Spin-up/spin-down of neutron star in Be-X-ray binary system GX 304-1

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ABSTRACT

We analyze spin-up/spin-down of the neutron star in Be X-ray binary system GX 304-1 observed by Swift/XRT and Fermi/GBM instruments in the period of the source activity from April 2010 to January 2013 and discuss possible mechanisms of angular momentum transfer to/from the neutron star. We argue that the neutron star spin-down at quiescent states of the source with an X-ray luminosity of $L_x \sim 10^{34}$ erg s$^{-1}$ between a series of Type I outbursts and spin-up during the outbursts can be explained by quasi-spherical settling accretion onto the neutron star. The outbursts occur near the neutron star periastron passages where the density is enhanced due to the presence of an equatorial Be-disc tilted to the orbital plane. We also propose an explanation to the counterintuitive smaller spin-up rate observed at higher luminosity in a double-peak Type I outburst due to lower value of the specific angular momentum of matter captured from the quasi-spherical wind from the Be-star by the neutron star moving in an elliptical orbit with eccentricity $e \gtrsim 0.5$.

Key words: X-ray:binaries – (stars:)pulsars:individual – GX 304-1

1 INTRODUCTION

In the early 1970s, the phenomenon of pulsating X-ray source due to accretion of matter onto a magnetized rotating neutron star in a binary system was predicted (e.g. Shvartsman 1971) and discovered by UHURU satellite (Giacconi et al. 1971). Over the following decades a lot of observational properties of X-ray pulsars have been established, including measurements of spin-up and spin-down rates from accurate timing analysis (see Bildsten et al. 1997, for a review) and measurements of cyclotron resonance features in their X-ray spectra (see Caballero & Wilms 2012, for a recent summary). The latter suggests the presence of $10^{12} - 10^{13}$ G magnetic fields near the surfaces of accreting neutron stars. The measurements of spin-up/spin-down rate in X-ray pulsars reflect the torques applied to the neutron star by accreting matter and can be served as a tool to investigate the interaction of accreting plasma with magnetospheres of rotating neutron stars.

Most of the observed X-ray pulsars (XPSRs) reside in massive binary systems, with early-type optical OB- or Be-companions, and belong to the class of high-mass X-ray binaries (HMXB) (see, e.g., Shvartsman 1971, for a recent review). Formation of HMXBs naturally follows from evolution of massive binary stars (Bhattacharya & van den Heuvel 1991). Accretion onto a neutron star (NS) in such a system occurs from a non-stationary stellar wind of massive optical companions. If the specific angular momentum of gravitationally captured matter is sufficiently high, an accretion disc can be formed around the neutron star, otherwise accretion can proceed quasi-spherically (see e.g. Burnard et al. 1983 and Shakura et al. 2012, 2014a for recent discussion of different regimes of a quasi-spherical accretion onto NSs).

Measurements of pulse period variations in such systems can provide clues for understanding different processes responsible for the angular momentum transfer, the structure of the accretion flows in binary systems, their dependence on system’s parameters, X-ray luminosity, etc. This fact was recognized practically immediately after the discovery of X-ray pulsars (Schreier et al. 1972) and first observations of their pulse period variations (see, e.g. Giacconi et al. 1972, Fabbiano & Schreier 1977, Becker et al. 1978). Different physical mechanisms for torques acting on the magnetized neutron star in X-ray pulsars have been proposed to explain these variations (see, e.g. Ghosh & Lamb 1979, Lovelace et al. 1995, Wang 1995, Rappaport et al. 2004).
Kluźniak & Rappaport 2007; Shakura et al. 2013a). Observational data suggest that different mechanisms can operate in different objects, and even in one and the same object under different conditions.

