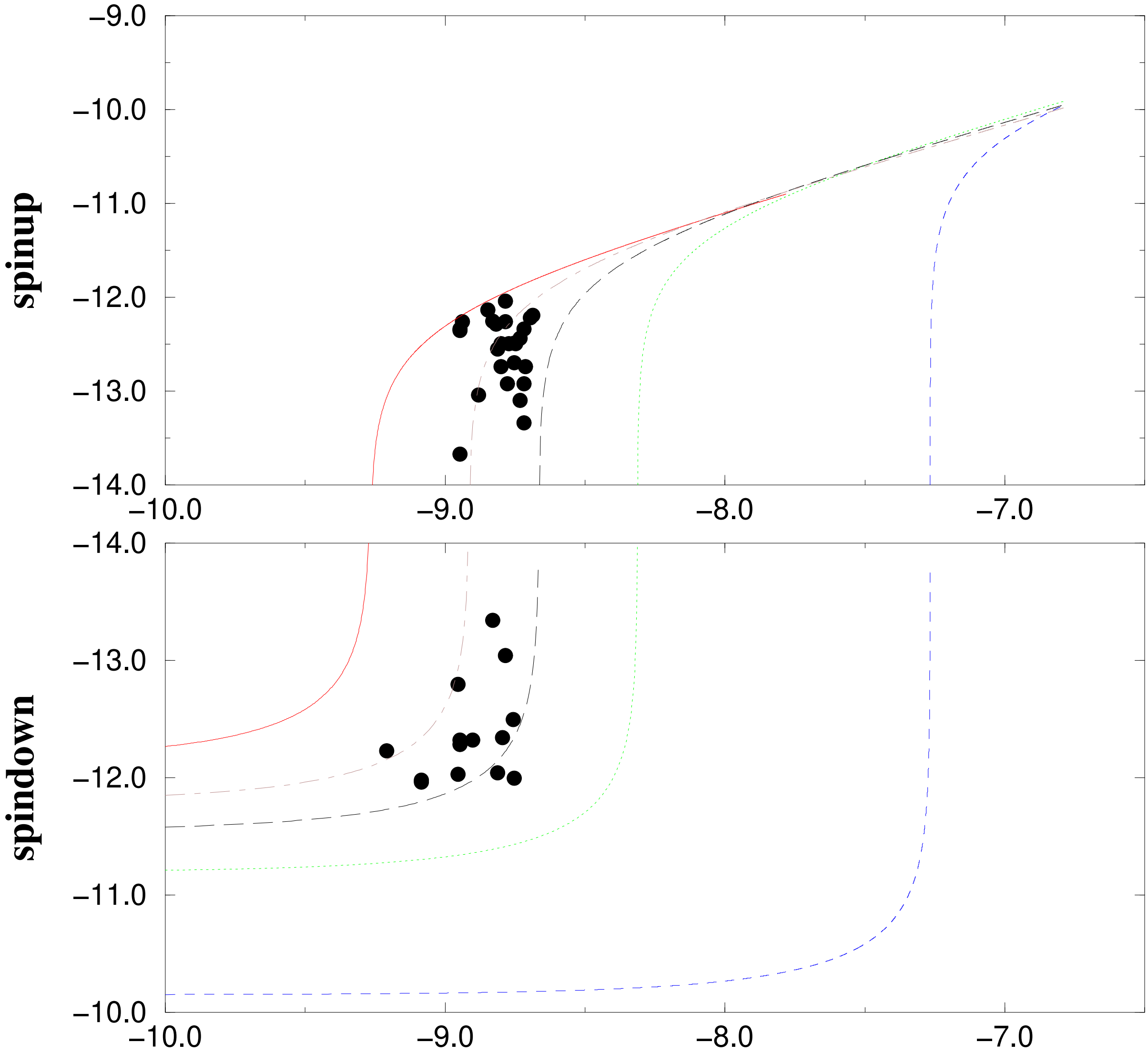

Figure 1: Dependence of period derivative, $\dot{p}$, on the parameter $p^{7/3}f$, $f-$ observed flux, for Her X-1. Both axis are in logarithmic scale. Observations (Bildsten et al., 1997) are shown with black dots. Five curves are plotted for different values of the magnetic field. Solid curve: $\mu = 0.1 \cdot 10^{30}\,\mathrm{G}\cdot\mathrm{cm}^3$. Dot-dashed curve: $\mu = 0.15 \cdot 10^{30}\,\mathrm{G}\cdot\mathrm{cm}^3$. Long dashed curve: $\mu = 0.2 \cdot 10^{30}\,\mathrm{G}\cdot\mathrm{cm}^3$. Dotted curve: $\mu = 0.3 \cdot 10^{30}\,\mathrm{G}\cdot\mathrm{cm}^3$. Dashed curve: $\mu = 1 \cdot 10^{30}\,\mathrm{G}\cdot\mathrm{cm}^3$. All curves are plotted for the distance $d = 4\,\mathrm{kpc}$.

