Decades’ long-term variations in NS-LMXBs observed with MAXI/GSC, RXTE/ASM and Ginga/ASM

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Abstract

We investigated the decades’ long-term X-ray variations in bright low-mass X-ray binaries containing a neutron star (NS-LMXB). The light curves of MAXI/GSC and RXTE/ASM covers ~ 26 yr, and high-quality X-ray light curves are obtained from 33 NS-LMXBs. Among them, together with Ginga/ASM, two sources (GX 3+1 and GX 9+1) showed an apparent sinusoidal variation with the period of ~ 5 yr and ~ 10 yr in the 34 yr light curve. Their X-ray luminosities were $(1-4) \times 10^{37}$ erg s$^{-1}$ in the middle of the luminosity distribution of the NS-LMXB. Other seven sources (Ser X-1, 4U 1735-444, GX 9+9, 4U 1746-37, 4U 1708-40, 4U 1822-000, and 1A 1246-588) have also similar sinusoidal variation, although the profiles (amplitude, period, and phase) are variable. Comparing the 21 sources with known orbital periods, a possible cause of the long-term sinusoidal variation might be the mass transfer cycles induced by the irradiation to the donor star.

Key words: accretion, accretion disks — stars: neutron — X-rays: binaries

1 Introduction

Many of the bright X-ray sources are low mass X-ray binaries with a weakly magnetized neutron star (NS-LMXB: see Barret 2001 for a review). Based on the temporal activity, NS-LMXBs are divided into two types: persistent type and transient type. Furthermore, many persistent NS-LMXBs and bright phases of transient NS-LMXBs are divided into two groups: Z sources and Atoll sources, based on their behavior on the color–color diagram and the hardness–intensity diagram (Hasinger & van der Klis 1989). Z sources are very bright, and the luminosities sometimes become close to the Eddington luminosity ($L_E$). On the other hand, Atoll sources are generally less bright ($< 0.5 L_E$).

The orbital periods of NS-LMXBs range from minutes to ~ 20 d (Liu et al. 2007). Moreover, long-term variations on the time scale beyond the orbital period are known. These super-orbital periods range in tens to hundreds of days, which are thought to be related to the properties of the accretion disk, such as radiation-induced warping and precession (see Charles et al. 2008 for a review). On the other hand, several NS-LMXBs display very long-term quasi-periodic modulations (approximately several to tens of years). The variations are thought to have a different origin. Kotze and Charles (2010) (hereafter KC10) suggest that the long-term variations are due to the variation of the mass-transfer rate from the donor, which is a consequence of solar-like magnetic cycles (Applegate & Patterson 1987, Warner 1988). Solar-like cycles of ~ 10 yr are observed from many late type stars (Baliunas et al. 1995).

It is pointed out the importance of irradiation in NS-LMXBs for the outburst properties and their long-term evolution (Ritter 2008). The former is relevant to irradiating the accretion disk. Irradiation during an outburst leads to drastic changes in the outburst properties because the irradiation changes the conditions for the occurrence of disk instabilities. The latter is relevant to the irradiating donor star. The irradiation of the donor star can destabilize mass transfer and lead to irradiation-driven
mass transfer cycles, i.e., to a secular evolution. However, it is not clear to estimate the effect of irradiation for the secular evolution because of several unclear factors.

GX 3+1 shows the long-term variation on the time scale of years superimposed with the short-term variations on the time scale of hours (Seifina & Titarchuk 2012). The short-term variations are due to the transitions between branches in terms of its color–color diagram, which are independent of the long-term variation. The spectral index is constant during the long-term variations.

In this paper, we pay attention to the sinusoidal variation and report the analysis of the long-term variations during 1996–2021 for 41 NS-LMXBs. In section 2, we present the details of X-ray light curve analysis. We show the results in section 3. We discuss the cause of the sinusoidal variation in section 4.

2 Observations and data analysis

The long-term X-ray activity is continuously monitored with MAXI (Monitor of All-sky X-ray Image: Matsuoka et al. 2009) since 2009 August. We obtained long-term one-day bin light curves of MAXI/GSC (Gas Slit Camera: Mihara et al. 2011; Sugizaki et al. 2011) for 41 NS-LMXBs from 2009 August to 2021 December. We also analyzed the data of the same sources observed with the ASM (All Sky Monitor: Levine et al. 1996) onboard RXTE (Rossi X-ray Timing Explorer: Bradt et al. 1993) in 2–10 keV from 1996 February to 2011 December. The ASM data are obtained from the archived results provided by the RXTE-ASM teams at MIT and NASA/GSFC.

