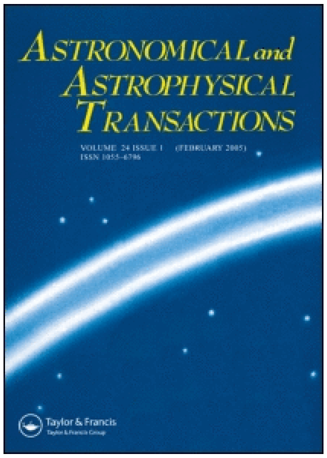

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MAGNETIC FIELDS OF NEUTRON STARS IN X-RAY PULSARS

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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 from the BATSE data on timing of X-ray pulsars using the observed maximum spin-down rate.

Cyclotron lines at energies $\geq$ 100 keV in several Be-transients are predicted for future observations.

KEY WORDS Stars: binaries, stars: magnetic fields, stars: neutron, X-rays: stars

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 emitting X-rays, but the Galactic population of NSs is much larger: about 10^8–10^9 objects. Here the first number, 10^8, comes mainly from radiopulsar statistics, and should be considered as a low limit, because it is not clear if all NSs pass through the stage of a radiopulsar, since the initial parameters (spin period and magnetic field) of the significant part of NSs can be different from 'standard' values: $B_0 \sim 10^{12}$ G, $p_0 \sim$ (1–20) ms. For example, NSs can be born below the death-line due to small initial magnetic fields, or due to relatively long spin periods (the fall-back after a supernova explosion can also be important, because the magnetic moment or spin period can be changed during this process). The second number, 10^9, is in correspondence with models of chemical evolution of the Galaxy. So only a tiny fraction of one of the most fascinating astrophysical objects is observed at present.

NSs can appear as sources of a different nature: as isolated objects (radiopulsars, old isolated accreting NSs, soft γ-repeaters, young radioquiet cooling NSs, etc.) and as binary companions. In binaries NSs usually appear as X-ray sources in close systems, powered by wind or disk accretion from a secondary companion. X-ray

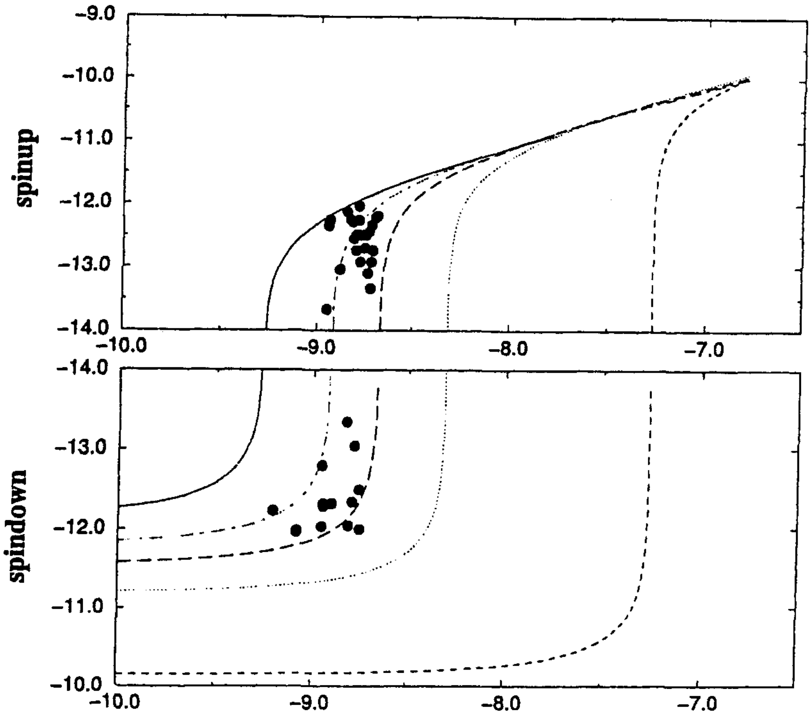

Figure 1 Dependence of period derivative, $\dot{p}$, on the parameter $p^{7/3}f$, f – observed flux, for Her X-1. Both axes are logarithmic scales. Observations (Bildsten *et al.*, 1997) are shown with black dots. Five curves are plotted for different values of the magnetic field. Solid curve: $\mu =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

pulsars are probably one of the most prominent among these sources, because the important parameters of NSs (spin period, magnetic field, etc.) can be determined.