The method is based on several measurements of period derivative, $\dot{p}$, and X-ray pulsar's flux, f. Fitting distance, d, and magnetic momentum, μ, one can obtain good correspondence with the observed p, $\dot{p}$ and f, and that way produce good estimates of distance and magnetic field (see also another way of estimating of these parameters based on the equilibrium period and spin-up measurements applied to GRO1744-28 in (Joss & Rappaport[3])).

Lets consider only disk accretion due to application of our method to the system, in which most probably accretion is of the disk type. In that case one can write (see Lipunov[4]):

$$\dot{p} = \frac{4\pi^2\mu^2}{3\,G\,I\,M} - \sqrt{0.45}\,2^{-1/14}\frac{\mu^{2/7}}{I}\,(GM)^{-3/7}\left[p^{7/3}L\right]^{6/7} R^{6/7}, \qquad (3)$$

Table 2: Magnetic fields, magnetic momentum and radii

X-RAY PULSAR	Magnetic momentum (calcul.), 10^{30}G cm^3	Magnetic field (observ.), 10^{12}G	Neutron star radius, km
GRO 1744-28	0.58	$\sim (2-5)$	$\sim (8.3-6.1)$
HER X-1	0.3	3	5.8
4U 0115+63	5.17	1.1	21.1
A 0535+26	101.23	11	26.4
VELA X-1	18.5	2.3	25.2
4U 1535-52	56.4	1.9	39
GX 301-2	281.9	3.5	54.4

where $L = 4\pi d^2 \cdot f$ – luminosity, f – the observed flux.

So, with some small uncertainty in the equation above we know all parameters (I, M, R etc.) except μ and d. Fitting observed points with them we can obtain estimates of μ and d. Uncertainties mainly depend on applicability of that simple model.

To illustrate the method, we apply it to the X-ray pulsar GRO J1008-57, discovered by BATSE (Bildsten et al.[1)]). It is a 93.5 s X-ray pulsar, with the BATSE flux about 10^{-9} erg cm^{-2} s^{-1}. The source was identified with a Be-system with $\sim 135^d$ orbital period.

On figure 2 we show observations (as black dots) and calculated curves for the disk model on the plane $\dot{p} - p^{7/3}f$, where f – observed flux (logarithms of these quantities are shown). Curves were plotted for different values of the source distance, d, and NS magnetic momentum, μ. Spin-up and spin-down rates were obtained from graphs in Bildsten et al.[1)].

If one uses maximum spin-up, or maximum spin-down values to evaluate parameters of the pulsar, then one can obtain values different from the best fit (they are also shown on the figure): $d \approx 8$ kpc, $\mu \approx 37.6 \cdot 10^{30}$ G$\cdot$ cm^3 for maximum spin-up, and two values for maximum spin-down: $d \approx 4$ kpc, $\mu \approx 37.6 \cdot 10^{30}$ G$\cdot$ cm^3 and the one close to our best fit (two similar values of maximum spin-down were observed for different fluxes, but we mark, that formally maximum spin-down corresponds to the values, which are close to our best fit). It can be used as an estimate of the errors of our method: accuracy is about the factor of 2 in distance, and about the same value in magnetic field, as can be seen from the figure.

Determination of magnetic field (and, probably, distance) only from X-ray observations can be very useful in uncertain situations, for example, when only X-ray observations without precise localizations are available.

