Method of estimating distances to X-ray pulsars and their magnetic fields

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Abstract

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. Estimates of the distance: approximately 6 kpc, and the magnetic momentum: approximately $4 \cdot 10^{31}\, G \cdot cm^3$, are obtained.

1 Introduction

Neutron stars (NS) can appear as isolated objects (radiopulsars, old isolated accreting NS, etc.) and as X-ray sources in close binary systems. The most prominent of the last ones are X-ray pulsars, where important parameters of NS can be determined.

Now more than 40 X-ray pulsars are known (see, for example, Bildsten et al., 1997). Observations of optical counterparts give an opportunity to obtain distances to these objects with high precision, and with hyroline detections one can obtain the value of magnetic field of a NS. But lines are not detected in all sources of that type (partly because they can lay out of the range of necessary spectral sensitivity of devices, when field are high), and magnetic field can be estimated from period measurements (see Lipunov, 1982, 1992). Precise distance measurements usually are not available immediately after X-ray discovery (especially, if error boxes, as for example in the BATSE case, are large). So, methods of their determination basing only on X-ray observations can be useful.

Here we propose a simple method to determine magnetic field and distance to X-ray pulsar using only X-ray flux and period variations measurements.

2 Method

In Lipunov (1982) it was proposed to use maximum spin-up and spin-down values to obtain limits on the magnetic momentum of X-ray pulsars in disk or wind models, using known values of luminosity (method, based on maximum spin-down, is very insensitive to uncertainties in luminosity and produces better results).

In this short note we propose a rough simple method to determine magnetic field without known distance and to determine distance itself. The method is based on several measurements of period derivative, $\dot{p}$, and X-ray pulsar's flux, f. Fitting two parameters: distance, d, and magnetic momentum, μ, one can obtain good correspondence with the observed $\dot{p}$ and f, and that way produce good estimates of distance and magnetic field.

Here we consider only disk accretion. In that case one can write (see Lipunov, 1982, 1992):

$$\frac{dI\omega}{dt} = \dot{M}\left(GM\epsilon R_A\right)^{1/2} - k_t\frac{\mu^2}{R_c^3}, \tag{1}$$

where ω – spin frequency of a NS, M – its mass, I– its moment of inertia, R_A - Alfven radius, R_c – corotation radius. We use the following values: $\epsilon = 0.45$, $k_t = 1/3$ (see Lipunov, 1992). The first term on the right side represents acceleration of a NS from an accretion disk, and the second term represents deceleration. The form of the deceleration term is general, only typical radius of interaction should be changed. It is equal to R_c for accretors, R_l - light cylinder radius for ejectors, and R_A for propellers (see the details in Lipunov 1992).

Lets rewrite eq. (1) in terms of period and its derivative:

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

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

So, in eq. (2) 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. If μ is known, one can immediately obtain d from eq. (2) even from one determination of $\dot{p}$ (in that case it is better to use spin-down value). Uncertainties mainly depend on applicability of that simple model.

3 Illustration of the method

To illustrate the method, we apply it to the X-ray pulsar GRO J1008-57, discovered by BATSE (Bildsten et al., 1997). It is a 93.5 s X-ray pulsar, with the flux about $10^{-9} erg\,cm^{-2}s^{-1}$. A 33 day outburst was observed by BATSE in August 1993. The source was also observed by EXOSAT (Macomb et al., 1994) and ASCA (Day et al., 1995). ROSAT made possible to localize the source with high precision (Petre & Gehrels, 1994), and it was identified with a Be-system (Coe et al., 1994) with $\sim 135^d$ orbital period (Shrader et al. 1999). We use here only 1993 outburst, described in Bildsten et al. (1997).

The authors in Bildsten et al. (1997) show flux and frequency history of the source with 1 day integration. In the maximum of the burst errors are rather small, and we neglect them. Points with large errors were not used.

We used standard values of NS parameters: $I = 10^{45}\,g\,cm^2$, moment of inertia; $R = 10\,km$, NS radius; $M = 1.4 M_{\odot}$, NS mass.

On figures 1-2 we show observations (as black dots) and theoretical curves (in disk model, see Shrader et al. 1999, who proposed a disk formation during the outbursts, in contrast with Macomb et al. (1994), who proposed wind accretion) 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.