Strong progress in observational X-ray astronomy in the last decade with modern space observatories and instruments, especially with all-sky X-ray facilities, like Swift, MAXI, Fermi/GBM, RXTE/ASM allowed us to monitor states of many X-ray sources and measure their pulse periods with a high precision. These data can be used to test and verify different theories of the angular momentum transfer in binary systems. Among X-ray pulsars, binary systems with Be-companions form a subclass showing significant variations of the source luminosity and pulse period. The stellar wind from rapidly rotating Be-stars is strongly asymmetric and frequently forms equatorial excretion disc. In addition, such systems typically have a large orbital eccentricity resulting from relatively recent supernova explosion. The presence of these two features (equatorial disc and large eccentricity) enables the matter to accrete onto the neutron star directly from the equatorial Be-star disc during its orbital motion near the periastron passage. The enhanced accretion is accompanied by a short (compared to the orbital period) increase in the observed X-ray flux by several orders of magnitude (typically up to ~ $10^{37}$ erg s$^{-1}$), which is identified as a Type I outburst. In addition to such events, there are Type II outbursts, which are due to a non-stationary increase of amount of matter in the circumstellar disc around the Be-star, which can occur at any orbital phase. The duration of Type II outbursts varies from weeks to months, during which the source X-ray luminosity can reach the Eddington limit ($\sim 10^{38}$ erg s$^{-1}$). More details about X-ray pulsars in Be-systems can be found in the recent review of Reid 2011.

During such outbursts, in addition to the X-ray luminosity increase, the angular momentum from the equatorial disc around the Be-star is transferred to the compact object, leading to the neutron star spin-up. However, the angular momentum supplied only when the neutron star is sufficiently close to the optical companion, and after some time the accretion rate starts decreasing and even can vanish altogether. From that moment on the gradual spin-down of the neutron star is observed as a rule (see, e.g., site of the Fermi/GBM data http://gammaray.nsstc.nasa.gov/gbm/science/pulsars/). Obviously, the observed characteristics of X-ray pulsars, including outbursts and pulse period variations, and the corresponding mechanisms of the angular momentum transfer depend upon properties of the binary system and the neutron star itself, including the orbital period, eccentricity, magnetic field and spin frequency of the neutron star, etc.

In this paper, we examine the spin evolution of the X-ray pulsar GX 304-1 with the aim to understand the angular momentum transfer mechanism to the neutron star. GX 304-1 (other names are 4U 1258-61, 2S 1258-613) is the X-ray pulsar with a period of $\approx 272$ sec (Huckle et al. 1977; McClintock et al. 1977), which is located in the direction of Coalsack Nebula, in a highly optically opaque region of the sky. GX 304-1 has been identified with a Be-star system (Mason et al. 1978), which is located at a distance of $d \approx 2.4$ kpc (Parkes et al. 1980). Using observations by the Vela 5B satellite, Priedhorsky & Terrell 1983 discovered a 132.5-day periodicity of outbursts due to the orbital motion of the neutron star. After approximately 30 years of quiescence, at the end of 2009 the source renewed the outburst activity that lasted until the beginning of 2013. Observations of the RXTE and Suzaku satellites during the outburst in August 2010 allowed Yamamoto et al. 2011 to discover the cyclotron resonance scattering feature in the source spectrum at around $\approx 54$ keV and to estimate the neutron star surface magnetic field $B \approx 4.7 \times 10^{12}$ G. Timing and spectral analysis of RXTE/PCA observations of this outburst by Devasia et al. 2011 discovered a QPO feature at frequency $\approx 0.125$ Hz presented in the power-density spectrum with an rms amplitude increasing from ~ 3% at 7 keV to ~ 9% at 40 keV, which was interpreted as evidence for an accretion disc existing during the outburst. An analysis of the INTEGRAL observations of the source during its outburst in January - February 2012 by Klochkov et al. 2012 revealed a positive correlation of the cyclotron line centroid energy with X-ray flux variations, suggesting the local sub-Eddington regime of accretion near the NS surface Staubert et al. 2007. Thus, observations of the X-ray pulsar GX 304-1 offer good opportunity to study different possible mechanisms of the neutron star spin-up/spin-down.

2 DATA REDUCTION AND OBSERVATIONAL RESULTS

In the period from April 2010 to January 2013 GX 304-1 demonstrated a series Type I outbursts corresponding to periastron passages with the binary orbital period $P_b \approx 132.5$ days. During these outbursts GX 304-1 was monitored in hard X-rays (15-50 keV) by the Swift/BAT instrument (Krimm et al. 2013; http://swift.gsfc.nasa.gov/results/transients/weak/GX304-1); it was also observed several dozen times with the Swift/XRT telescope in soft X-rays < 10 keV (Burrows et al. 2005). Variations of its pulse period have been recorded with the Fermi/GBM monitor (http://gammaray.msfc.nasa.gov/gbm/science/pulsars/lightcurves/gx304m1.html). In the present paper, we made use of all of these data to examine spin-up/spin-down behavior of the neutron star in GX 304-1.

