Luminosity and spin-period evolution of GX 304–1 during outbursts from 2009 to 2013 observed with the MAXI/GSC, RXTE/PCA, and Fermi/GBM

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Abstract

A report is made on the luminosity and pulse period evolution of the Be binary X-ray pulsar GX 304–1 during a series of outbursts from 2009 to 2013 observed by MAXI/GSC, RXTE/PCA, and Fermi/GBM. In total, 12 outbursts repeated by ∼132.2 d were observed, which is consistent with the X-ray periodicity of this object observed in the 1970s. These 12 outbursts, together with those in the 1970s, were all found to recur with a well-defined period of 132.189 ± 0.02 d, which can be identified with the orbital period. The pulse period of ∼275 s, obtained from the RXTE/PCA and Fermi/GBM data, apparently exhibited a periodic modulation synchronized with the outburst period, suggesting the pulsar orbital motion, which is superposed on a secular spin-up trend throughout the entire active phase. The observed pulse period changes were successfully represented by a model composed of the binary orbital modulation and pulsar spin up caused by mass accretion through an accretion disk. The orbital elements obtained from the best-fit model, including the projected orbital semi-major axis aₓ sin i ≃ 500–600 light-s and an eccentricity e ≃ 0.5, are typical of Be binary X-ray pulsars.

Key words: pulsars: individual (GX 304–1) — stars: neutron — X-rays: binaries

1 Introduction

X-ray binary pulsars (XBPs) are systems consisting of magnetized neutron stars and mass-donating stellar companions. According to the type of the companion, they are classified into several subgroups, including Super Giant XBPs and Be XBPs as major members (e.g., Reig 2011). Since these neutron stars are strongly magnetized, the matter flows from the companion are dominated by the magnetic pressure inside the Alfven radius, and are then funneled onto the magnetic poles along the magnetic field lines. Since the accreting matter transfers its angular momentum at the Alfven radius to the neutron star, the spin-up rate and the mass accretion rate (i.e., the X-ray luminosity) of an XBP are thought to be closely correlated (e.g.,...
of RXTE data revealed the complex pulse profile dependence on the energy band as well as the luminosity, and the quasi-periodic oscillation at $\sim 0.12$ Hz (Devasia et al. 2011). The period and pulsed flux have also been monitored by the Fermi GBM pulsar project (Finger & Jenke 2013). All these data thus provide us with a valuable opportunity to study the relation between the luminosity and spin period of the XBP.

In this paper, we analyze the X-ray outburst light curve of GX 304–1 during the active period from 2009 to 2013 obtained with the MAXI GSC, and the pulse period variations derived from the RXTE/PCA and Fermi/GBM data. Our goal is to separate the orbital doppler effects and the intrinsic pulse period change. The observation and data reduction are described in section 2, while the data analysis and results are described in section 3. We discuss the results in section 4.

2 Observation

2.1 MAXI monitoring

Since the MAXI (Monitor of All-sky X-ray Image: Matsuoka et al. 2009) experiment on board the ISS (International Space Station) commenced in 2009 August, the GSC (Gas Slit Camera: Mihara et al. 2011), one of the two MAXI detectors, has been scanning almost the whole sky every 92-minute orbital cycle in the 2–30 keV band. We utilized archived GSC light-curve data for GX 304–1 in 2–4 keV, 4–10 keV, and 10–20 keV bands, which are processed with a standard procedure (Sugizaki et al. 2011) by the MAXI team and available from the MAXI web site. Figure 1 (top) shows the 2–20 keV MAXI/GSC light curve from 2009 August to 2013 December in 1 d time bins. It clearly reveals the recurrent outburst activity by a $\sim 132.2$ d interval, which is consistent with the 132.5 $\pm 0.4$ d periodicity found in the 1971–1972 outbursts with Vela 5B (Priedhorsky & Terrell 1983). Figure 1 covers 12 epochs of the outbursts predicted from the 132.2 d-period cycle, which we consecutively name A, B, C, …, L. Outburst I in 2012 August reached $\sim 2.4$ photons cm$^{-2}$ s$^{-1}$ ($\sim 0.6$ Crab) in the 2–20 keV band, which is the highest flaring event ever observed from this source.