Now we know more than 40 X-ray pulsars (see e.g. Bildsten *et al.*, 1997; Borkus, 1998). Observations of the optical counterparts of X-ray sources give us an opportunity to determine the distances to these objects and other parameters with relatively high precision. And with hyroline detection one can obtain the value of the magnetic field, B, of a NS. But lines are not detected in all sources of that type (for example, because they can lie out of the range of necessary spectral sensitivity of devices, when fields are too high, $> 10^{13}$ G), and the magnetic field can be estimated from period measurements (see e.g. Lipunov, 1982; 1992). Precise distance measurements are usually not available immediately after X-ray discovery (especially if localization error boxes are large and X-ray sources have a transient nature). In that sense methods of simultaneous determination of field and distance based only on X-ray observations can be useful, and several of them were previously suggested by different authors.

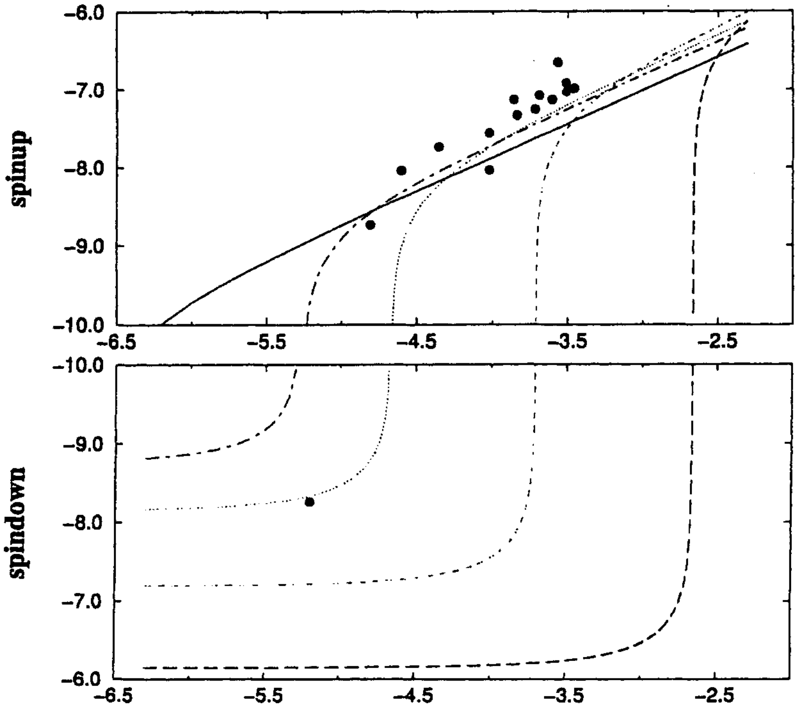

Figure 2 Dependence of period derivative, $\dot{p}$, on the parameter $p^{7/3}f$; f – observed flux, for A0535+26. Both axes are logarithmic scales. Observations (Bildsten *et al.*, 1997) are shown with black dots. Five curves are plotted for different values of the magnetic field. Solid curve: $\mu = 1 \times 10^{30}$ G cm^3. Dot-dashed curve: $\mu = 5 \times 10^{30}$ G cm^3. Dotted curve: $\mu = 10 \times 10^{30}$ G cm^3. Dashed curve: $\mu = 30 \times 10^{30}$ G cm^3. Long dashed curve: $\mu = 100 \times 10^{30}$ G cm^3. All curves are plotted for the distance $d = 2$ kpc.

Here we try to obtain new estimates of the magnetic fields of NSs in X-ray pulsars from their period variations using new data.

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, 1992). We use both of these methods.

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

$$\frac{\mathrm{d}I\omega}{\mathrm{d}t} = -k_r \frac{\mu^2}{R_{\mathrm{co}}^3},$$

Table 1. Spin-down and magnetic moment estimates.

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

where I is the NS's moment of inertia; $\omega = 2\pi/p$, the spin frequency; μ is the magnetic moment, and $R_{co} = (GM/\omega^2)^{1/3}$ is the corotation radius. We used $k_t = 1/3$, $I = 10^{45}$ g cm^2, $M = 1.4M_\odot$. We can use this approximation without spin-up (accelerating) momentum, because we choose moments with maximum spin-down, when spin-down (braking momentum) is much larger than the accelerating momentum. This estimate should normally be considered as a low limit on the value of the magnetic field, since we cannot be sure that no accelerating momentum exists at that moment.