The source hard X-ray light curve measured by the Swift/BAT telescope is shown in Fig. 1. Seven giant outbursts (below referred to as #1-#7), where the source intensity reached about 2 Crabs in the 15–50 keV energy band, are clearly seen in the light curve. Note here that the pulsar’s X-ray luminosity in the outbursts increases...
by almost three orders of magnitude in ~ 10 days, suggesting a very quick and strong increase in accretion rate onto the neutron star. Outbursts profiles from #1 to #5 are very similar – they have a nearly symmetric shape and their maxima are separated by the orbital period (indicated by vertical red lines in Fig.1). One of such outbursts (#1) is presented in the left insertion in the figure. At the same time, the profiles of two outbursts (#6 and #7) are completely different – they have a double-peak structure with a lower precursor and dominating second peak; in addition, the orbital phase corresponding to maxima of outbursts #1-#5, here occurs at the minima between the outburst peaks (see the right insertion in Fig.1). Possible reasons of such drastic changes in the outburst profile may be connected with the evolution and changes in the equatorial disc around the Be-star and will be discussed below.

The corresponding behavior of the source luminosity in the 2 – 10 keV energy band according to the XRT telescope data is presented in Fig.2 and Table 1. The reduction of data obtained by the XRT telescope was done using the standard software FTOOLS v6.15. When no XRT observations were available, to estimate a peak X-ray flux in the 2-10 keV we used the Swift/BAT 15-50 keV flux and assumed the spectral shape $E^{−2}\exp(−E/E_f)$ with parameters $\Gamma = 1, E_f = 17$ keV from Klochkov et al. (2014).

As mentioned above, the source intensity increased by about three orders of magnitude during outbursts in comparison with the quiescent state. It is necessary to note that in contrast to the neutron star spin-up, processes of the neutron star spin-down in X-ray binaries are still poorly understood. In wind-fed X-ray pulsars, the spin-down torque depends on the source luminosity and other parameters (Shakura et al. 2012, 2013a, Postnov et al. 2014). It is seen from Fig.2 and Table 1 that in the low states between outbursts the 2 – 10 keV luminosity of GX 304-1 drops down to a few × 10$^{34}$ erg s$^{-1}$. Note that GX 304-1 was observed with the Swift/XRT telescope starting from April 2005, i.e. long before the beginning of its outburst activity, and during these observations the source luminosity stayed virtually at the same low level. Thus we can conclude that the lowest observed (at the moment) luminosity for the source GX 304-1 is about $(1 – 2) \times 10^{34}$ erg s$^{-1}$ in the 2-10 energy band.

The observed luminosity of GX 304-1 measured by the Swift/XRT instrument in the 2-10 keV energy band. Note a big power difference between the outbursts and quiescent states.

The evolution of the neutron star spin frequency in GX 304-1 in the period from August 2010 to March 2013 as obtained from the Fermi/GBM monitor data is presented in Fig.3. As seen from Figs.1 and 3, the neutron star exhibits regular spin-up episodes during Type I outbursts when the source flux is high enough for X-ray pulsations to be detected. The neutron star spin-up behaviour is different during different outbursts – typically it is nearly constant for single-peak Type I outbursts (the left insertion in Fig.3 for outburst #1) and have an obvious break for the double-peak outburst #7 (the right insertion in Fig.3).

To determine the spin-up rate in the outbursts, the linear trends of the spin frequency changes were approximated with the least squares method. Thanks to high quality of the Fermi/GBM data these measurements can be done with good accuracy (see Table 1). It is seen from Table 1 that the spin-up rate during single-peak Type I outbursts was approximately the same $\dot{\nu}_su \approx 25 \times 10^{-8}$ Hz d$^{-1}$. In contrast, the double-peak outburst #7 demonstrates two different values of the spin-up rate: while during the first, weaker, peak the spin-up rate was approximately the same (within the errors) as during previous single-peak outbursts, it was about three times as low during the second, higher, peak (see Fig.3 and Table 1).

Spin-down rate estimates during the low states of the source between the outbursts are not so obvious and straightforward, because no X-ray pulsations were detected by the Fermi/GBM monitor. We can only compare the neutron star spin frequency at the end of the spin-up phase of one outburst with that measured at the beginning of the next outburst.

It is interesting to note that at the beginning of most of the outbursts short episodes of the continuing spin-down can be seen. This can be easily understood, because in order to change the neutron star spin-down rate during the low states of the source. Taking into account uncertainties in the distance measurements to GX 304-1 (Parkes et al. 1981, Menzies 1981), in our estimations we use the source luminosity as derived from the XRT fluxes.