If the source distance of $D = 2.4$ kpc, the energy spectrum of a cutoff power law with a photon index $\Gamma = 0.35$, and an e-fold energy $E_{\text{fold}} = 11$ keV (Yamamoto et al. 2011a) are employed, the observed flux of 1 photon cm$^{-2}$ s$^{-1}$ in the 2–20 keV band corresponds to the bolometric luminosity of $1.38 \times 10^{37}$ erg s$^{-1}$ in an isotropic emission source. We use the conversion factor to estimate the luminosity from the MAXI/GSC data hereafter. The
scale of the estimated luminosity is shown at the right-hand ordinate of the light curve [figure 1 (top)].

2.2 Fermi GBM data

The GBM (Gamma-ray Burst Monitor; Meegan et al. 2009) on board the Fermi Gamma-Ray Space Telescope is an all-sky instrument, sensitive to X-rays and gamma-rays with energies between 8 keV and 40 MeV. The Fermi GBM pulsar project2 provides the results of timing analysis of a number of positively detected X-ray pulsars, including their pulse periods and pulsed fluxes (Finger et al. 2009; Camero-Arranz et al. 2010). We utilized the archived results of GX 304−1 to systematically investigate the long-term variations of the pulse timing from 2010 to 2013.

Figure 1 (bottom) shows time variations of the barycentric pulse period and the pulsed photon flux in the 25–50 keV band of GX 304−1, as made publicly available by the project. The pulsed emission was detected over bright phases of the nine consecutive outbursts from B to J. The period range of 275.2–275.6 s during outburst C is consistent with the results of 275.37 s from the RXTE data (Devasia et al. 2011) and 275.46 s from the Suzaku data (Yamamoto et al. 2011a), both obtained in the same outbursts.

2.3 RXTE observations and data reduction

The RXTE observations of GX 304−1 were performed on the outbursts B, C, D, and E, using the Proportional Counter Array (PCA: Jahoda et al. 2006) operating in 3–60 keV and the High-Energy X-ray Timing Experiment (HEXTE: Rothschild et al. 1998) providing 20–250 keV data. As indicated in figure 1 (top), a total of 71 observations covered the outbursts C, D, and E with a high frequency of almost once per day, each with an exposure of 0.5–18 ks. We analyzed the PCA data to study the pulse timing properties with photon statistics and time resolution better than those available with other instruments.

Data reduction and analysis were performed using the standard RXTE analysis tools released as a part of HEASOFT 6.14, and the CALDB files of version 20111205 provided by NASA/GSFC. All the data were first screened with the standard selection criteria, that the spacecraft pointing offset should be smaller than 0.02, the earth-limb elevation angle be larger than 10°, and the time since the last SAA passage be longer than 30 minutes. We used data only from the top layer of the PCU-2 unit, which is the best calibrated among all PCUs. In the timing analysis, we used the reduced data with Good-Xenon data mode, Generic event-data mode (E_125us_64M_0_1s), or Generic binned-data mode (B_250ms_128M_0_254), which has a time resolution better than 0.25 s.

3 Analysis

3.1 Outburst intervals and orbital period

To quantify the outburst periodicity, we determined their peak epochs by fitting each profile with a Gaussian function. Since some of the peaks have asymmetric profiles and hence cannot be approximated by a single Gaussian function, the fit was performed within a narrow span of ∼50 d around each peak so that the fit is reasonably accepted. If an outburst has multiple peaks, their peak epochs were determined separately. Table 1 summarizes the obtained epochs, fluxes, and the luminosities estimated from the typical energy spectrum at the peaks.

X-ray outbursts of Be X-ray binaries are known to be largely classified into normal-type (type-I) and giant-type (type-II) ones (e.g., review by Reig 2011). The normal outbursts emerge near the pulsar periastron passage and their peak luminosity reaches ∼10^37 erg s⁻¹, while the giant ones may appear at any orbital phase and can be more significantly luminous than the other type of events. The regular periodicity of the observed outbursts suggests that they are