The obtained count rates of GSC and ASM were converted to luminosities by assuming a Crab-like spectrum (Kirsch et al. 2005) and the distance listed in table 1. ASM data are converted to a flux in Crab unit using the nominal relation of 1 Crab = 75 counts s⁻¹ for ASM. GSC data are converted to a flux in Crab unit using the nominal relation of 1 Crab = 3.45 photons s⁻¹ cm⁻² in 2–10 keV for GSC. The assumption of a Crab-like spectrum is acceptable in the hard state (low luminosity ≤ 5 × 10^{36} erg s⁻¹) because the energy spectrum is approximated by a power law with a photon index of 1–2. On the other hand, in the soft state (high luminosity ≥ 10^{37} erg s⁻¹), the energy spectrum is dominated by the thermal emission, and the luminosity obtained by assuming Crab-like spectrum is underestimated in the 2–10 keV band (Asai et al. 2015). In this paper, we do not care about it because we handle only the relative difference.

We excluded following data in each source.

GX 3+1: Data of MJD = 56187–56287 and 56652–56997 for contamination by Swift J174510.8–262411. Data of MJD = 55916–55922 for another south-west source.

SLX 1735–269: Data of MJD = 56187–56287 and 56652–56997 for contamination by Swift J174510.8–262411.

4U 1624–490: Data of MJD = 58460–58580 for contamination by MAXI J1631–479.

4U 1708–40: Data of the count rate above 1 photons cm⁻² s⁻¹ by solar X-ray leakage.

4U 1916–053: Data of MJD = 55945–55951 and MJD = 56311–56315 by solar X-ray leakage.

4U 1323–619: Data of MJD = 58509–58610 for contamination by MAXI J1348–630.

Ser X-1: Data with the errors above 0.012 Crab in 2–10 keV.

We analyzed ASM and GSC data of the 41 NS-LMXBs and investigated the long-term variability during ~ 26 yr (see table 1). The X-ray light curves are shown in the Appendix. Here we used GSC data for the overlapped period during MJD = 55100–55800. Table 1 shows the flux ratio of ASM and GSC during the overlapped period.

We estimated the luminosity in the 2–10 keV energy band from MJD = 55100 to MJD = 59662 for the 41 NS-LMXBs using GSC data and listed in L_{ave}. High-quality persistent light curves are obtained from 33 sources. The remaining eight sources are excluded from the following analyses. Six of excluded eight sources are transients sources. The active period of HETE J1900.1–2455 is too short (< 10 yr) to investigate the long-term variability. Other sources (EXO 1745–248, Aql X-1, XTE J1709-267, 4U 1608–522, and 4U 1745–203) are below the GSC detection limit during quiescence. The other excluded two sources, SAX J1747.0–2853 and 4U 1724–307, have contamination from nearby sources.

KC10 indicated that all the 20 sources in their paper were considered to be better fitted with a single sine wave than with a constant value. We also focus on the properties of the sinusoidal variation. Here, we tried to classify observed variations into five types as follows. The types are described in the comment column of table 1.

CP (clear periodic variation): Two bright Atoll sources (GX 3+1 and GX 9+1) show clear sinusoidal variations. We define CP sources as can be fitted with a single sinusoidal curve and a tilted line. We focus on these sources in the next session.

MP (modified periodic variation): Seven sources (Ser X-1, 4U 1735–444, GX 9+1, 4U 1746–37, 4U 1708–40, 4U 1822–000, and 1A 1246–588) show the modified periodic variation. It is difficult to fit their light curves with the periodic model functions. We also focus on these sources in the next session.