The best fit (both for spin-up and spin-down) gives $d \approx 5.8\,kpc$ and $\mu \approx 37.6 \cdot 10^{30}\,G \cdot cm^3$. It is shown on both figures. The distance is in correspondence with the value in Shrader et al. (1999), and such field value is not unusual for NS in general and for X-ray pulsars in particular (see, for example, Lipunov, 1992 and Bildsten et al., 1997). Tests on some other X-ray pulsars with know distances and magnetic fields also showed good results.

4 Discussion and conclusions

The method is only approximate and depends on several assumptions (disk accretion, specified values of M, I, R, etc.). Estimates of μ, for example, can be only in rough correspondence with observations of magnetic field B, if standard value of the NS radius, $R = 10\,km$ is used (see, for example, the case of Her X-1 in Lipunov 1992). Non-standard values of I and M can also make the picture more complicated.

The method can be, in principal, generalized for applications to wind-accreting systems, and to disk-accreting systems with complicated time behavior (when, for example, $\dot{p}$ changes appear with nearly constant flux, or even when $\dot{p}$ changes are uncorrelated with flux variations).

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 shown on the figures): $d \approx 8\,kpc$, $\mu \approx 37.6 \cdot 10^{30}\,G \cdot cm^3$ 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

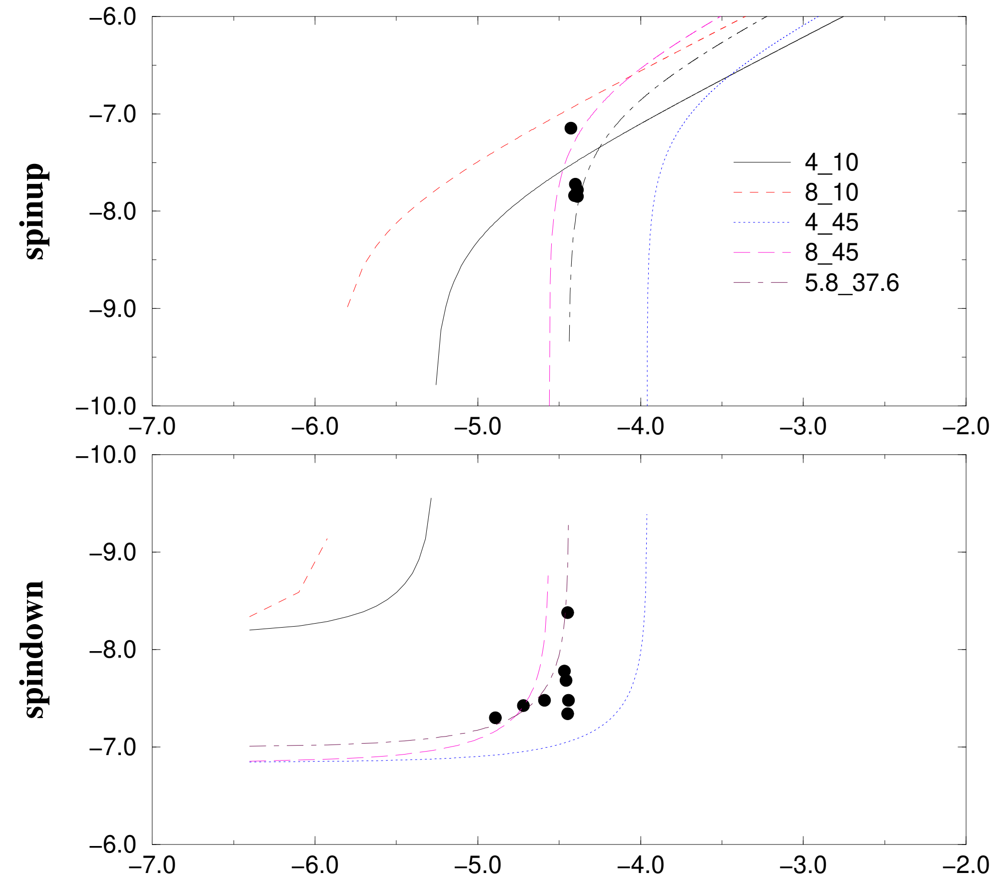