Fig. 1. (Top) MAXI GSC 2–20 keV light curve of GX 304−1 from 2009 August 15 (MJD 55058) to 2014 January 21 (MJD 56678) in 1 d time bins. Arrows indicate the expected outburst epochs of the 132.2 d cycle. The 12 epochs involved in the light curve are named A, B, C, . . . , L, as labeled. Vertical bars in blue indicate the epochs of the RXTE pointing observations. (Bottom) Barycentric pulse period (red cross) and pulsed 12–50 keV flux (black solid triangle) measured by the Fermi GBM. (Color online)
mostly categorized into the normal type. Actually, the first seven outbursts from A to G, with a single-peak profile, satisfy all the normal-type conditions. Similarly, the outbursts observed in 1971–1972 with Vela 5B also exhibited the same periodicity and their peak fluxes were at the same level (Priedhorsky & Terrell 1983). Therefore, they should be categorized into the normal type, too.

To refine the orbital period, we extrapolated the periodicity of the 2009–2012 outbursts (A to G) to that in 1971–1972 assuming that they are at the same orbital phase. The top panel of figure 2 shows a plot of the peak epochs $T_{\text{peak}}$ in 2009–2013 against the number $n$ of 132.2 d cycles from the initial epoch of MJD 41675.6 (1972 December 14) in the Vela 5B era. Thus, the epochs $T_{\text{peak}}$ of $n = 0$ (MJD 41675.6) and $n = 102–108$ (outbursts A to G) lie on a straight line, around which the data of $n = 102–108$ scatter by 2.1 d in standard deviation. We employed this deviation as the uncertainty in each data item, and fitted the epochs with a linear function to obtained the best period estimate of 132.1885 ± 0.022 and the initial peak epoch of MJD 41675.0 ± 2.2 with 1 \( \sigma \) error. The best-fit function,

$$T_{\text{peak}} = 41675.0 + 132.189 \times n \ (\text{MJD})$$  \hspace{1cm} (1)

is drawn together on the data at the top panel of figure 2, and the bottom panel shows the data-to-model residuals. Their values are listed in table 1.

| OutID\(^\dagger\) | Epoch (MJD) | Residual\(^\dagger\) (d) | Peak flux§ (photons cm\(^{-2}\) s\(^{-1}\)) | Luminosity# (10\(^{37}\) erg s\(^{-1}\)) |
|-----------------|-------------|-----------------|-----------------|-----------------|
| A               | 55154.00 ± 0.11 | −4.18           | 0.198 ± 0.005   | 0.27            |
| B               | 55289.30 ± 0.10 | −1.07           | 0.275 ± 0.004   | 0.38            |
| C               | 55425.52 ± 0.02 | 2.96            | 1.822 ± 0.008   | 2.51            |
| D               | 55555.70 ± 0.03 | 0.95            | 1.182 ± 0.008   | 1.63            |
| E               | 55688.66 ± 0.03 | 1.73            | 1.141 ± 0.008   | 1.57            |
| F               | 55817.98 ± 0.03 | −1.14           | 1.137 ± 0.008   | 1.57            |
| G               | 55952.10 ± 0.05 | 0.79            | 1.266 ± 0.009   | 1.75            |
| H\(*\)          | 56075.67 ± 0.09 | −7.84           | 0.564 ± 0.025   | 0.78            |
| H               | 56090.93 ± 0.21 | 7.43            | 0.864 ± 0.014   | 1.19            |
| I\(*\)          | 56210.72 ± 0.05 | −4.97           | 0.978 ± 0.012   | 1.35            |
| I               | 56235.79 ± 0.05 | 20.10           | 1.997 ± 0.020   | 2.76            |
| J\(*\)          | 56337.64 ± 0.58 | −10.24          | 0.098 ± 0.003   | 0.13            |
| J               | 56354.21 ± 0.23 | 6.33            | 0.151 ± 0.009   | 0.21            |
| J               | 56370.84 ± 0.37 | 22.96           | 0.186 ± 0.012   | 0.26            |
| K               | 56483.86 ± 0.15 | 3.80            | 0.177 ± 0.009   | 0.24            |
| L               | 56617.61 ± 1.09 | 5.35            | 0.045 ± 0.004   | 0.06            |

\(\dagger\)Second or third highest peak in an outburst cycle.
\(\dagger\)Outburst ID designated by the number of period cycles (figure 1).
\(\dagger\)Residual of peak epoch from the best-fit period cycle of equation (1).
\(§\)Peak photon flux in 2–20 keV band in units of photons cm\(^{-2}\) s\(^{-1}\).
\(#\)Bolometric luminosity estimated from the 2–20 keV photon flux.

