ARE MOST OF X-RAY BINARIES RECURRENT TRANSIENTS?

Janusz Ziółkowski
N. Copernicus Astronomical Center
Polish Academy of Sciences
ul. Bartycka 18, 00-716 Warsaw, Poland

INTRODUCTION

The aim of this paper is to argue that some day in the not-too-distant future one of the well-known X-ray pulsars, say, Cen X-3 (although better examples would be probably GX 301-2 or GX 1+4), will disappear from the X-ray sky. It will reappear again after some, say, tens of years and its pulse period will be then longer than it is now.

The basis for making such a prediction comes from an apparent conflict between the lifetimes of X-ray pulsars as deduced from the observed number of these objects and their association with massive X-ray binaries (Ziółkowski 1977, 1978) and the time scales of the observed spin-ups of these pulsars (Rappaport and Joss 1977, Schreier 1977, Sanford 1977). The latter time scales are found to be by 2 to 3 orders of magnitude shorter than the lifetimes. To remove this conflict, I suggested (Ziółkowski 1978) that X-ray pulsars are, in fact, recurrent transient sources with intermittent phases of: a) X-ray emission and the associated spin-up due to accretion and b) no accretion, no X-ray emission and spin-down due to magnetic braking (sometimes called "Kundt's mechanism"). In this picture, the increase of the pulsar period during phase b) roughly cancels out the decrease during phase a) and the average period remains equal to certain equilibrium value P_{eq} (period at which the outer edge of the magnetosphere rotates with the Keplerian velocity [Davidson and Ostriker 1973]). This "saw-tooth" model is, of course, a very crude one, but for our purposes in this paper we do not need to go into more sophisticated modelling (which is available) of either phase a) or b). I want only to demonstrate that this simple model recently found observational support in the behaviour of the transient X-ray pulsar A 0535-26 (Li et al. 1979). Furthermore, some quantitative estimates made using the above simple model do agree with the observed characteristics of A 0535-26.

LIFETIMES AND SPIN-UP TIME SCALES OF X-RAY PULSARS

Most of the X-ray pulsars are associated with massive X-ray binaries. Out of about 17 pulsars known so far, 13 are confirmed or

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suspected members of massive binaries and only two are known to be members of low-mass systems. For this reason, we may assume that the lifetimes of X-ray pulsars are comparable with the lifetimes of massive X-ray binaries. These latter lifetimes may be estimated by the following simple considerations. Present masses of the optical O-B components of massive X-ray binaries are $\gtrsim 15\ M_\odot$ (Conti 1978). Their original masses were probably $\gtrsim 30\ M_\odot$ (Ziółkowski 1977, 1978). The surface density of massive early-type stars in the disc of the galaxy is 9.4 kpc^{-2} for stars more massive than 15 $M_\odot$ and 2.4 kpc^{-2} for stars more massive than 30 $M_\odot$ (Ostriker et al. 1974). Roughly one-third of them are probably members of close spectroscopic binaries (Blaauw and van Albada 1974, Bohannan and Garmany 1978). Let us assume that in half of these binaries the companion is a compact object at a distance small enough to become a strong X-ray source during certain phase of binary evolution. Then we have in the galaxy no more than, respectively, 1000 ($M \gtrsim 15\ M_\odot$) or 250 ($M \gtrsim 30\ M_\odot$) potential massive X-ray binaries. These objects are now seen only as massive O-B stars, but are expected to become bright X-ray sources some day. Let us note that in the above considerations the history of the binary systems prior to the formation of the compact component is not important; what is important is the fact that the number of potential massive X-ray binaries cannot be larger than certain fraction of all massive O-B stars in the galaxy. Now, if we assume that about 50 out of $\gtrsim 150$ galactic X-ray sources are massive X-ray binaries, then we obtain, respectively, 20 and 5 for the ratio of main sequence lifetime of O-B component to the lifetime of X-ray emission phase of binary evolution. Recalling that main sequence lifetimes are 10^7 years for a 15 $M_\odot$ star and 5×10^6 years for 30 $M_\odot$ star (Ziółkowski 1972), we get finally 5×10^5 to 10^6 years for the typical lifetime of a massive X-ray binary. This implies that the typical lifetime of an X-ray pulsar should be also of this order.

On the other hand, the observed spin-up time scales of X-ray pulsars are much shorter, typically in the range 10^2 to 10^4 years (Rappaport and Joss 1977, Schreier 1977, Sanford 1977). The difference is 2 to 3 orders of magnitude. In the "saw-tooth" model, the slope of the small sections (phase a)) corresponds to the time scale of the spin-up, while the slope of the line $P = P_{eq}$ is comparable to the lifetime of the X-ray pulsar.