NP (no periodic variation): Nineteen sources show no periodic variation. Eight sources (Z sources and GX 13+1) of them show almost constant baseline although there are
Table 1. List of NS-LMXBs observed with MAXI/GSC and RXTE/ASM.

| Name       | Type† | $L_{\text{ave}}$ | Distance | $P_{\text{orb}}$ | ASM/GSC§ | Comment ‡ | Reference # |
|------------|-------|------------------|----------|-----------------|----------|------------|-------------|
| Sco X-1    | Z     | 222              | 2.8      | 18.90           | 0.95     | NP         | (1)         |
| GX 17+2    | Z     | 209              | 12.6     | –               | 0.97     | NP         | (2)         |
| GX 5−1     | Z     | 173              | 9        | –               | 0.94     | NP         | (3)         |
| Cyg X-2    | Z     | 129              | 11       | 235.2           | 0.97     | NP         | (4)         |
| GX 349+2   | Z     | 126              | 5        | 22.5            | 0.88     | NP         | (3)         |
| LMC X-2    | Z     | 99               | 50       | 8.16            | 1.02     | NP         | (5)         |
| GX 340+0   | Z     | 96               | 11       | –               | 0.98     | NP         | (3)         |
| GX 13+1    | Z, A  | 35               | 7        | 577.6           | 0.92     | NP         | (1)         |
| 4U 1820−303| A, UCXB | 34          | 7.6      | 0.19            | 1.02     | FV         | (1)         |
| Ser X-1    | A     | 33               | 8.4      | 2               | 0.96     | MP         | (1)         |
| GX 9+1     | A     | 29               | 5.0      | –               | 0.96     | CP         | (1)         |
| 4U 1705−440| A     | 21               | 7.4      | –               | 1.00     | FV         | (1)         |
| 4U 1735−444| A     | 22               | 8.5      | 4.65            | 1.00     | MP         | (4)         |
| 4U 1624−490| ADC   | 21               | 15       | 20.89           | 1.06     | NP         | (7)         |
| SAX J1747.0−2853 | T | 20 | 9 | – | – | – | (8) |
| GX 9+9     | A     | 12               | 5.0      | 4.20            | 0.98     | NP         | (3)         |
| 4U 1254−690| A     | 11               | 13       | 3.93            | 0.99     | NP         | (10)        |
| Cir X-1    | Z, A  | 12               | 7.8      | 398.4           | 1.04     | LV         | (6)         |
| GX 3+1     | A     | 10               | 4.5      | –               | 1.14     | CP         | (9)         |
| GS 1826−238| T     | 8.4              | 7.0      | 2.088           | 1.41     | LV         | (11)        |
| 4U 1746−37 | A     | 6.8              | 11.0     | 5.16            | 0.76     | MP         | (1)         |
| 4U 1708−40 | -     | 5.3              | 8        | –               | 0.83     | MP         | (12)        |
| 4U 1724−307| -     | 4.1              | 7.4      | –               | –        | –          | (1)         |
| 4U 1543−624| UCXB  | 3.9              | 9.2      | 0.303           | 1.02     | NP         | (1)         |
| 4U 1636−536| A     | 3.8              | 6.0      | 3.80            | 0.99     | LV         | (1)         |
| Aql X-1    | T     | 2.7              | 5.0      | 18.95           | –        | –          | (1)         |
| 4U 2127+119(M15 X-2)| UCXB | 2.4          | 10.3     | 0.376           | 0.90     | NP         | (13)        |
| 4U 0513−40 | UCXB  | 2.3              | 12       | –               | 1.03     | NP         | (14)        |
| EXO 1745−248| T | 2.0              | 5.9      | –               | –        | –          | (15)        |
| 4U 1608−522| T     | 1.9              | 4.1      | 12.89           | –        | –          | (1)         |
| 4U 1822−000| -     | 1.8              | 6.3      | 3.2             | 0.92     | MP         | (16)        |
| XTE J1709−267| T  | 1.4              | 8.5      | –               | –        | –          | (17)        |
| 4U 1916−053| UCXB  | 1.2              | 8.9      | 0.83            | 1.40     | NP         | (18)        |
| 4U 1745−203| T     | 1.1              | 8.5      | –               | –        | –          | (15)        |
| 4U 0614+091| UCXB  | 1.1              | 3.2      | –               | 0.94     | NP         | (18)        |
| SLX 1735−269|-   | 1.0              | 7.3      | 2.64            | –        | –          | (4)         |
| HETE J1900.1−2455 | T  | 0.9              | 5        | 1.39            | –        | –          | (4)         |
| 1H 0918−548| UCXB  | 0.5              | 4.8      | –               | 0.94     | NP         | (19)        |
| 1A 1246−588| UCXB  | 0.4              | 5        | –               | 0.83     | MP         | (20)        |
| 4U 1323−619| -     | 0.3              | 4.2      | 2.93            | 0.64     | NP         | (21)        |
| 1H 1556−605| -     | 0.3              | 4        | 9.1             | 1.58     | NP         | (3)         |