\(\ast\)Fig. 2. (Top) Epochs of outburst peaks against the number of 132.2 d period cycles counted from that on MJD 41675 (1972 December 14). The solid line represents the best-fit linear function to the data of cycle = 0 at MJD 41675 and cycle = 102–108. (Bottom) Residuals of the data from the best-fit linear function. The areas of the circles are proportional to the outburst-peak intensity in both panels.
As presented in figure 2 and table 1, we also extended the best-fit linear function to \( n = 113 \) (outburst L). The residuals suggest that the outburst periodicity changed after \( n = 109 \) (outburst H), as investigated below.

### 3.2 Evolution of outburst orbital profile

Figure 3 left shows expanded three-color MAXI/GSC light curves of the individual outbursts, as a function of time from the peak predicted by equation (1). The hardness ratios are presented in the right panels.

The light curves of the outbursts A to G in figure 3 (left) reconfirm that their peak epoch agrees, within a scatter of 2.1 d with the prediction of the best-fit cycle. However, these profiles vary considerably from cycle to cycle. While outburst D has a slight enhancement over the symmetrical profile prior to the peak, outbursts F and G have a subsequent small peak after the main peak.

As expected from figure 1, outbursts H and I, the latter being the brightest, clearly deviate in figures 2 and 3 from equation (1), because they both show double-peaked profiles. This suggests that these two, or at least outburst I, are possibly giant outbursts. In outburst J, no distinct main peak is seen and low-level activity continued for 40 days.

During bright outburst phases, the two hardness ratios in figure 3 (right) slightly change with a positive correlation to the flux. In addition, the \( (4–10 \text{ keV}/2–4 \text{ keV}) \) hardness ratio exhibits sharp increases at the peak in outbursts E, F, and G. They correspond to dips in the softest light curve (red), and thus can be attributed to an increase in the absorption column density.

### 3.3 Pulse period changes

To investigate the change in the pulse period with a better precision and sensitivity than those available with the Fermi GBM shown in red in figure 1 (bottom), we analyzed the RXTE/PCA data, which samples outbursts C, D, and E on the almost daily basis. The data for outburst C has already been analyzed by Devasia et al. (2011) and the results revealed a complex pulse profile that depends on the energy and the luminosity. We performed the timing analysis taking account of these properties as follows. The top and middle panels of figure 4 show the MAXI/GSC 2–20 keV light curves in 1 d time bins, and those of the 2–6 keV RXTE/PCA count rates per 272 s, approximately equal to the pulse period. The large variability in the PCA count rate around the outburst peaks represents a variation component other than the 275 s pulsation, as Devasia et al. (2011) reported in outburst C.

We performed the pulse period search by the folding method using \texttt{efsearch} in XRONOS for the PCA data after the barycentric correction was applied with \texttt{fxbary} in FTOOLS. To optimize the period determination accuracy, the folding analysis was carried out by combining data taken within each interval up to 2 days. The energy band was limited to 2–6 keV because of the sharp dip structure in the pulse profile below 8 keV (Devasia et al. 2011). The errors on the obtained pulse period were estimated by the method of Larsson (1996) using the folded pulse profile with 64 phase bins.

Figure 4 (bottom) shows the obtained pulse period against the observation epochs, where the results of the Fermi GBM pulsar project, the same as in figure 1, are plotted together. The RXTE/PCA and the Fermi/GBM results are consistent with each other.

### 3.4 Determining the binary orbital elements

The pulse period evolution in figures 1 and 4 is characterized by two distinct effects. One is cyclic modulation synchronized with the 132.2 d outburst period, considered as due to the orbital Doppler effects. The other is a secular spin-up trend over the 3 years, obviously due to the accretion torque. Thus, the observed pulse period evolution is considered to be a complex composite of these two effects. Since both of them are supposed to depend on the orbital phase, it is not straightforward to separate them. Hence, we construct a semi-empirical model representing the two effects and then fit it to the data, in an attempt to simultaneously determine the orbital elements and the luminosity-dependent intrinsic pulse period change.