Figure 2. Spin frequency evolution of GX 304-1 as measured by the Fermi/GBM monitor. Note that the double-peak outburst #7 is characterized by two different spin-up rates.

Figure 3. Spin frequency evolution of GX 304-1 as measured by the Fermi/GBM monitor. Note that the double-peak outburst #7 is characterized by two different spin-up rates.
tron star rotation from spin-down to spin-up a certain amount of star inertia. Angular momentum should be transferred to overcome the neutron errors) and are about one order of magnitude (by the absolute value) of the Be-star. Correspondingly, the accretion rate onto the neutron star that deter-

\[ \dot{M}_\text{eq} \approx 940|\mu|^{12/11} \left( \frac{P_b}{10^4} \right) M_{16}^{-4/11} \nu_b^4, \]

where \( \mu_{30} \equiv \mu/10^{30} \text{[G cm}^3\text{]} \) is the neutron star dipole magnetic moment related to the surface equatorial dipole magnetic field as \( \mu \approx B R^2/2 \) (\( R \) is the neutron star radius assumed to be 10 km), \( \dot{M}_b = M/10^{10} \text{[g s}^{-1}\text{]} \) is the accretion rate onto the neutron star related to the accretion X-ray luminosity as \( L = 0.1 M c^2, \) \( P_b \) is the binary orbital period and \( \nu_b \equiv v/10^8 \text{[cm s}^{-1}\text{]} \) is the characteristic stellar wind velocity. As stressed in Shakura et al. (2014a), due to very strong dependence upon the stellar wind velocity \( (P_{\text{eq}} \propto v^4) \), this formula, when the neutron star magnetic field \( \mu \) is known, can be rather used to estimate the velocity of the stellar wind captured by the neutron star:

\[ \nu_b = 0.57 M_{16}^{3/11} \mu_{30}^{-3/11} \left( \frac{P_{\text{eq}}/1000}{P_b/10^4} \right)^{1/4}. \]

Substituting for GX 304-1 \( \mu_{30} \approx 2.34 \), \( P_b = 1325 \text{ d}, M_{16} \approx 0.02 \) (for the low-state, where the source spends most of the time; this, however, is not very important in view of very weak dependence on \( M \) in Eq. (3)), we find \( \nu_b \approx 0.2 \). This low wind velocity is typical for quasi-spherical winds observed in Be-stars (Water et al. 1988). We also note that the QPOs at \( \approx 0.125 \text{ Hz} \) reported by Devias et al. (2011) during outburst \#1 may be due to the accretion rate variations with typical free-fall time from the Alfvén radius \( \approx 3 \times 10^9 \text{ cm} \) in the quasi-spherical accretion case. Indeed, usually the presence of QPOs is interpreted as an indication of the accretion disc. For example, in the popular beat-frequency model (Alpar & Shaham 1983), the QPO frequency is treated as the beat frequency between the magnetospheric rotation and the matter rotation at the inner disc radius. In the quasi-spherical case, there is the characteristic time related to the Rayleigh-Taylor instability at the magnetospheric boundary, which is of the order of the free-fall time of matter at the magnetosphere. Therefore, one can expect the characteristic variability in X-ray flux with this time, i.e. at the frequency corresponding to the free-fall time and its harmonics. QPOs arising due to matter entering the rotating neutron star magnetosphere via instabilities were discussed in Jernigan et al. (2000).

The characteristic parameters and radii pertinent to neutron star spin-up/spin-down in GX 304-1 are summarized in Table 2.

### 3 QUASI-SPHERICAL ACCRETION IN GX 304-1

The observed spin-up/spin-down behavior of GX 304-1 can be readily occur in the frame of theory of quasi-spherical accretion from stellar wind of the optical companion. The settling accretion is expected to occur in wind-fed accreting neutron stars with sufficiently slow spin periods at X-ray luminosities \( L_x < 4 \times 10^{36} \text{ erg s}^{-1} \). The basic difference of this regime from the classical Bondi-Hoyle case is that the matter flow to the neutron star is controlled by the development of the Rayleigh-Taylor instability in a boundary layer above the magnetosphere, which depends on the cooling time \( t_{\text{cool}} \) of accreting plasma. The mean plasma radial infall velocity in this regime is less than the free-fall velocity: \( u_c = u_{ff} f(u), \) where \( f(u) \approx (t_{\text{cool}}/t_{ff})^{1/3} < 0.5 \) (\( t_{ff} = R/u_{ff} \) is the free-fall time). Correspondingly, the accretion rate onto the neutron star that determines the observed X-ray luminosity is \( \dot{M} \approx M_b f(u), \) where \( M_b \) is the classical Bondi-Hoyle rate. See Shakura et al. (2012, 2014a) for the detailed derivation, characteristics and applications to spin-up/spin-down of slowly rotating low-luminosity X-ray pulsars and Shakura et al. (2014b) for explanation of bright flares in Super-giant Fast X-ray Transients.