I should mention that the difference between the two time scales could be somewhat decreased by arguing that counts of massive stars are incomplete and that there is a concentration of these stars towards galactic center; e.g., van den Heuvel rather prefers 10^5 years as a typical lifetime of a massive X-ray binary. This is still much longer than a typical spin-up time scale. On the other hand (as we shall see in the next section), phase b) of the "saw-tooth" is typically longer than the phase a), which means that we observe less than half of the relevant X-ray sources (and perhaps only as little as one-tenth of them). This, of course, works in the opposite direction, i.e., makes the conflict of time scales more severe.

SPIN-UP AND SPIN-DOWN MECHANISMS

The change of the rotational period $P = 2\pi/\Omega$ of an X-ray pulsar can be described by the equation (Lamb et al. 1973, Rappaport and Joss 1977):

$$\frac{\dot{P}}{P} = \frac{\dot{M}}{I}\frac{dI}{dM} - \frac{\dot{M}}{I\Omega} h_a + \frac{T}{I\Omega} , \tag{1}$$

where I and M are the moment of inertia and the mass of the neutron star, h_a, is the component of the specific angular moment parallel to $\vec{\Omega}$ of the matter crossing the Alfvén surface, and T is the external (magnetic and viscous) torque. The first term on the right hand side of equation (1) is in most cases much smaller than either the second term (accelerating accretion torque) or the third term (braking magnetic torque). If we have the rotational period close to the equilibrium value ($P \approx P_{eq}$), then depending on whether the instantaneous value of P is slightly higher or lower than P_{eq}, we might encounter two different situations:

1) If $P \gtrsim P_{eq}$, then accretion is possible and the spinning-up torque is present. If we assume for simplicity that the external torque is negligible in such a situation, then the characteristic time scale of the spin-up is:

$$t_{su} = - \frac{P}{\dot{P}} = \frac{I\Omega}{\dot{M}} \frac{1}{R_A^2\,\Omega} = \frac{I}{\dot{M}\,R_A^2} , \tag{2}$$

where R_A is the radius of the magnetosphere, or (Rappaport and Joss 1977):

$$t_{su} = 1.4 \times 10^4 \; f_1 \; P^{-1} \; L_{37}^{-6/7} \tag{3}$$

$$f_1 = (\xi \; v_{ff}/v_r)^{-1/7} \; I_{45} \; \mu_{30}^{-2/7} \; R_6^{-6/7} \times \times (M/M_\odot)^{3/7} \tag{3A}$$

where P, L_{37}, I_{45}, μ_{30} and R_6 are (respectively): period, X-ray luminosity, moment of inertia, magnetic moment and radius of the neutron star in the units of (respectively): sec, 10^{37} erg sec^{-1}, 10^{45} g cm^2, 10^{30} Gs cm^3 and 10^6 cm. The quantity ξ is the fractional solid angle subtended at the neutron star by the infalling matter at the Alfvén surface and v_{ff}/v_r is the ratio of the free-fall velocity to radial drift velocity at the Alfvén surface. Let us note that in the case of $P = P_{eq}$, the magnetic pressure $B^2/8\pi$ should be balanced against $\rho\, v_r^2$ and this leads to a different dependence of f_1 on the ratio v_{ff}/v_r than

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found by Lamb et al. (1973) or Rappaport and Joss (1977). This remains true as long as $|P/P_{eq} - 1| \lesssim v_r/v_{ff}$.

The comparison with observational data demonstrated (Rappaport and Joss 1977) that the relation (3) is obeyed reasonably well by pulsars for which spin-up rates are known from the observations. This agreement strongly supports the view that: 1) X-ray pulsars are indeed rotating neutron stars accreting from the discs (Rappaport and Joss 1977) and that 2) their rotational periods are close to equilibrium periods (Lamb 1977).

2) If $P \lesssim P_{eq}$, then accretion is inhibited and the braking magnetic torque is present (Kundt's mechanism). This torque T can be roughly estimated (Kundt 1976, van den Heuvel 1977)* as equal to $\rho v_r^2 R_A \times \xi\, 4\pi R_A^2 \approx \dot{M} v_r R_A$. Equation (1) then yields the characteristic spin-down time scale:

$$t_{sd} = \frac{P}{\dot{P}} \approx \frac{I\Omega}{\dot{M} v_r R_A} = \frac{I}{\dot{M} R_A^2} \frac{v_K}{v_r}, \tag{4}$$

where v_K is the Keplerian velocity at the Alfvén surface. From equations (2) and (4) we have:

$$\frac{t_{sd}}{t_{su}} \approx \frac{v_K}{v_r} \tag{5}$$

If roughly constant period is to be maintained, this means that phase b) of the "saw-tooth" is longer than phase a) by a factor of the order of v_K/v_r (the theory of the accretion discs guess is that $v_K/v_r \sim$ 10 to 100). We should remember, however, that if the braking torque during phase a) is not negligible, then the time scale for the spin-up might be significantly longer and we have $t_{sd}/t_{su} < v_K/v_r$. The observations indicate that, indeed, in some cases, e.g. Her X-1 (Rappaport and Joss 1977), the external torques are not negligible during the accretion phase.