Be XBs are known to exhibit spin-up episodes during bright outburst phases (e.g., Bildsten et al. 1997). This is naturally explained by an increase in the accretion rate, and the associated transfer of the angular momentum to the neutron star via disk–magnetosphere interactions. In the classical theoretical model by Ghosh and Lamb (1979), the pulsar spin-up rate \( -\dot{P}_{\text{GL}} \) (s yr\(^{-1}\)) is given by

\[
-\dot{P}_{\text{GL}} = 5.0 \times 10^{-5} \mu_{30} h(\omega_s) R_{\text{NS6}}^2 M_{\text{NS6}}^{-2} I_{45}^{-1} p_{\text{spin}}^2 I_{37}^{-2} ,
\]

(2)

where \( \mu_{30} \), \( R_{\text{NS6}} \), \( M_{\text{NS6}} \), \( I_{45} \), \( p_{\text{spin}} \), and \( L_{17} \) are the magnetic dipole moment of the neutron star in units of \( 10^{30} \text{ G cm}^3 \), radius in \( 10^6 \text{ cm} \), mass in \( M_{\odot} \), moment of inertia in \( 10^{45} \text{ g cm}^2 \), spin period in s, and the luminosity in \( 10^{37} \text{ erg s}^{-1} \), respectively, while \( h(\omega_s) \) is a dimensionless torque that depends on the fastness parameter \( \omega_s \), defined by the ratio of the angular velocity of the pulsar spin to that of the Kepler rotation of accreting matter at around the Alfvén radius.

In the application of equation (2), GX 304–1 is particularly suited for several reasons. First, the value of \( \mu_{30} \) can be accurately estimated from the CRSF
Fig. 3. (Left) Light curves of the outbursts A to L, in 2–4 keV (red), 4–10 keV (black), and 10–20 keV (green) bands shown as a function of day modulo the 132.189 d outburst period. Arrows at the top of each panel indicate the peak position determined by Gaussian fit (table 1). (Right) Time evolution of 4–10 keV/2–4 keV (red) and 10–20 keV/4–10 keV (black) hardness ratios.
Fig. 4. Details of outbursts C (left), D (center), and E (right). (Top) MAXI/GSC light curves in the 2–20 keV band, in 1 d time bins. (Middle) The 2–6 keV RXTE/PCA count rate per 272 s time bin during the pointing observations. (Bottom) Barycentric pulse periods obtained from the RXTE/PCA data (blue dot) and the Fermi/GBM pulsar archive data (red cross). All vertical error bars represent the 1σ uncertainty.

detection at 54 keV, which implies a surface magnetic field of $B_s = 4.7 \times 10^{12}(1 + z_G^1) G$ (Yamamoto et al. 2011a). If the canonical neutron-star mass $M_{\text{NS}} = 1.4 M_\odot$ and radius $R_{\text{NS}} = 10^6$ cm are assumed, the gravitational redshift $z_G$ is 0.3, and then $\mu_{30}$ is calculated as

$$\mu_{30} \approx \frac{1}{2} B_s R_{\text{NS}}^3 = 3.1 (10^{30} \text{ G cm}^3)$$

(Wasserman & Shapiro 1983). Second, a continuous record of $L_{37}$ is available from the MAXI GSC light curve; we calculate it with the conversion factor as described in subsection 2.1. Furthermore, $n(\omega_s) \approx 1$ can be regarded approximately as a constant from the long spin period, $P_{\text{spin}} \approx 275$ s, such that $\omega_s \ll 1$ (Ghosh & Lamb 1979). We also employ $I_{45}$ calculated from its approximate equation with $M_{\text{NS}}$ and $R_{\text{NS}}$ given by Ravenhall and Pethick (1994) as

$$I_{45} \approx 0.21 \frac{M_{\text{NS}} R_{\text{NS}}^2}{1 - 2GM_{\text{NS}}/R_{\text{NS}} c^2} = 1.0 (10^{45} \text{ g cm}^2).$$

Combining these pieces of information, equation (2) yields

$$-P_{\text{GL}} \simeq 1.7 \times 10^{-2} L_{37}^{\frac{7}{2}} (\text{s d}^{-1}).$$