The X-ray luminosity of GX 304-1 stays most of the time at a low level of a few \( \times 10^{34} \text{ erg s}^{-1} \), and the peak luminosities during the most of Type I outbursts is less than \( 10^{37} \text{ erg s}^{-1} \) (see Fig. 11.2), which favors the settling accretion regime. Next, the observed spin period \( P = 275 \text{ s} \) of the neutron star in GX 304-1 with the standard surface magnetic field value, as inferred from cyclotron line measurements, \( B = 4.7 \times 10^{12} \text{ G} \), is consistent with the expected equilibrium period of quasi-spherically accreting neutron stars in the regime of settling accretion

\[ P_{\text{eq}} \approx 940|\mu|^{12/11} \left( \frac{P_b}{10^4} \right) M_{16}^{-4/11} \nu_b^4. \]

### 3.1 Spin-down between Type I outbursts

In the frame of the quasi-spherical settling accretion theory Shakura et al. (2012, 2014a), the equilibrium X-ray luminosity at which accretion torques acting on the neutron star with parameters

\[ \mu_{30} \approx 2.34, \text{ } P_b = 1325 \text{ d}, \text{ } M_{16} \approx 0.02 \]

Using \( B = 10^{12} \text{[G]} E_{\text{eq}}/(11.6 \text{keV}) \) and neglecting gravitational redshift.
as in GX 304-1 vanishes, is $L_{\text{sd}} \sim 10^{36} \text{ erg s}^{-1}$. At lower X-ray luminosities, when $M_{\text{sd}} \propto \dot{M}_{\text{eq}} \approx 10^{16} \text{ g s}^{-1}$, the spin-down rate is

$$\dot{\omega}_{\text{sd}} \approx -10^{-8} [\text{Hz d}^{-1}] \Pi_{\text{sd}}^{13/11} M_{\text{eq}}^{11/11} \left( \frac{P_{\text{b}}}{100 \text{ s}} \right)^{-1}$$

(3)

where $\Pi_{\text{sd}} = (1 - z/Z)KK_1K_3^{-3/11}$ is a combination of dimensionless parameters of the theory (in notations of Eq. (42) in Shakura et al. 2014a)). The physical sense of these parameters is as follows: $K \sim 1$ is a geometrical factor due to integrating the magnetic torques over the magnetospheric surface, $K_1 \sim 1$ is a factor that takes into account the difference of the realistic magnetospheric shape from the sphere and the characteristic scale of turbulent motions near the magnetosphere (in units of the Alfvén radius $R_A$), $\zeta < 1$ is the dimensionless thickness of the boundary layer (in units of $R_A$), $0 < z < 2/3$ is the dimensionless specific torque applied to the neutron star in units of $MR_A^2 \dot{\omega}$ due to matter falling from different parts of the magnetosphere, $Z \sim KK_1K_3f(u)$ is the dimensionless coupling coefficient describing of the angular momentum transfer to the magnetosphere in the settling accretion regime. This combination of parameters should not be strongly different in different objects (see Shakura et al. 2014a, Postnov et al. 2014 for more details). For parameters of GX 304-1 and $M_{\text{eq},\text{low}} \approx 0.02$, Eq. (3) yields the observed value $\dot{\omega}_{\text{sd}} \approx -2.5 \times 10^{-8} \text{ Hz d}^{-1}$ for $\Pi_{\text{sd}} \approx 4.6$. Note that this value is reasonably close to the value of $\Pi$ derived from the independent analysis of equilibrium wind-accreting X-ray pulsars Vela X-1 and GX 301-2 (Shakura et al. 2012, 2014a).