We used graphs from (Bildsten *et al.*, 1997) to derive spin-up and spin-down rates and measurements of flux variatinos. Data on these graphs is shown with one-day time resolution. Usually errors are relatively small, and we neglect them.

Such estimates were obtained several times by different authors with different data sets, but usually these sets had worse time resolution (see some examples Lipunov, 1992). And the BATSE data (Bildsten *et al.*, 1997) gives an excellent opportunity to repeat these simple calculations.

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

$$p_{\text{eq. disk}} = 2.7\mu_{30}^{6/7}L_{37}^{-3/7}\ \text{s}. \qquad (1)$$

Table 2. Parameters of X-ray pulsars.

X-RAY PULSAR	*Period, s*	*Mean luminosity*, 10^{37} *erg* s^{-1}	*Orbital Period, days*
GRO 1744-28	0.467	20	11.76
HER X-1	1.24	0.2	
4U 0115+63	3.61	0.8	24.3
CEN X-3	4.84	5	
4U 1627-67	7.66	0.7	0.0289
2S 1417-624	17.6	4	42.1
GRO J 1948+32	18.7		
OAO 1657-415	37.7	0.04	10.44
EXO 2030+375	41.7	0.02	46.0
GRO 1008-57	93.5		
A 0535+26	105	2	110
GX 1+4	120	4	
VELA X-1	283	0.15	8.96
4U 1145-61	292	0.005	187
A 1118-616	406	4	0.5
4U 1535-52	530	0.4	3.73
GX 301-2	681	0.1	41.5

For wind-accreting systems we have:

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

Here L_{37} is the luminosity in units of 10^{37} erg s^{-1}, T_{10} is the orbital period in units of 10 days, and μ_{30} is the magnetic moment in units of 10^{30} G cm^3.

Estimates of the magnetic moment, μ, obtained with different assumptions are shown in Table 1. In Table 1 we use the following notation: LMXRB – Low Mass X-Ray Binary; HMSG – High Mass SuperGiant; BeTR – Be-transient source. Three values are shown in the table: an estimate from spin-down obtained with the BATSE data (Bildsten *et al.*, 1997); an estimate from the equilibrium period for wind-fed systems (Eq. (2)); an estimate from the equilibrium period for disk-accreting systems (Eq. (1)). Both of the last two estimates were made for X-ray pulsars about which we were not sure if they are disk or wind-accreting systems; less probable values (wind accretion in Be-transients) are marked with an asterix. In two cases (4U 1145-61 and OAO 1657-415) the magnetic moment calculated from the maximum spin-down value is much higher than moments calculated with the hypothesis of equilibrium, which can indicate, for example, that this hypothesis does not work in these cases.

In Table 2 we show values which were used for estimates with the hypothesis of the equilibrium period: spin period, mean luminosity in units of 10^{37} erg s^{-1} and orbital period in units of 10 days (see the compiled catalogue of X-ray pulsars on the Web at the URL: http://xray.sai.msu.ru/~polar/html/publications/cat/x-ray_n2.www).

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 known only the value of the magnetic field should be fitted, and in Figures 1 and 2 we show such estimates for two X-ray pulsars. In these figures we show $\dot{p}$ vs. $p^{7/3}L$. This dependence can be clearly understood from Eq. (3) below.

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.*, 1997) are plotted as black dots, and theoretical curves for different values of the magnetic moment are also shown. Ideally, the best curve for the magnetic moment should exist, which fits all observational points. In reality points have some errors, distances to the sources are also known with some uncertainty, and the simple model of spin-up and spin-down can be only the first approximation. But these estimates of the magnetic moment are more precise than the ones obtained with the equilibrium hypothesis.

These estimates can be different from other ones obtained from the equilibrium periods or from a single value of spin-down as can be seen from Table 1.

3 DISCUSSION AND CONCLUSIONS

We made estimates of the magnetic field of NSs in X-ray pulsars. Estimates which were made with the assumption that $p = p_{\mathrm{eq}}$ are rather rough. This can be seen, for example, from Table 1, where the 'low limit value', obtained from the maximum spin-down rate, in several cases is higher than estimates obtained from the equilibrium. Obtained values depend (except 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 this is only the first approximation. For example, our estimate for the source GRO 1744-28 is $\mu \sim (0.6\text{–}0.9) \times 10^{03}$ G cm^3, and it is smaller than the estimate shown by Borkus (1998), which is $B \sim (2\text{–}5) \times 10^{12}$ G (we note that the estimate obtained by Joss and Rappaport (1997) is significantly lower than both: Borkus and our estimates). But if one takes 'non-standard' value for R, these estimates of μ and B can be in good correspondence.