Acknowledgments

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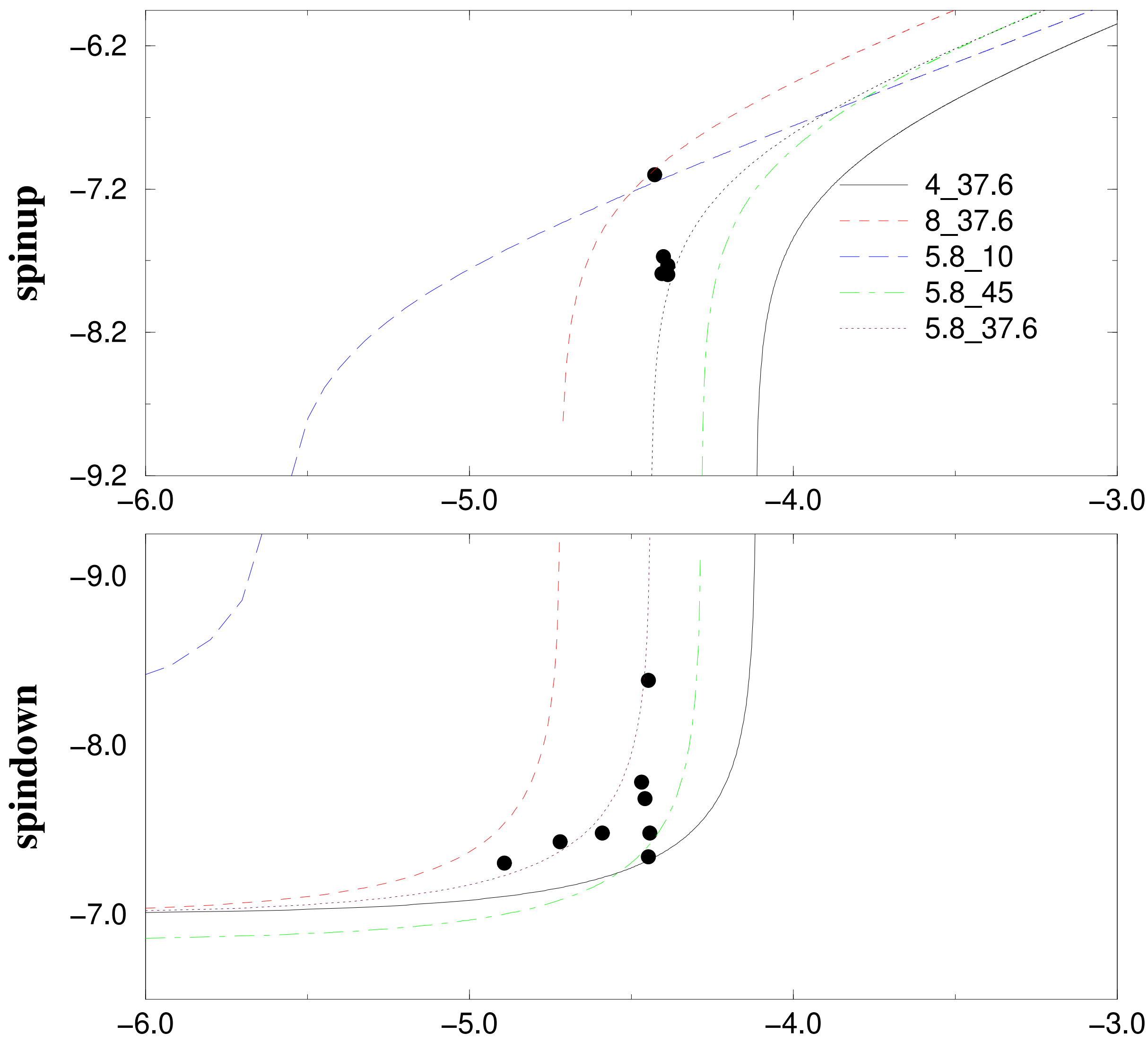

Figure 2: Dependence of period derivative, $\dot{p}$, on the parameter $p^{7/3}f$, $f-$ observed flux, for GRO 1008-57. Both are axis in logarithmic scale. Observations (Bildsten et al., 1997) are shown with black dots. Five curves are plotted for disk accretion for different values of distance to the pulsar and NS magnetic momentum. Solid curve: $d = 4\,\mathrm{kpc}$, $\mu = 10 \cdot 10^{30}\,\mathrm{G} \cdot \mathrm{cm}^3$. Dashed curve: $d = 8\,\mathrm{kpc}$, $\mu = 10 \cdot 10^{30}\,\mathrm{G} \cdot \mathrm{cm}^3$. Long dashed curve: $d = 8\,\mathrm{kpc}$, $\mu = 45 \cdot 10^{30}\,\mathrm{G} \cdot \mathrm{cm}^3$. Dot-dashed curve (the best fit): $d = 5.8\,\mathrm{kpc}$, $\mu = 37.6 \cdot 10^{30}\,\mathrm{G} \cdot \mathrm{cm}^3$. Dotted curve: $d = 4\,\mathrm{kpc}$, $\mu = 45 \cdot 10^{30}\,\mathrm{G} \cdot \mathrm{cm}^3$.

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