* The source types are indicated by 'Z'-Z source, 'A'-Atoll source, 'ADC'-ADC source, 'UCXB'-Ultra Compact X-ray Binary, 'T'-transient.
† Luminosity in the 2–10 keV band in the unit of $10^{36}$ erg s$^{-1}$ from MJD=55100 to MJD=59662.
‡ Orbital periods of systems are adopted from Liu et al. (2007) except for Ser X-1 (Cornelisse et al. 2013).
§ ASM/GSC for MJD=55100–55460.
¶ Type of variation: 'CP' show a clear periodic variation, 'MP' show a modified periodic variation, 'NP' show no periodic variation, 'FV' show fast variability, 'LV' show large variability, ‘–’ are Transient and Contamination sources.
# Reference of distance. (1) Liu et al. (2007), (2) Lin et al. (2012), (3) Christian and Swank (1997), (4) Galloway et al. (2008), (5) Freedman et al. (2001) (6) D’Ai et al. (2012), (7) Xiang et al. (2007), (8) Natalucci et al. (2000) (9) Kuulkers and van der Klis (2000), (10) in’t Zand et al. (2003), (11) Barret et al. (2000), (12) Revnivtsev et al. (2011), (13) White and Angelini (2001), (14) Harris (1996), (15) Valenti et al. (2007), (16) Shahbaz et al. (2007), (17) Luidlum et al. (2017), (18) Kuulkers et al. (2010), (19) Jonker and Nelemans (2004), (20) Jonker et al. (2007), (21) Gambino et al. (2016).
small variations around baseline. Other eight sources (X-ray luminosities $< \sim 3 \times 10^{37}$ erg s$^{-1}$) of them show almost constant. The remaining three sources (4U 1543—624, 4U 1916—053, and 1H 1556—605) show a decreasing trend in luminosity.

**FV (fast variation):** Two sources (4U 1820—303 and 4U 1705—440) have the luminosity change with a shorter variability than 1 yr. The variation seems to have a different origin from that of the sinusoidal variation investigated in this paper.

**LV (large variation):** Three sources (Cir X-1, 4U 1636—536, and GS 1826—238) show the large luminosity change of 1—2 orders of magnitude. Again, the large luminosity change seems to have a different origin from that of the sinusoidal variation investigated in this paper.

Figure 1a shows the average luminosity against the binary separation for 21 sources. The orbital periods of 21 sources are known among 33 sources. The binary separation was estimated by Kepler’s third law assuming a neutron star mass of 1.4 $M_\odot$ and the mass of the donor star of 0.5 $M_\odot$ although their actual masses are uncertain. We also display the types in the figure. Especially, filled marks indicate periodic variation, which are relevant to the long-term variation investigated in this paper.

Figure 1b shows the irradiating flux on the donor star against the binary separation. Here we treated the donor star as a point source and calculated simply irradiation flux $F = L/4\pi d^2$, where $L$ and $d$ denote the average luminosity and the binary separation, respectively.

Next, we pick up CP and MP sources with periodic and modified periodic variation. To confirm the property of variation, we also analyzed the archive data of the X-ray All Sky Monitor (ASM; Tsunemi et al. 1989) on board the Ginga satellite (Makino & ASTRO-C Team 1987). The Ginga/ASM data from 1987 to 1991 are obtained from the archived site of DARTS. The 1–6 keV counts s$^{-1}$ are converted to the 2–10 keV flux assuming the spectrum of Crab nebula. For 1A 1246—588 (MP), there were no data of Ginga/ASM.

### 3 Results

Figure 2 shows the light curves of two CP sources (GX 3+1 and GX 9+1) with the apparent sinusoidal variation from 1987 to 2021. First, we fitted the light curves of GX 3+1 and GX 9+1 with a sinusoidal and linear function model. The fitting parameters are shown in table 2.

