# Supersonic propeller spindown of neutron stars in wind-fed mass-exchange close binaries

N. R. Ikhsanov[⋆]

Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany

Central Astronomical Observatory of the Russian Academy of Sciences at Pulkovo, Pulkovo 65–1, 196140 Saint-Petersburg, Russia

**Abstract.** The supersonic propeller spindown of a neutron star moving in a strong stellar wind of its massive companion is discussed. I show that the supersonic propeller model presented by Davies & Pringle (1981) is self-consistent if the strength of the stellar wind of the normal companion is $\dot{M}_c \lesssim 2.2 \times 10^{18} \, (M_{\rm ns}/M_\odot) \, V_8 \, {\rm g\,s^{-1}}$. Under these conditions the model can be used for the interpretation of the long-period pulsars in Be/X-ray transients. The spin history of the neutron star in the long period Be/X-ray transient A0535+26 is considered.

**Key words.** accretion – propeller spindown – stars: close binaries – stars: neutron star – stars: Be/X-ray transients

## 1. Introduction

According to the present views on the evolution of inter-acting close binary systems (e.g. Lipunov 1992 and references therein), a newly formed neutron star is presumed to rotate rapidly, with a period of a fraction of a second. During the further system evolution, the rotational rate of the neutron star decreases, initially by the generation of the magneto-dipole waves and ejection of relativistic particles (*pulsar-like spindown*) and later by means of the interaction between the magnetosphere of the neutron star and the stellar wind of its companion (*propeller spindown*). When the spin period of the neutron star reaches the critical value (so called break period, $P_{\rm br}$) the accretion of material onto its surface begins and the star switches on as an X-ray pulsar.

This scenario can be applied to the interpretation of the observed periods of X-ray pulsars, provided the duration of the neutron star spindown epoch $t_{\rm sd}$, is smaller than the time, $t_{\rm ms}$, the companion star spends on the main sequence. In the particular case of massive X-ray close binaries which display pulses with long periods ($P_{\rm s} \gtrsim 100\,{\rm s}$), this condition implies the spindown rate of neutron stars during the previous epoch

$$\dot{P} \gtrsim 2 \times 10^{-13} \left[\frac{P_{\rm s}}{100\,{\rm s}}\right] \left[\frac{t_{\rm ms}}{10^7\,{\rm yr}}\right]^{-1}.$$

Since this value is essentially larger than the observed average spindown rate of neutron stars (see e.g. Taylor et al. 1993), the question about the mechanism which can be responsible for the required spindown rate arises.

A detailed investigation of the spindown epoch of neutron stars in massive wind-fed close binaries has been presented by Davies et al. (1979) and Davies & Pringle (1981, hereafter DP81). In particular, they have shown that the star magnetosphere during the propeller spindown epoch is surrounded by a hot, spherical quasi-static envelope. The interaction between the magnetosphere and the envelope leads to the deceleration of the rotation rate of the neutron star: the rotational energy loss by the star is convected up through the envelope by the turbulent motions and lost through its outer boundary. The neutron star remains in the propeller state as long as the energy input to the envelope due to the propeller action by the star dominates the radiative losses from the envelope plasma. According to DP81, this condition is satisfied if (i) the spin period of the star is smaller than the break period (a subsonic propeller case), and (ii) the strength of the normal companion stellar wind, $\dot{M}_c$, is smaller than the critical value $\dot{M}_{\rm max}$ (a supersonic propeller case).

The first item was discussed in my previous paper (Ikhsanov 2001a). In this letter I address the second item. I show that the value of $\dot{M}_{\rm max}$ is by a factor of $10^3$ larger than that estimated in DP81. After this correction, the duration of the spindown epoch proves to be essentially reduced. This fact significantly increases the number of long-period X-ray pulsars which can be interpreted within the canonical spindown scenario.

⋆ e-mail: ikhsanov@mpifr-bonn.mpg.de

## 2. Evaluation of $\dot{M}_{max}$

I consider a close binary system consisting of a fast rotating, magnetized neutron star and an O or B type main sequence companion which underfills its Roche lobe and loses mass in the form of stellar wind. The neutron star, which moves through the wind of its companion, is assumed to be in the state of *supersonic propeller*. This means that the magnetospheric radius of the neutron star exceeds its corotation radius, but is smaller than both the radius of the light cylinder and the accretion radius. Under these conditions the magnetosphere of the neutron star is surrounded by a turbulent spherical plasma atmosphere, in which the plasma pressure $p \propto R^{-3/2}$ and the plasma density $\rho \propto R^{-1/2}$. The temperature throughout the atmosphere is of the order of the free-fall temperature,

$$T(R) \simeq T_{ff}(R) = (GM_{ns}m_p)/(kR), \tag{1}$$

and the sound speed, $V_s$, as well as the velocity of turbulent motions, $V_t$, are of the order of the free-fall velocity

$$V_s \sim V_t \sim V_{ff}(R) = \sqrt{2GM_{ns}/R}. \tag{2}$$

Here $m_p$ is the proton mass, $k$ and $G$ are the Boltzmann and the gravitational constants, respectively, and $M_{ns}$ is the mass of the neutron star. The Mach number throughout the envelope is $M_{Mach} \equiv V_t/V_s \simeq 1$ (see for discussion DP81, p. 213).