Equation (2) implies that the spin-up rate $-\dot{P}_{\text{spin}}$ follows the luminosity $L$ as $-\dot{P}_{\text{spin}} \propto L^{\frac{7}{2}}$. The relation has been calibrated with actual X-ray data (Reynolds et al. 1996; Bildsten et al. 1997). Besides this, the comparison of absolute spin-up rates with equation (2) has been hampered by a large uncertainty in the bolometric luminosity correction, which is in turn due to beaming effects (e.g., Bildsten et al. 1997; Wilson et al. 2002). We hence employ a spin-up model expressed by $-\dot{P}_{\text{spin}} = \alpha L_{37}^{\frac{7}{2}}$, in which the power-law index and the constant coefficient $\alpha$ are treated as free parameters.

XBPs are also known to spin down during quiescence due to the propeller effects. In fact, GX 304–1 exhibited a spin down by $\sim 3$ s for the 28 years of quiescence from 1980 to 2008, with an average period derivative of $\dot{P} \simeq 3 \times 10^{-9} \text{ s s}^{-1}$. The rate, though much smaller than the spin-up rate during bright phases ($\dot{P} \sim -10^{-7} \text{ s s}^{-1}$), may not be negligible. We accounted for its contribution with a constant spin-down parameter, $\beta$, added to $\dot{P}_{\text{spin}}$ as an offset.

By using the spin-up and spin-down models discussed above, the intrinsic pulsar spin period $P_{\text{spin}}(t)$ is expressed as

$$P_{\text{spin}}(t) = P_0 + \int_{\tau_0}^{t} P_{\text{spin}}(\tau) \, d\tau$$

$$= P_0 + \int_{\tau_0}^{t} [\alpha L_{37}^{\frac{7}{2}}(\tau) + \beta] \, d\tau,$$

where we set the time origin $\tau_0$ at the periastron passage in outburst C and denote the pulse period at $\tau_0$ as $P_0 = P_{\text{spin}}(\tau_0)$. 

$P_{\text{GL}}(t)$ is calculated from equation (3) by first obtaining $\dot{P}_{\text{GL}}$, which is the contribution of the gravitational radiation friction to the spin-period derivative.

$$-\dot{P}_{\text{GL}} = \frac{12}{5} \frac{M_{\text{NS}} R_{\text{NS}}^2}{1 - 2GM_{\text{NS}}/R_{\text{NS}} c^2} \frac{\epsilon}{1 - \epsilon^2} \dot{P},$$

where $\epsilon$ is the mass ratio between the primary and secondary stars. $\epsilon$ is determined from the period derivative as

$$\dot{P} = \frac{P_0}{P(t)} \frac{1}{4\pi^2} \frac{M_{\text{NS}} R_{\text{NS}}^2}{1 - 2GM_{\text{NS}}/R_{\text{NS}} c^2} \frac{\epsilon}{1 - \epsilon^2} \dot{P}_{\text{GL}}.$$
The period modulation due to the binary motion can be calculated using the binary orbital elements, which consist of the orbital period $P_B$, the eccentricity $e$, the projected semi-major axis $a_e \sin i$, the argument of the periastron $\omega_0$, and the epoch of periastron passage which we identified with $\tau_0$ defined above. The pulsar orbital velocity $v_1(t)$ along the line of sight is given as

$$v_1(t) = \frac{2\pi a_e \sin i}{P_B \sqrt{1 - e^2}} \left[ \cos \left( v(t) + \omega_0 \right) + e \cos \omega_0 \right], \quad (8)$$

where $v(t)$ is a parameter called “true anomaly” describing the motion on the elliptical orbit, and calculated from Kepler’s equation. The observed barycentric period, $P_{\text{obs}}(t)$, is then expressed by

$$P_{\text{obs}}(t) = P_{\text{spin}}(t) \left[ 1 + \frac{v_1(t)}{c} \right] \left[ 1 - \frac{v_1^2(t)}{c^2} \right]^{-\frac{1}{2}} \approx P_{\text{spin}}(t) \left[ 1 + \frac{v_1(t)}{c} \right]. \quad (9)$$