Next, in order to investigate the variability of the sinusoidal profile of two CP sources and seven MP sources, we fit each peak with a Gaussian profile (figure 3 and 4). The parameters are the width (sigma) of Gaussian profile (GW) and the peak luminosity (GN). Those correspond to the period and amplitude of the sinusoidal variation, respectively. In order to see variability of the peak luminosity and width, we plotted the GN against the GW in figure 5. The amplitude and periods of two CP sources (GX 3+1 and GX 9+1) are more stable than those of MP sources. The average GWs for each source are $\sim 300$—2300 d, which correspond approximately to a half sinusoidal period of GX 3+1 ($\sim 2.5$ yr) and a period of GX 9+1 ($\sim 10$ yr), respectively.

The individual properties in the nine sources are as follows:

**GX 3+1 (figure 2a and 3a):** The sinusoidal variation is clear, although the shapes of sinusoidal profiles are complex with some peaks. The baseline decreases. The long-term period is $\sim 6$ yr, which is similar to the results of KC10. The long-term periodic variation turned to be stable over the twice time-length in KC10.

**GX 9+1 (figure 2b and 3b):** The sinusoidal variation is also clear but with a little longer period ($\sim 11$ yr) than that of GX 3+1. The baseline has gradually increased in $\sim 25$ yr, which is against the KC10 report that the baseline was constant for $\sim 13$ yr observed by RXTE/ASM. The period of long-term is similar to the results ($\sim 12$ yr) of KC10.

**Ser X-1 (figure 4a):** Quasi periodic modulation is clear. The period is not constant, but seems to become longer.

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5 <https://data.darts.isas.jaxa.jp/pub/ginga/GINGA-ASM-1.2/>.
Fig. 2. Light curves observed by Ginga/ASM, RXTE/ASM, and MAXI/GSC. For GX 3+1 and GX 9+1, we show the fitted sinusoidal curves in red (Color online). The model function and parameters are shown in Table 2. The data of GX 9+1 has a discrepancy between ASM and GSC fluxes. MAXI data are processed in a regular way as for other sources. There is no contamination source nor background uncertainty by the ridge emission. So we plotted the data as they are.

Table 2. Fitting results of a sinusoidal and linear function model. Plots in figure 2.

| Name   | Model* | Average luminosity   | Sin | Slope† |
|--------|--------|----------------------|-----|--------|
|        |        | ($10^{36}$ erg s$^{-1}$) | $A^\dagger$ | $P^{\ddagger}$ (d) | ($10^{36}$ erg s$^{-1}$ d$^{-1}$) |
| GX 3+1 | CONS+LINR+SIN | 9.7                  | 0.28 | 2046 | $-4.81 \times 10^{-4}$ |
| GX 9+1 | CONS+LINR+SIN | 29.5                 | 0.09 | 3542 | $1.90 \times 10^{-5}$ |

* Model components. CONS: constant component, LINR: linear component, SIN: sinusoidal component.
† Amplitude of sinusoidal component against average luminosity.
‡ Period of sinusoidal component.
§ Slope of baseline.

Fig. 3. Light curves of two CP sources fitted the gaussian peaks. Parameters are shown in Table 3. The fitting results were shown in red color curve. (Color online)
Fig. 4. Light curves of seven MP sources fitted the gaussian peaks. Parameters are shown in table 3. The fitting results were shown in red color curve. For 1A1246–588, there were no data of Ginga/ASM. (Color online)
KC10 reported the period of $\sim 7.3$ yr observed by RXTE/ASM. In the MAXI/GSC era, the period is longer and amplitude may be larger.

4U 1735–444 (figure 4b): The sinusoidal variation is clear. However, the period is not constant, but seems to become shorter. KC10 reported the period of $\sim 10$ yr from the large hump around MJD=53000. In the MAXI/GSC era, the period is shorter, about a half, and amplitude may be smaller.

GX 9+9 (figure 4c): Although KC10 reported that the baseline was increasing, it cannot be extrapolated in the MAXI/GSC era. The light curve dropped after RXTE/ASM. Since then the baseline has stayed almost constant. However, the long-term period is similar to the results ($\sim 4$ yr) of KC10 throughout by RXTE/ASM and MAXI/GSC. The amplitude of the sinusoidal variation seems to be smaller in the MAXI/GSC era.

4U 1746–37 (figure 4d): Quasi periodic modulation is clear. However, the period and the amplitude is not constant. KC10 reported the period of $\sim 4.36$ yr observed by RXTE/ASM.