The atmosphere is extended from the magnetospheric boundary up to the accretion radius of the neutron star

$$R_\alpha \equiv (2GM_{ns})/V_{rel}^2, \tag{3}$$

where $V_{rel}$ is the relative velocity between the neutron star and the wind of the normal companion. The plasma pressure at the outer edge of the atmosphere is equal to the ram pressure of the surrounding gas, which overflows the atmosphere as the neutron star moves through the stellar wind of its normal companion. The mass overflow rate, which is usually called the *strength of the stellar wind*, is

$$\dot{M}_c = \pi R_\alpha^2 \rho_\infty V_{rel},$$

where $\rho_\infty$ is the plasma density of the stellar wind just beyond the outer edge of the atmosphere.

As shown by Davies & Pringle, the supersonic propeller model remains self-consistent as long as the energy input to the atmosphere due to the propeller action by the neutron star dominates the radiative losses. This condition can be expressed in terms of the convective efficiency parameter (see DP81, p. 221) as

$$\Gamma = M_{Mach}^2 \left[ \frac{V_t t_{br}}{R} \right] = \frac{V_t^3 t_{br}}{V_s^2 R} \gtrsim 1. \tag{4}$$

Here $t_{br}$ is the bremsstrahlung cooling time:

$$t_{br} = 6.3 \times 10^4 \left[ \frac{T}{10^9\,\mathrm{K}} \right]^{1/2} \left[ \frac{n}{10^{11}\,\mathrm{cm}^{-3}} \right]^{-1}\,\mathrm{s}, \tag{5}$$

and $n$ is the number density of the atmospheric plasma, which at the outer radius of the atmosphere can be evaluated as

$$n(R_\alpha) \simeq \frac{\dot{M}_c}{\pi R_\alpha^2 V_{rel} m_p}. \tag{6}$$

Taking into account that in the supersonic propeller case $V_s \sim V_t \propto R^{-1/2}$, $\rho \propto R^{-1/2}$, and $T \propto R^{-1}$, one finds $\Gamma \propto R^{-3/2}$. This indicates that the cooling dominates first at the outer radius of the atmosphere and thus the model presented above is consistent if $\Gamma(R_\alpha) \gtrsim 1$.

Combining Eqs. (1)–(6) I find this condition to be satisfied if the strength of the normal companion stellar wind is $\dot{M}_c \lesssim \dot{M}_{max}$, where

$$\dot{M}_{max} = 2.2 \times 10^{18}\, m\, V_8\,\mathrm{g\,s}^{-1}. \tag{7}$$

Comparing this result with Eq. (4.9) in DP81, one can conclude that the value of the upper limit to the strength of the stellar wind derived by Davies & Pringle is underestimated by a factor of 1000.

## 3. Discussion

The normal companions of more than half of the presently known long period X-ray pulsars are Be/Oe stars (see e.g. Liu et al. 2000). The stellar wind of these stars is not homogeneous. It consists of a high velocity low density component at high latitudes, and a low velocity high density circumstellar disk at the equatorial plane. Since $\dot{M}_c \propto \rho V_{rel}^{-1}$ the strength of the stellar wind at the equatorial plane is essentially larger than that at high latitudes. This particular property plays the key role in the interpretation of Be/X-ray transients: the powerful $(L_x \sim 10^{36} \div 10^{38}\,\mathrm{erg\,s}^{-1})$ X-ray outbursts observed in these systems are associated with the interaction between the neutron star and the circumstellar disk surrounding its Be companion (see e.g. Negueruela 1998 and references therein). In the frame of this model, the strength of the stellar wind in the disk is $\dot{M}_c \sim 10^{16}$–$10^{18}\,\mathrm{g\,s}^{-1}$ that is almost three orders of magnitude larger than $\dot{M}_{max}$ derived by DP81. On this basis, Be/X-ray binaries were excluded from the list of systems in which the long periods of neutron stars can be interpreted within the spindown scenario presented by Davies & Pringle.

However the situation becomes completely different after applying the correction to the value of $\dot{M}_{max}$ presented in this letter. Then the model of supersonic propeller constructed by Davies & Pringle proves to be valid even if the neutron star is situated in a strong stellar wind moving through the circumstellar disk of its Be/Oe companion. Furthermore, the spindown time scale of neutron stars situated in a strong stellar wind is significantly smaller than that of neutron stars in a weak stellar wind. That is why the number of long-period pulsars which can be analyzed within the canonical spindown scenario essentially increases.