$$\dot{\omega}_{\text{sd}} \approx -10^{-9} [\text{Hz d}^{-1}] \Pi_{\text{sd}}^{13/11} M_{\text{eq}}^{11/11} \left( \frac{P_{\text{b}}}{10 \text{ d}} \right)^{-1}$$

(4)

where the dimensionless parameter of the theory $\Pi_{\text{sd}} = KK_1K_3^{-7/11}$ (see Eq. (41) in Shakura et al. 2014a)). Taking $\Pi_{\text{sd}} = 4.6$ as inferred from the analysis of the spin-down between the outbursts (see the previous paragraph), we obtain $\dot{\omega}_{\text{sd}} \approx 25 \times 10^{-8} \text{ Hz d}^{-1}$, as actually observed. Therefore, we conclude that the observed spin-up rate in Type I outbursts #1-#6, and the spin-down rate at low states between the outbursts are in agreement with the settling accretion theory predictions for GX 304-1.

### 3.3 Double-peak outburst #7

The double-peak outbursts #6 and #7 (see Fig. 3 right inset for #7) make the special case. Indeed, unlike previous Type I outbursts, these outbursts show a double-peak structure, mostly pronounced in outburst #7. This outburst consists of a fainter precursor that peaked ~ 10 days before the periastron passage and lasted ~ 10 days, and was followed by a brighter main flare that peaked ~ 15 days after the periastron passage. The most enigmatic feature is that the spin-up rate during the weaker precursor was ~ 3 times as high as that of the brighter second flare. This is counterintuitive, since the spin-up torque in any model is proportional to $M$ (e.g. ~ $M^{7/11}$ for the standard disc accretion (Ghosh & Lamb 1979) and ~ $M^{7/11}$ for the settling quasi-spherical accretion (Shakura et al. 2013)).

A plausible explanation can be as follows. The stellar wind from rapidly rotating Be-star is highly asymmetric and can form an equatorial disc in the equatorial plane of the Be-star (see Thomas et al. 1979 for spectroscopic evidence of an equatorial disc around Be-star in GX 304-1). The Be-disc can be inclined to the orbital plane of the binary system due to, for example, non-zero kick velocity acquired by the neutron star during the supernova explosion. In this case the nodal line of the disc and the orbital plane may not be perpendicular to the major semi-axis line, i.e. the orbit of the neutron star around the Be-star can enter the disc at smaller radius ($r_A$) and go out of the disc at larger radius $r_B > r_A$, as depicted in Fig. 4. The precursor initiated by the stellar wind density enhancement when neutron star approaches point A can still be at the stage of settling accretion (the peak luminosity is about $6 \times 10^{36} \text{ erg s}^{-1}$, which is marginal for this regime with $f(u) \sim 0.5$ (Shakura et al. 2012), allowing for distance uncertain-
ties to the source), so the neutron star spin-up properties should be similar to the previous outbursts. The main flare after the periastron at point B is two times as bright, i.e. must be in the free-fall Bondi regime (see Fig. 5). Assuming $v_w \gg v$ and substituting for $j$ and $r$ from Eq. (5) into Eq. (6), we find the spin-up torque

$$I \dot{\omega}_n = \frac{1}{4} MR_B^2 \sqrt{\frac{GM}{p^3}} (1 + e \cos \varphi)^2,$$

(Here $I \approx 10^{45}$ g cm$^2$ is the neutron star moment of inertia). Therefore,

$$\frac{\dot{\omega}_n(B)}{\dot{\omega}_n(A)} = \frac{\dot{M}(B)}{\dot{M}(A)} \frac{(1 + e \cos \varphi_B)^2}{(1 + e \cos \varphi_A)^2}.$$  

(8)

In our case the true anomaly of two flares (before and after periastron) is determined by the Be-disc node line, i.e. $\varphi_B = \varphi_A + \pi$, and neglecting wind velocity variations with radius (i.e. assuming $v_w = \text{const}$), we obtain $M(B) = M_B$ (Bondi regime), $M(A) = f(u)M_B \sim 0.5M_B$ (settling regime), so that

$$\frac{\dot{\omega}_n(B)}{\dot{\omega}_n(A)} = 2\frac{1 - e \cos \varphi_A}{1 + e \cos \varphi_A}.$$  

(9)

Clearly, it is not difficult to find the combination of the orbital eccentricity $e$ and the true anomaly $\varphi_A$, matching the observed spin-up ratio $\dot{\omega}_n(B)/\dot{\omega}_n(A) \sim 0.3$ (see Fig. 5). The acceptable angle $\varphi_A$ varies from $\sim 0.5$ rad to $\sim 1.1$ rad for orbital eccentricity ranging from $\sim 0.5$ to $0.9$, respectively. We stress that in this picture the role of the equatorial Be-disc is simply in enhancing the wind density when the neutron star approaches the disc node line in its orbital motion. The specific angular momentum of the Be-disc matter at points A and B should be of the order of the Keplerian value $\sqrt{GM/R}$, which is close to the orbital neutron star value. But under our assumption $v_w \gg v$ its addition to the captured spherical wind matter is not expected to be substantial.

