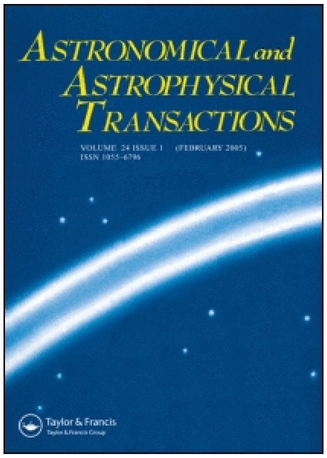

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METHOD OF ESTIMATING DISTANCES TO X-RAY PULSARS AND THEIR MAGNETIC FIELDS

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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 moment 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 moment approximately 4×10^{31} G cm^3, are obtained.

KEY WORDS Neutron stars, binary systems, X-ray pulsars

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 lie out of the range of necessary spectral sensitivity of devices, when the field are high), and the magnetic field can be estimated from period measurements (see Lipunov, 1982, 1992). Precise distance measurements are usually not available immediately after an X-ray discovery (especially, if error boxes, as for example in the BATSE case, are large). So, methods of their determination basecly only on X-ray observations can be useful.

Here we propose a simple method to determine the 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 moment of X-ray pulsars in disk or wind models, using known values of luminosity (the 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 the distance itself. The method is based on several measurements of the period derivative, $\dot{p}$, and the X-ray pulsar's flux, f. Fitting two parameters: distance, d, and magnetic moment, μ, one can obtain a 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):

$$\frac{\mathrm{d}I\omega}{\mathrm{d}t} = \dot{M}(GM\epsilon R_A)^{1/2} - k_t\frac{\mu^2}{R_c^3}, \tag{1}$$

where ω – spin frequency of a NS, M – its mass. I – its moment of inertia, R_A – 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-hand 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 the 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).

Let us rewrite eq. (1) in terms of the period and its derivative:

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

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

So, in eq. (2) we know all the 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 the spin-down value). Uncertainties mainly depend on the 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 and Gehrels, 1994), and it was identified with a Be-system (Coe *et al.*, 1994) with