Figure 1: Dependence of period derivative, $\dot{p}$, on the parameter $p^{7/3}f$, $f-$ observed flux. Both axis are in logarithmic scale. Observations (Bildsten et al., 1997) are shown with black dots. Five curves are plotted for disk accretion for different values of distance to the pulsar and NS magnetic momentum. Solid curve: $d = 4\,kpc$, $\mu = 37.6 \cdot 10^{30}\,G \cdot cm^3$. Dashed curve: $d = 8\,kpc$, $\mu = 37.6 \cdot 10^{30}\,G \cdot cm^3$. Long dashed curve: $d = 5.8\,kpc$, $\mu = 10 \cdot 10^{30}\,G \cdot cm^3$. Dot-dashed curve: $d = 5.8\,kpc$, $\mu = 45 \cdot 10^{30}\,G \cdot cm^3$. Dotted curve (the best fit): $d = 5.8\,kpc$, $\mu = 37.6 \cdot 10^{30}\,G \cdot cm^3$.

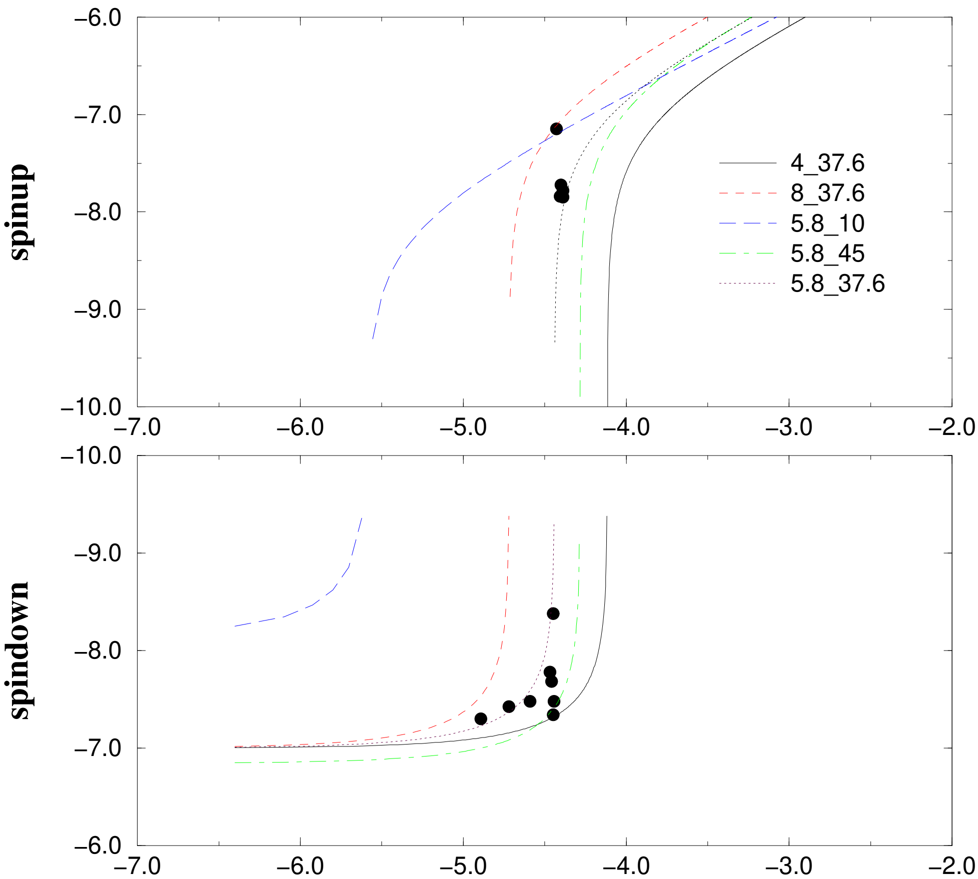

Figure 2: Dependence of period derivative, $\dot{p}$, on the parameter $p^{7/3}f$, $f-$ observed flux. Both are axis in logarithmic scale. Observations (Bildsten et al., 1997) are shown with black dots. Five curves are plotted for disk accretion for different values of distance to the pulsar and NS magnetic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

figures.

In some very uncertain situations, for example, when only X-ray observations without precision localization are available, our method can give (basing on several observational points, not one!, as, for example, in the case of maximum spin-down determination of magnetic momentum), rough, but useful estimates of important parameters: distance and magnetic momentum.

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