Thus we can conclude that the model of quasi-spherical settling accretion is consistent with observations of both spin-up episodes during the outbursts at periastron passages of the neutron star and spin-down between the outbursts in slowly rotating wind-fed X-ray pulsar GX 304-1. The first, weaker, flare (precursor) in the unusual double-peak outburst started before the periastron passage at MJD 56205 can be due to continuing quasi-spherical accretion from the quasi-spherical low-velocity wind of Be-star, while the second, more powerful flare, developed after the periastron passage which started at MJD 56229, is in the free-fall Bondi regime of quasi-spherical accretion. The lower spin-up rate during the second flare is explained by smaller specific angular momentum of matter captured from the quasi-spherical wind from the Be-star by the neutron star moving in elliptical orbit.

Figure 4. Schematics of the neutron star orbit around Be-star surrounded by a tilted equatorial disc (face-on view). The neutron star first meets the disc node line at point A and leaves the disc at point B. In so far as the Be-disc radius is smaller than or comparable to the periapsis distance, a single-peak Type I outburst is expected to occur near the periastron passage. As the radius of the Be-disc increases (the dashed ellipse), the neutron star meets the disc at point A and leaves it at point B.

Figure 5. Ratio of the pulsar spin-up rates at the neutron star crossing the Be-disc node line (points B and A in Fig. 4), Eq. (6), as a function of the angle $\varphi_A$ for different orbital eccentricities (0.1 to 0.9, the solid lines from top to bottom). The dashed gray line corresponds to the observed ratio 0.3 in the main (B) and precursor (B) flares in outburst #7.
Apparently, the complicated behavior of the excretion disc around Be-star may cause the observed switching between accretion regimes near the periastron passage. We also note that the time separation between the precursor and the giant flare in double-peak outbursts #6 and #7 increases (see Fig. 1), which may be due to growing radius of the excretion disc around the Be-star. The growing radius of the Be-disc in principle could be checked by optical observations (Corbet et al. 1988). Unfortunately, no optical monitoring was reported during the source activity in 2009-2013.

4 DISCUSSION AND CONCLUSION

Let us discuss an alternative explanation to the observed spin-up/spin-down behavior in GX 304-1. First, assume that an accretion disc is always present around the neutron star (see e.g. SPH simulations (Havasak & Okazaki 2004)). Observations of QPOs in outburst #1 (Devasia et al. 2011) may be an indication of the disc. During giant outbursts the total accretion luminosity of the source can be as high as $10^{37}$ erg s$^{-1}$ (Table 1), which can be uncomfortably high for the settling quasi-spherical accretion. The spin-up rate during disc accretion can be written as

$$\dot{\omega}_{\text{radisc}} \sim \dot{M} \sqrt{G M_{\text{disc}}/I} \approx 4.6 \times 10^{-8} \text{ [Hz d}^{-1}] M_{16}^{4/7} \tag{10}$$

(here we neglected spin-down torques due to interaction of the magnetosphere with accretion disc (see e.g. discussion of models in Wang 1996; Kluzniak & Rappaport 2007), which is justified at high accretion rates, and assumed $\alpha = 0.1$ for the thin accretion disc in GX 304-1). Clearly, the plausible mass accretion rate onto the neutron star $M_{16} \approx 7 - 8 \times 10^{-16} \text{ [Hz d}^{-1}]$ (see Table 1). A caveat in the disc spin-up at all times, however, is that, as mentioned above, it is difficult to explain the lower spin-up rate observed in the second, more luminous, flare of the double-peak outburst #7.