OBSERVATIONAL EVIDENCE

A 0535-26 is a recurrent transient X-ray pulsar, which was observed to undergo five outbursts since its discovery in April 1975 (Li et al. 1979). The interval between the outbursts was in the range 4 to 18 months and the typical active state (i.e., X-ray emission phase) was roughly by one order of magnitude shorter than the typical interval between the outbursts. During the active phases the pulsar was observed

*Davis et al. (1979) argued recently that Kundt's approach leads in general to serious overestimate of the braking torque, but their criticism does not apply to the case of $P \approx P_{eq}$.

to spin-up on the time scales ~ 70 to 160 years, but the average pulse period appeared to be constant on much longer time scale (Li et al. 1979). This indicates that during the inactive phases, slow-downs on the time scale ~ 10^3 years must occur that roughly cancel the spin-ups of the active phases. It is clear that the behaviour of this pulsar is quite consistent with the "saw-tooth" model. Now, let us make some quantitative estimates. The average pulse period of A 0535-26 is 103.8 sec and the typical X-ray luminosity is ~ 0.5 I_{Crab} (Li et al. 1979) which with the distance 2.8 kpc (Giangrande et al. 1978) gives L ~ 10^{37} erg sec^{-1}. The equation (3) gives then the theoretical spin-up time scale t_{su} ~ 140 years, in excellent agreement with the observations. The lack of the precise correlation between the observed spin-up time scales and the observed X-ray luminosities during the different outbursts (Li et al. 1979) might indicate that the braking torques and/or orbital effects are not quite negligible during the active states. The observed ratio of spin-down and spin-up time scales is ~ 10, again in good agreement with equation (5).

Another example of a pulsar which exhibits similar "saw-tooth" behaviour is perhaps Her X-1, which is known to be a transient source with active and non-active states lasting 1 to 15 years (Jones et al. 1973). Unfortunately, nothing is known about the possible spin-downs during the non-active states. We will have to wait perhaps 10 years or more before this information is available. If the "saw-tooth" model is correct in this case, then the observed t_{sd}/t_{su} is ~ 1, and the observed t_{su} (~ 3 x 10^5 years) is by an order of magnitude longer than the theoretical t_{su} calculated from the equation (3). This fact is probably due to significant braking torques acting during the active phase (Rappaport and Joss 1977) or due to the fact that a transition region between the disc and the magnetosphere is possibly not thin (Ghosh and Lamb 1978).

One might hope that more observational data relevant for the "saw-tooth" model will be available after the next outbursts of the transient X-ray pulsars A 1118-61 and 4 U 0115+63 are observed. These data might come sooner than the data from Her X-1.

Finally, I would like to comment on the fact that the theoretical equilibrium periods calculated for different pulsars often fail to agree with the observed periods. The theoretical formula for equilibrium period may be written as follows (van den Heuvel 1977, Lamb 1977):

$$P_{eq} = 2.7\ f_2\ L_{37}^{-3/7}\ \text{sec} \tag{6}$$

$$f_2 = (\xi\ v_{ff}/v_r)^{3/7}\ \mu_{30}^{6/7}\ R_6^{-3/7}\ (M/M_\odot)^{-2/7} \tag{6A}$$

It is clear that factor f_2 is much more sensitive to the intrinsic pulsar parameters than factor f_1 in the equation (3). Therefore, it is not surprising that the observational data fit the equation (3) (derived under the assumption $P \approx P_{eq}$) much better than equation (6) ($P = P_{eq}$) if both f_1 and f_2 are assumed to be constants.

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DISCUSSION FOLLOWING ZIOLKOWSKI and ERGMA AND TUTUKOV

Shu: I would like to make a mathematical comment. It might be useful to regard your $\dot{P}/P$ equation as a differential equation for a relaxation oscillator. Have you thought about what possible dependence $\dot{M}$ might have on P so that your equation has solutions ('sawtooth') characteristic of a relaxation oscillator?

Ziolkowski: No, I have not. Perhpas I should try. I know that different groups of people were discussing physical reasons which might make an equilibrium solution unstable, but, according to my knowledge, no one used the approach you suggest.

Mitrofanov: Matter accreted by a neutron star increases its angular momentum. On the other hand, its interaction with the rotating magnetosphere near the Alfven surface results in decreasing the angular momentum either because of outflow (the Illarionov-Sunyaev mechanism) or because of heating (Mitrofanov). So, the equilibrium between these two processes seems to occur - rather than the alternating spin-up and spin-down phases.

Sugimoto (to Eergma and Tutukov): According to our generalized theory of shell flashes, the pressure of the burning shell remains almost constant to a good approximation. Therefore the corresponding arrow in your Figure should bend somewhat to the left. I would like to say, however, that your picture and treatment appear to be very good.

Tutukov: Our simple model is sufficient to study main properties of thermonuclear bursts in the nuclear-fuel-rich envelope of an accreting neutron star. The model can be further developed to take into account, within the same degree of approximation, effects such as rotation, magnetic field, or the change in pressure at the bottom of the nuclear burning shell.