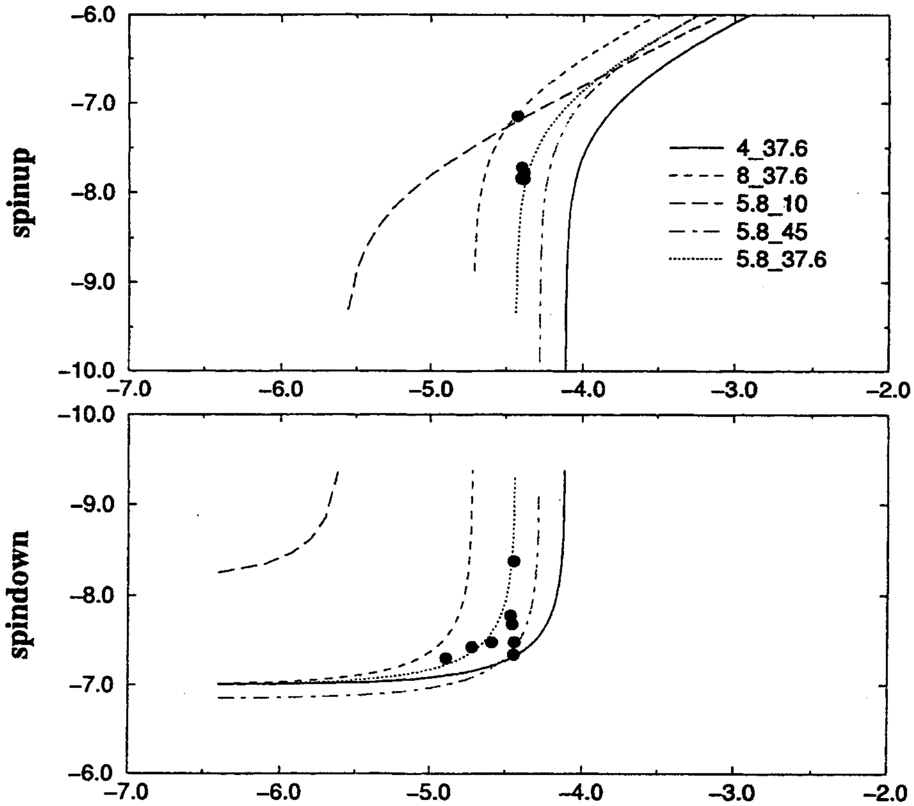

Figure 1 Dependence of period derivative, $\dot{p}$, on the parameter $p^{7/3}f$, f – observed flux. Both axes are in a logarithmic scale. Observations (Bildsten *et al.*, 1997) are shown with black dots. Five curves are plotted for disk accretion for different values of distance to the pulsar and NS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

$\sim 135^d$ orbital period (Shrader *et al.*, 1999). Here we use only the 1993 outburst, described in Bildsten *et al.* (1997).

The authors in Bildsten *et al.* (1997) show the 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; $M = 1.4M_{\odot}$, NS mass.

On Figures 1–2 we show observations (as black dots) and theoretical curves (in the disk model, see Shrader *et al.*, 1999, who proposed disk formation during the

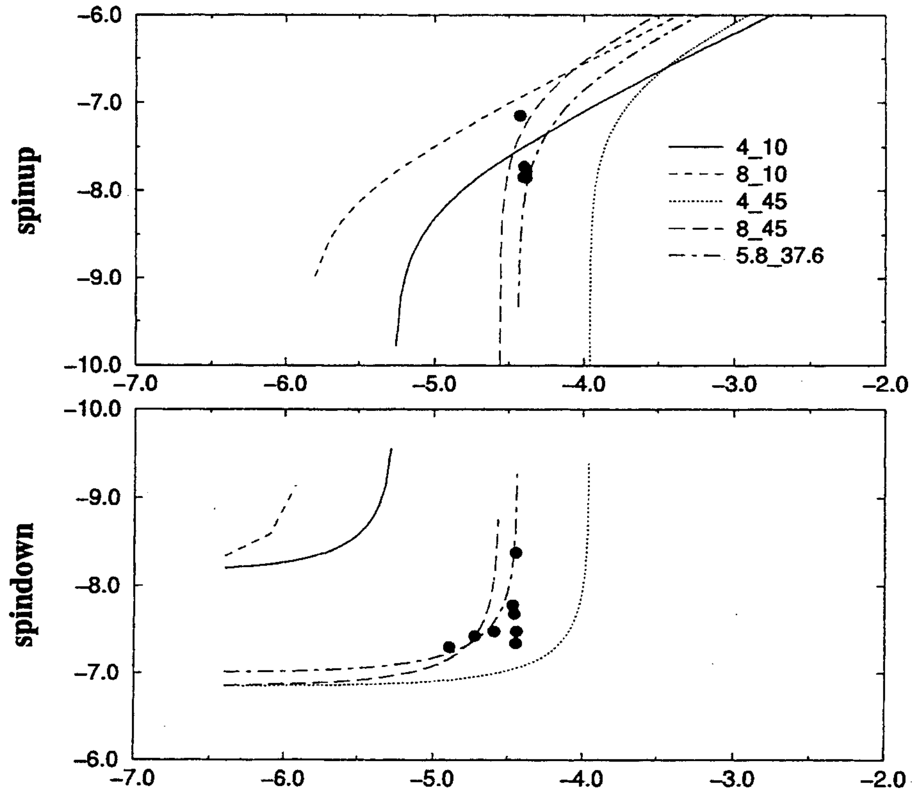

Figure 2 Dependence of period derivative, $\dot{p}$, on the parameter $p^{7/3}f$, f – observed flux. Both axes are in a logarithmic scale. Observations (Bildsten *et al.*, 1997) are shown with black dots. Five curves are plotted for disk accretion for different values of distance to the pulsar and NS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

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 moment, μ.

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. It is shown on both figures. The distance is in correspondence with the value in Shrader *et al.* (1999), and such a 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 known 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 the 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, $\mu \approx 37.6 \times 10^{30}$ 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 remark 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 of the magnetic field, as can be seen from the figures.

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

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