4U 1708–40 (figure 4e): Quasi periodic modulation is clear. However, the period and the amplitude is not constant. Although we divided the data into small peak with short period, the data of MAXI/GSC era can also be fitted with one gaussian profile for large one peak. KC10 did not report this source, because they focused on the Z sources and Atoll sources.

4U 1822–000 (figure 4f): Quasi periodic modulation is clear. However, the period and the amplitude is not constant.
Fig. 5. The center luminosity of Gaussian model (GN) as a function of the width of Gaussian model (GW). Filled circles represent data of CP sources. Filled triangles and open squares represent data of MP sources. To avoid the confusion of data points, we use two kind of marks.

Although we divided the data between MJD=54800 and 57000 into two small peak with short period, the data can also be fitted with one gaussian profile for large one peak. KC10 did not report this source.

1A 1246–588 (figure 4g): Quasi periodic modulation is seen. However, the period and the amplitude is not constant. KC10 did not report this source.

4 Discussion

The long-term sinusoidal variations were presented for the two CP sources (GX 3+1 and GX 9+1). The long-term periods range in ~5 yr and ~10 yr as shown in table 2–3 and figure 2–3. We also investigated the seven MP sources with modified periodic variation, and estimated periods of quasi-periodic modulation (table 3 and figure 4). The rage of each average period was approximately from ~2.5 yr to ~10 yr. These time scales are much longer than the orbital period (~2–5 hr), although, strictly speaking, those of the four sources (CP: GX 3+1, GX 9+1 and MP:4U 1708–40, 1A 1246–588) are unknown.

We discuss mechanisms of long-term variation. First, we focus on the physical motion of the accretion disk. Precession of accretion disk may occur due to excitation of resonances in case of mass ratio of $q = M_d/M_{NS} \sim 0.25–0.33$ (Whitehurst & King 1991). It is likely to occur in the case of LMXBs with donor mass of $0.35M_\odot–0.46M_\odot$. Although the donor mass of our CP and MP sources are not known, precession of accretion disk could be possible. In general, according to Inoue (2012), precession occurs when the ratio of the precession period $P_p$ to the binary orbital period $P_B$ is $P_p/P_B = 10–100$. The ratios of our results are $P_p/P_B \geq 10^4$. There is no such case in figure 2 of Inoue (2012). However, if we extrapolate one line for $P_p/P_B = 10^4$, the range of donor mass for $0.14M_\odot–0.42M_\odot$ ($q \sim 0.1–0.3$) would be possible. Since donor mass is not known, the disk precession scenario could be possible.

On the other hand, another possibility of radiation-induced warping is excluded. Kotze and Charles (2012) explicitly dis-
cuss the stability of radiation-induced warping. In the region below the bottom solid line in their figure 1, a radiation-induced warping of the disk is unlikely, and there is in fact no superorbital cycle observed in this region. Our four sources lie between the values of mass ratio: \( q = M_\text{e}/M_\text{NS} \sim 0.3 \) and orbital period \( \sim 2 - 5 \text{ hr} \). Thus the radiation-induced warping of the accretion disk is unlikely.

Next, we consider the possibility of the variation of mass transfer rate from the donor. KC10 suggested that they are consequence of the solar-like magnetic cycles seen in the late-type star (Applegate & Patterson 1987, Warner 1988). They pointed out that the flux modulation of a sin wave of \( \leq 30 \) percent is plausible by the magnetic cycles. In our result, the flux modulation (see the amplitude of table 2) is \( \leq 30 \) percent. Thus the solar cycle-like variations can be responsible for its long-term variations.

Here, we discuss another possibility of the variation of mass transfer rate from the donor. It is the irradiation by the central X-ray source to the donor star. Ritter (2008) showed that irradiation-driven mass transfer cycles could only occur when the irradiation is sustained for a sufficiently long time. Büning and Ritter (2004) shows the numerical results in terms of irradiation-driven mass transfer cycles and then indicates the possibility that NS-LMXB undergoes those cycles. Their numerical results show that the stability of the mass transfer rate from the donor star is a function of the orbital period.

In figure 1, filled marks represent quasi periodic modulation (MP: Ser X-1, 4U 1735–444, GX 9+9, 4U 1746–37, 4U 1822–000) in our analysis. In figure 1b, the filled marked five MP sources are located in the region which is middle in the binary separation and high irradiation average flux. The region may tend to show a periodic modulation.