We show several examples in Table 3. NSs radii are calculated from the following simple formula:

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

Here μ are taken from Table 1, and values of B are taken from Nagase (1992), Borkus (1998) and Wang (1996). 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 the formation of a temporal reverse disk is possible for the cases of fast spin-down, so the maximum spin-down cannot be the best field estimate, and estimates from the equilibrium period for the wind-accretion case are in better correspondence with

Table 3. Magnetic fields, magnetic moment and radii.

X-RAY PULSAR	*Magnetic momentum (calc.),* 10^{30} *G cm*^{3}	*Magnetic field (observ.),* 10^{12} *G*	*Neutron star radius, km*
GRO 1744-28	0.58	~ (2–5)	~ (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

observations. For A 0535+26 our estimate was obtained only from the equilibrium period, and since this system is transient it can be far from equilibrium. We note that in general the existence of a high magnetic field in that source, as it comes from our estimates, is confirmed by observations. In the case of 4U 0115+63 errors for maximum spin-down rate are not very small, and the discrepancy between observed and calculated values can be due to this (since we neglect these errors). We also note that Ginga was not sensitive enough in the spectral region ≥ 40 keV, where the cyclotron lines for $\mu \geq (2–3) \times 10^{30}$ G cm^3 are situated.

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

Estimates obtained from maximum spin-down rate and estimates obtained with the hypothesis of equilibrium period are in rough correspondence, except the sources OAO 1657-415 and 4U 1145-61, where maximum spin-down estimates are significantly higher. This can be an indication that systems are far from equilibrium (especially in the case of the Be-transient 4U 1145-61), or that some additional mechanism of spin-down (outflows, reverse disks, etc.) is at work. In the case of OAO 1657-415 the estimate based on maximum spin-down rate can be incorrect similar to GX 301-2 for the reasons which were discussed above.

Observations of period and flux variations can also be used for simultaneous determination of the magnetic field of a NS and the distance to the X-ray source (Popov, 1999).

The method is based on several measurements of the period derivative, $\dot{p}$, and the X-ray pulsar's flux, f. Fitting the distance, d, and magnetic moment, μ, one can obtain good correspondence with the observed p, $\dot{p}$ and f, and that way produce good estimates of the distance and magnetic field (see also another way of estimating these parameters based on the equilibrium period and spin-up measurements applied to GR01744-28 FB by Joss and Rappaport (1997) and Rappaport and Joss (1997).

To illustrate the method, we apply it in (Popov, 1999) to the X-ray pulsar GRO J1008-57, discovered by BATSE (Bildsten *et al.*. 1997). The best fit (both for spin-up and spin-down) gives $d \approx 5.8$ kpc and $\mu \approx 37.6 \times 10^{30}$ G cm^3. The distance is in correspondence with the value in (Shrader *et al.*, 1999), and this field value is not unusual for NSs in general and for X-ray pulsars in particular (see, for example, Lipunov (1992) and Bildsten *et al.* (1997)), and this value of μ is consistent with maximum spin-down (see Table 1). Tests on some other X-ray pulsars with known distances and magnetic fields also showed good results.

The method of distance and field estimates is approximate and depends on several assumptions (type of accretion, specified values of M, I, R, etc.). Estimates of μ, for example, can only be in rough correspondence with determinations of the magnetic field B with hyrolines, if the standard value of the NS radius, $R = 10$ km, is used (see, for example, the case of Her X-1 by Lipunov (1992)). When the field and the distance are known with high precision, observations of period and flux observations can be used to put limits on the equation of state (see e.g. Schaab and Weigel, 1999).

If one uses maximum spin-up, or maximum spin-down values to evaluate the parameters of the pulsar, then one can obtain values different from the best fit (they are also shown on the figures): $d \approx 8$ kpc, $\mu \approx 37.6 \times 10^{30}$ G cm^3 for maximum spin-up, and two values for maximum spin-down: $d \approx 4$ kpc, $\mu \approx 37.6 \times 10^{30}$ G cm^3 and the one close to our best fit (two similar values of maximum spin-down were observed for different fluxes, but we note 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 a factor of 2 in distance, and about the same value in magnetic field, as can be seen from the figures.

The 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.

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