The persistent X-ray luminosity between outbursts clearly indicates that accretion does not stop during the orbital motion of the neutron star even at the orbit apastron. While it is possible to produce a spin-down torque during low-luminosity disc accretion, for example in models (Wang 1996; Kluzniak & Rappaport 2007), it is difficult to reconcile the observed 275-s neutron star period with these models, even by assuming that most of the time the accretion rate is as low as $M_{16} \sim 0.01$. Indeed, the equilibrium period in the sophisticated model by Kluzniak & Rappaport (2007) is $P_{eq} \approx 1.14 [\text{ms}] M_{16}^{3/7} B_{18}^{-1/7} \approx 83 \text{ s}$ for parameters of GX 304-1 $B_{18} \approx 4.7 \times 10^{-1}$ and $M_{18} \approx 10^{-4}$, more than three times as short as observed. (Incidentally, we stress here the general problem of explaining the observed long periods of X-ray pulsars in BeXRB systems in the frame of the standard disc accretion onto neutron stars with the standard magnetic field about $10^{12}$ G; quasi-spherical settling wind accretion does not have this problem, see Postnov et al. 2014).

Thus we conclude that the quasi-spherical settling accretion onto the slowly rotating neutron star with standard magnetic field from stellar wind of the companion Be-star seems to be a likely explanation to the observed spin-down between Type I outbursts in GX 304-1. The angular momentum from the neutron star is removed due to interaction of the magnetosphere with convective hot shell formed from the matter with low angular momentum captured from the quasi-spherical low-velocity wind of the Be-star. The Be-disc can be inclined to the binary orbital plane due to the natal kick acquired by the neutron star during supernova explosion. When the radius of the circumstellar disc is smaller or comparable with the periastron distance, a single-peak Type I outburst occurs near the orbital periastron passage. When the radius of the Be-disc increases above the orbital periastron distance, a double-peak outburst near the periastron can be produced, with the second (post-periastron) peak being at the more effective quasi-spherical Bondi accretion stage from the stellar wind of Be-star. The lower spin-up rate during the second flare can be explained by lower value of the specific angular momentum of matter captured from the quasi-spherical wind from the Be-star by the neutron star moving in elliptical orbit. Once the orbital parameters of GX 304-1 will be determined, the orbital phase of the precursor and post-periastron flares in double-peak outbursts can be used to find the Be-disc node line angle. Further optical and X-ray observations of the system are encouraged to disentangle the complicated structure of the Be-star wind and to check the proposed model for X-ray outbursts.

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REFERENCES

Alpar M. A., Shaham J., 1985, Nature, 316, 239
Becker R. H., Rothschild R. E., Boldt E. A., Holt S. S., Pravdo S. H., Serlemitsos P. J., Swank J. H., 1978, ApJ, 221, 912
Bhattacharya D., van den Heuvel E. P. J., 1991, Phys.Rep., 203, 1
Bildsten L. et al., 1997, ApJS, 113, 367
Burnard D. J., Arons J., Lea S. M., 1983, ApJ, 266, 175
Burrows D. N., Hill J. E., Nousek J. A., Kenna A. J., Wells A. et al., 2005, Space Sci. Rev., 120, 165
Caballero I., Wilms J., 2012, Mem. Soc. Astron. It., 83, 230
Corbet R. H. D., Smale A. P., Menzies J. W., Branduardi-Raymont G., Charles P. A., Mason K. O., Booth L., 1986, MNRAS, 221, 961
Devasia J., James M., Paul B., Indulekha K., 2011, MNRAS, 417, 348
Fabbiano G., Schreier E., 1977, ApJ, 214, 235
Filippova E.V., Tsygankov A.A., Sunyaev R.A., 2005, Astron. Lett. 31, 729
Giacconi R., Gursky H., Kellogg E., Schreier E., Tananbaum H., 1971, ApJ, 167, L67
Giacconi R., Gursky H., Kellogg E., Levinson R., Schreier E., Tananbaum H., 1973, ApJ, 184, 227
Ghosh P., Lamb F., 1979, ApJ, 234, 296
Hayasakki K., Okazaki A. T., 2004, MNRAS, 350, 971
Huckle H. E., Mason K. O., White N. E., Sanford P. W., Marschi L., Tarenghi M., Tapia S., 1977, MNRAS, 180, 21
Illarionov A., Sunyaev R., 1975, A&A, 39, 185
Jernigan J. G., Klein R. I., Arons J., 2000, ApJ, 530, 875
Klochkov D., Doroshenko V., Santangelo A., Stauber R., Ferrigno C. et al., 2012, A&A, 542, L28
Klužniak W., Rappaport S., 2007, ApJ, 671, 1990