We applied the model $P_{\text{obs}}(t)$ consisting of equations (7)–(9) to the observed barycentric periods obtained from the RXTE/PCA timing analysis in subsection 3.3 and Fermi/GBM archival products. The model involves nine free parameters: $P_0$, $\alpha$, $\beta$, and $\gamma$ in equation (7), and the orbital elements in equation (8). We utilized the luminosity calculated from the MAXI/GSC 2–20 keV light curve in 1 d time bins, as described in subsection 2.1. The errors associated with the $L_{37}$ determinations propagate into those of equation (7), but this gives 1σ uncertainties only of $\sim 0.003$ s, which is smaller than those in the individual pulse period measurements, $\sim 0.01$ s. We fixed the orbital period $P_B$ at 132.189 d, derived from the outburst cycle over 28 years in subsection 3.1, and examine the fit with $\gamma$ fixed at the theoretical value of $6/7$ or free.

The model has been found to represent all data well. Figure 5 shows the results of those model fits (with $\gamma = 6/7$ and $\gamma$ free), and table 2 summarizes the best-fit parameters obtained. The obtained epoch of the periastron of outburst C, $\tau_0 \simeq 55425$ (MJD), agrees with that at the outburst flux peak (table 1) within the uncertainty of the peak-epoch periodicity, $\sim 2.1$ d. Comparing the two fit results, the fit with $\gamma$ free has a $\chi^2$ lower by 108.3 for a decrease of only one in the degree of freedom (dof). In figure 6, pulsar binary orbits suggested in the two fitting models are illustrated.

4 Discussion

4.1 Luminosity–spin-up relation

As a result of the model fit to the pulse period evolution, we successfully calibrate the relation between the luminosity $L$ and the spin-up rate, $-\dot{P}_{\text{spin}}$, which is considered to reflect the accretion manner. According to the model of Ghosh and Lamb (1979), the power-law index $\gamma$ becomes $6/7$ in a disk accretion and 1 in a wind accretion. The best-fit $\gamma$ obtained from the model with $\gamma$ free was $1.24 \pm 0.03$, which is significantly larger than $6/7 \simeq 0.86$ in the disk accretion. Meanwhile, the present result agrees with those of other typical Be XBP’s, A 0535+26 (Finger et al. 1996; Camero-Arranz et al. 2012), EXO 2030+375 (Reynolds et al. 1996; Wilson et al. 2002), and 2S 1417-624 (Finger et al. 1996; Inam et al. 2004). As Wilson et al. (2002) suggested, the result of $\gamma \gtrsim 1$ may imply the effect of either spin down or wind accretion during the low luminosity periods. In fact, the fit with $\gamma = 6/7$ yielded the significant spin-down of $\beta = 3.27 \pm 0.02 \times 10^{-9}$ s$^{-1}$ during the outburst intermissions. The rate is consistent with the average period derivative of $\sim 3 \times 10^{-9}$ s$^{-1}$ during the 1980–2008 quiescence.

Comparing the two model-fit results ($\gamma = 6/7$ and $\gamma$ free), the goodness of fit ($\chi^2$/dof) certainly prefers the one with $\gamma$ free. However, neither is acceptable statistically. As seen in figure 5, the difference between the two models is mostly in the outburst intermission, in which the period data are not available. Therefore, from the present result, it is hard to conclude which model better represents the real situation. The problem will be solved if the pulse period throughout the entire orbital phase is obtained.

From the best-fit parameters, we also obtained the normalization factor of the absolute spin-up rate, $\alpha$, compared to that predicted in the model of Ghosh and Lamb (1979), which is $0.017$ s d$^{-1}$ as derived in equation (5) in this source. The ratio $\alpha/0.017 \simeq 0.3$ in both models ($\gamma$ free and $\gamma = 6/7$) is significantly smaller than unity, as in some other Be XBP’s (Wilson et al. 2002). This discrepancy is reasonably explained by the uncertainty in the luminosity estimate. We calculate the luminosity from the observed fluxes sampled by MAXI/GSC scan survey in 1 d time bins assuming that the source emission is isotropic, as described in subsection 2.1. Because the observed flux is pulsating, the source emission is not completely isotropic. The obtained result corresponds to the beaming effect by a factor $\sim 3$.