However, in the region, there are also three sources (GS 1826–238, 4U 1636–536, and 4U 1254–690) of non-periodic modulation. The 2 LV sources (GS 1826–238 and 4U 1636–536) show the large luminosity change of \( 1 - 2 \) orders of magnitude, and it is difficult to see the flux modulation of the amplitude \( ( \leq 30 \) percent \) which a change of the mass transfer rate induces. The one NP source (4U 1254–690) has similar binary properties to that of GX 9+9 (CP). The cause of no clear periodic variation is unclear.

We discuss the features of the region in which a long-term variation trend to occur. One feature is high irradiation average flux \( (\geq 1 \times 10^{13} \text{ erg s}^{-1} \text{ cm}^{-2}) \). Even in the high irradiation-flux, there are four NP sources (Sco X-1, GX 349+2, LMC X-2 and 4U1624–490) without a long-term variation in the larger binary-separation region. Here, the three sources (Sco X-1, GX 349+2, and LMC X-2) are Z sources. KC10 reported that the amplitudes of long-term variation of the Z sources are small and noted that it is because their luminosity is close to the Eddington. Although the luminosity of 4U 1624–490 is not close to Eddington luminosity, the intrinsic luminosity is uncertain because it is an ADC source. Here, we focus on the donor star. The three sources (Sco X-1, GX 349+2 and LMC X-2) are Z sources, and the donor stars are suggested to be evolved stars (Hasinger & van der Klis 1989 for Z sources, Cherepashchuk et al. 2021 for Sco X-1). 4U 1642–490 did not belong to Z sources. However, Jones and Watson (1989) reported that the flaring behavior of the source shows similarity to the flaring blackbody component (in temperature and radius) of Sco X-1 and other Z sources. Although the donor star of 4U 1624–490 is not identified, it is possible to be an evolved star, similar to the Z sources. In this case, the mass transfer rate on to the neutron star may be above the Eddington luminosity.

On the other hand, in the high irradiation-flux, but in the smaller binary-separation region, there are four sources (4U 1820–303 and three NPs: 4U 1543–624, 4U 2127+119, and 4U 1916–053). The sources are Ultra Compact X-ray Binaries (UCXBs). The donors in UCXBs may be white dwarfs (WDs) or He stars (4U 1820–303: Rappaport et al. 1987, 4U 1543–624; Nelemans et al. 2004, 4U 2127+119: Dieball et al. 2005, and 4U 1916–053: Joss 1978, Nelemans et al. 2006). Lü et al. (2017) suggests that, if the donor star is a WD, the irradiation flux can only penetrate into a very thin layer of the WD surface, and the irradiation hardly affects the evolution of the persistent UCXB. The irradiation flux would not affect the mass transfer rate from the donor star.

In summary, the intense irradiation may induce variation of the mass transfer rate, and a sinusoidal periodic variation may appear. Our results also seem to show a dependence on the donor. A WD donor would not be affected by the irradiation. The periodicity might be related to the mass transfer cycles caused by the irradiation pointed out by Ritter (2008).

Appendix. Light curves of 41 NS-LMXB observed with MAXI/GSC and RXTE/ASM

The light curve used to analyze the long-term variation are presented in this Appendix (figure 6–14). The energy band is 2–10 keV band, and the period of data is from 1996 February to 2021 December. The left side of the vertical dash line is the data of RXTE/ASM, and the right is MAXI/GSC.
Fig. 6. Light curve in 2–10 keV of sources with Z sources and GX 13+1 (NP: no periodic variation). The left side of the vertical dash line was the data of RXTE/ASM, and the right was MAXI/GSC. The MAXI/ASM flux ratio is not adjusted.
Fig. 7. As figure 6, but for CP (clear periodic variation) sources.
Fig. 8. As figure 6, but for MP (modified periodic variation) sources.
Fig. 9. As figure 6, but for NP (no periodic variation) and almost constant sources.
Fig. 10. As figure 6, but for NP (no periodic variation) and decrease sources.

Fig. 11. As figure 6, but for FV (fast variability) sources.
Fig. 12. As figure 6, but for LV (large variability) sources.
Fig. 13. As figure 6, but for Transient sources.
Fig. 14. As figure 6, but for the source with contamination.
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