As an illustration, I consider a particular example of one of the best studied Be/X-ray transients A0535+26. This system consists of a $15\,M_\odot$ Be star and the magnetized neutron star ($\mu \simeq 10^{31}\,\mu_{31}\,\mathrm{G\,cm^3}$) rotating with the period $P \simeq 103\,P_{103}$ s. The rotational axis of the normal companion is almost parallel to the orbital axis of the system, so the trajectory of the neutron star lies in the plane of the circumstellar disk surrounding the Be star. The average value of the relative velocity between the neutron star and the surrounding material is $V_{\mathrm{rel}} \simeq 10^7\,V_7\,\mathrm{cm\,s^{-1}}$ and the average strength of the stellar wind is $\dot{M}_c \simeq 10^{17}\,\dot{M}_{17}\,\mathrm{g\,s^{-1}}$ (see for discussion Ikhsanov 2001b and references therein).

Under these conditions, $\dot{M}_{\mathrm{max}} \simeq 2 \times 10^{17}\,\mathrm{g\,s^{-1}}$ is larger than $\dot{M}_c$ and hence the supersonic propeller model of DP81 can be used. Following this model, the duration of the spindown epoch of the neutron star in A0535+26 can be expressed as

$$\tau_{\mathrm{sd}} = \tau_{\mathrm{a}} + \tau_{\mathrm{c}} + \tau_{\mathrm{d}} \simeq 6 \times 10^6\ \mathrm{yr}, \tag{8}$$

where $\tau_{\mathrm{a}}$ is the time scale of the pulsar-like spindown, which I evaluate following DP81 (see Eqs. (3.3.5) and (3.3.6) in their paper) as

$$\tau_{\mathrm{a}} = 4.8 \times 10^6\ \mu_{31}^{-3}\ \dot{M}_{17}^{-1/2}\ I_{45}\ V_7^{-1}\ \mathrm{s}, \tag{9}$$

$\tau_{\mathrm{c}}$ is the time scale of the supersonic propeller spindown, which according to DP81 (see Eqs. (3.1.7) and (3.3.6) in their paper) is

$$\tau_{\mathrm{c}} \simeq 10^6\ \mu_{31}^{-1}\ \dot{M}_{17}^{-1/2}\ I_{45}\ V_7^{-1}\ \mathrm{s}, \tag{10}$$

and $\tau_{\mathrm{d}}$ is the time scale of the subsonic propeller spindown, which can be estimated according to Ikhsanov (2001a: Eq. (10)) as

$$\tau_{\mathrm{d}} \simeq 10^3\ \mu_{31}^{-2}\ m\ I_{45}\ P_{103}\ \mathrm{yr}. \tag{11}$$

$I_{45}$ is the moment of inertia of the neutron star expressed in units $10^{45}\,\mathrm{g\,cm^2}$.

The break period, at which the neutron star in A0535+26 switches its state from subsonic propeller to accretor, can be evaluated using Eq. (8) in Ikhsanov (2001a) as

$$P_{\mathrm{br}} \simeq 100\ \mu_{31}^{16/21}\ \dot{M}_{17}^{-5/7}\ m^{-4/21}\ \mathrm{s}. \tag{12}$$

Thus, in the frame of the canonical spindown scenario, the neutron star in A0535+26 is expected to decelerate its rotation, on the time scale of the main-sequence lifetime of its companion, to the presently observed spin period.

## 4. Conclusion

Davies & Pringle (1981) is underestimated the upper limit to the strength of the stellar wind at which the supersonic propeller model is self-consistent by a factor of $10^3$. The incorporation of the re-estimated value into their spindown scenario shows that the propeller mechanism can be responsible for the origin of the long-period X-ray pulsars in Be/X-ray transients. Application of this scenario to particular objects will be presented in a forthcoming paper.

## References

Davies, R. E., Fabian, A. C., & Pringle, J. E. 1979, MNRAS, 186, 779

Davies, R. E., & Pringle, J. E. 1981, MNRAS, 196, 209 (DP81)

Ikhsanov, N. R. 2001a, A&A, 368, L5

Ikhsanov, N. R. 2001b, A&A, 367, 549

Lipunov, V. M. 1992, Astrophysics of neutron stars (Springer-Verlag, Heidelberg), Chap. 11

Liu, Q. Z., van Paradijs, J., & van den Heuvel, E. P. J. 2000, A&AS, 147, 25

Negueruela, I. 1998, A&A, 338, 505

Taylor, J. H., Manchester, R. N., & Line, A. G. 1993, ApJS, 88, 529

Letter to the Editor