4.2 Binary properties as Be/X-ray binary pulsars

From the obtained orbital elements, the mass function $f_M$ is calculated as

$$f_M = \frac{(M_c \sin i)^3}{(M_\ast + M_{\infty})^2} = \frac{4\pi^2 (d_x \sin i)^3}{G \frac{P_B^2}{2}}. \quad (10)$$

where $G$ is the gravitational constant and $M_c$ is the mass of the companion star. Table 2 yields $f_M = 7.6 \pm 0.3 M_\odot$ if
Fig. 5. (i) Bolometric luminosity estimated from the 2–20 MAXI/GSC light curve in 1 d time bins. (ii) Barycentric pulse period measured with the RXTE/PCA (blue) and the Fermi/GBM (red), fitted with equations (7)–(9). Black and green solid lines represent the best-fit model with free $\gamma$ and that with $\gamma = 6/7$, respectively. A dashed line represents the period modulation due to the orbital Doppler effect. (iii) Residuals of the data from the best-fit model with free $\gamma$. (iv) Residuals from the $\gamma = 6/7$ model.

$\gamma = 6/7$, and $13.3 \pm 2.5 M_\odot$ if $\gamma$ is left free. Assuming the mass of the pulsar to be $M_{\text{NS}} = 1.4 M_\odot$, the condition of $\sin i \leq 1.0$ constrains the companion mass as $M_* \geq 9.9 M_\odot$ for $f_M = 7.6 M_\odot$ and $\geq 15.7 M_\odot$ for $13.3 M_\odot$. This agrees with the typical Be-star mass. The system is actually suggested to be edge on ($i \sim 90^\circ$) from the emission and absorption lines in the optical spectra (Corbet et al. 1986).

The obtained orbital eccentricity of $e \simeq 0.5$ is typical of a Be/XBP subgroup that is characterized by a long spin period $P_{\text{spin}} \gtrsim 100$ s and a long orbital period $P_B \gtrsim 100$ d (Knigge et al. 2011). The value of $e \simeq 0.5$ and $B_s = 4.7 \times 10^{12}(1 + z_c)\text{ G}$ of GX 304–1 are in line with the positive correlation found by Yamamoto et al. (2014) between these two quantities.

4.3 Evolution of outburst light-curve profiles and Be disk

The outburst orbital profile is considered to reflect the spatial extent of the circumstellar disk around the Be star on the pulsar orbit. During the 3.5 years of the active period from 2009 October to 2012 November, the profile changed through a series of normal outbursts (A to G), giant outbursts with a large peak luminosity (H and I), and decay phase (J to L). This evolution behavior vary much resembles those of other Be X-ray binaries, including A 0535+26 (Camero-Arranz et al. 2012; Nakajima et al. 2014) and GRO J1008–57 (Kühnel et al. 2013; Yamamoto et al. 2014). Therefore, the same physical mechanism is considered to be working in those systems. To explain this,
Table 2. Best-fit orbital parameters.*

| Parameter | Model                               |
|-----------|-------------------------------------|
| $P_B$ (d) | 132.189 (fix)                        |
| $a_x \sin i$ (lt-s) | 498 ± 6 601 ± 38 |
| $e$       | 0.524 ± 0.007 0.462 ± 0.019         |
| $t_0$ (MJD) | 55423.020 ± 0.0010 55423.6 ± 0.5 |
| $P_0$ (s) | 275.4441 ± 0.0008 275.459 ± 0.008  |
| $\omega_0$ (°) | 122.5 ± 0.4 130.0 ± 4.4          |
| $\alpha /0.017$ | 3.27 ± 0.02 < 0.23        |
| $\beta$ (10$^{-9}$ s$^{-1}$) | 7.6 ± 0.3 13.3 ± 2.5           |
| $\gamma$ | 6/7 (fix) 1.243 ± 0.031            |
| $f_{\text{M}}$ (M$\odot$) | 7.6 ± 0.3 13.3 ± 2.5           |
| $\chi^2$/dof | 276.3/103 168.0/102               |

*All errors represent 1σ confidence limit of the statistical uncertainty.

Fig. 6. Pulsar binary orbits obtained in the two period-change models with $\gamma$ free (black) and $\gamma = 6/7$ (blue), projected on a plane including the line of sight. (Color online)

a couple of scenarios, including global one-armed oscillation and precession of the Be disk, have been proposed (Nakajima et al. 2014, and references therein). The detailed modeling is out of the scope of the present paper.

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