Very long-term X-ray variations in LMXBs: solar cycle-like variations in the donor?

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ABSTRACT
Long-term monitoring of Low Mass X-ray Binaries (LMXBs) by the All Sky Monitor on board the Rossi X-ray Timing Explorer now covers ~13 yr and shows that certain LMXB types display very long-term (approximately several to tens of years) quasi-periodic modulations. These time-scales are much longer than any ‘super-orbital’ periods reported hitherto and likely have a different origin. We suggest here that they are due to long-term variations in the mass-transfer rate from the donor, which are a consequence of solar-like magnetic cycles that lead to \( P_{\text{orb}} \) changes (as proposed by Richman, Applegate & Patterson for similar long-term variations in cataclysmic variables). Atoll sources display much larger amplitude modulations than Z sources over these time-scales, presumably because Z sources are Eddington limited and hence unable to respond as readily as Atoll sources to fluctuations in the mass-transfer rate from the donor.

Key words: accretion, accretion discs – binaries: close – stars: magnetic fields – stars: neutron – novae, cataclysmic variables – X-rays: binaries.

1 INTRODUCTION

Low Mass X-ray Binaries (LMXBs) contain a neutron star (NS) or black hole primary on to which material is transferred from a low-mass (\( M \leq 1 \, M_\odot \)) late-type, essentially normal main-sequence star (spectral type in the range A–M), with longer period systems containing a subgiant. There are ~190 luminous (\( \lesssim 10^{38} \text{ erg s}^{-1} \)) LMXBs known in our Galaxy (Liu, van Paradijs & van den Heuvel 2007). Cataclysmic variables (CVs) are very similar, but have white dwarf (WD) primaries at an \( \sim 10^3 \) factor reduction in luminosity and have orbital periods that range from hours to \( \sim 10^d \). While the flux from LMXBs is predominantly in X-rays which originate from the inner accretion disc and the NS surface (where applicable), the flux from CVs is predominantly in the optical and originates from the entire accretion disc, the hotspot(s) on the WD surface and the disc-mass-transfer stream impact region. (For details, see e.g. Frank, King & Raine 1992.)

Long-term, non-orbital, quasi-periodic variations on time-scales of approximately tens to hundreds of days in LMXBs were discovered early in X-ray astronomy (see Charles et al. 2008 for a recent review). These ‘super-orbital’ periods are thought to be related to the properties of the accretion disc, and there are two basic mechanisms actively under consideration: radiation-induced warping (Ogilvie & Dubus 2001) and precession (Whitehurst & King 1991) of the accretion disc. Radiation pressure from the intense X-rays arising near the compact object causes the warping of the accretion disc, while tidal forces in high mass-ratio binaries lead to the precession of the accretion disc (an effect first observed in CVs; see e.g. Warner 1995). Either of these effects can lead to the periodic obscuration of the compact object in X-ray binaries, causing a super-orbital modulation in the X-ray flux (Clarkson et al. 2003). The stability criteria established by Ogilvie & Dubus (2001) suggest that this effect should not arise in most LMXBs; however it is observed, for example, in the long-period LMXB Cyg X-2 (Clarkson et al. 2003).

The presence of even longer term quasi-periodic variations (on the order of decades) has been predicted in CVs as a consequence of the modulation in the mass-transfer rate due to a solar-type magnetic-activity cycle occurring in the donor star (Applegate & Patterson 1987; Warner 1988). The donor stars in short-period LMXBs and CVs are tidally locked and therefore rotate at the orbital period of the binary system, which is \( \lesssim 1 \, d \) for most systems. This rapid rotation is expected to generate much stronger magnetic fields (Schrijver & Zwaan 1992). Long-term variability changes in the surface activity of stars (such as starspot activity) have been detected on time-scales of decades (Baliunas & Vaughan 1985), similar to the ~11 yr magnetic-activity cycle of our Sun.

Applegate (1992) suggested that magnetically active donors become more oblate as their outer layers are spun up, due to angular momentum distribution changes brought about by their magnetic activity. As a result, the volume of the Roche lobe changes during...
the magnetic cycle, while the volume of the donor remains unchanged. The magnetic-activity cycle therefore governs the Roche-lobe volume and the structure of the donor, which will be varying in oblateness as the cycle progresses. Such a variation will modulate the amount by which the donor overfills the Roche lobe and therefore the mass-transfer rate will also vary on the magnetic-activity time-scale [as discussed by Richman et al. (1994, hereafter R94) for CVs].

Considering the similarities between LMXBs and CVs, it is not unreasonable to expect similar long-term modulations in LMXBs for the same reason. Online archival data sets now allow for a detailed investigation of long-term variations in the light curves of X-ray sources. Here, we report on an analysis of the ~13-yr X-ray history of LMXBs contained in the Rossi X-ray Timing Explorer (RXTE)/All Sky Monitor (ASM) data sets.

Shortly before completing this paper, we became aware of the paper of Durant et al. (2009). While they mention similar long-term time-scales of the X-ray flux modulations in the 16 brightest persistent LMXBs contained in the RXTE ASM data sets, we propose here a mechanism which would explain the observed dichotomy between Atoll and Z sources, and for the origin of these long time-scales.

2 OBSERVATIONS AND DATA ANALYSIS

2.1 RXTE/ASM

The ASM aboard the RXTE is provided and operated by the Massachusetts Institute of Technology (MIT). The ASM has observed the X-ray sky since early 1996 by scanning approximately 80 per cent of the sky during each orbit of the satellite, providing monitoring of a source every ~90 min for at least 90 s. The ASM contains three rotating Scanning Shadow Cameras, allowing positional measurement of previously unknown sources to within 3 arcmin precision and providing individual monitoring sessions, which are referred to as ‘dwells’.

Data are available in four energy bands: 1.5−3 keV (A), 3−5 keV (B), 5−12 keV (C) and a sum band 1.5−12 keV (A+B+C). Data for each energy band are reduced independently by taking background effects into account and made available as dwell-by-dwell or 1-d averages. Data are reduced and compiled weekly by the ASM team and made publicly available. For full details, see Levine et al. (1996).

The ASM monitoring began on 1996 February 20, and for this paper we were able to employ data sets spanning more than 13 yr. Therefore, these archival data sets contain the long-term intensity history of all X-ray sources in the RXTE catalogue. The fact that RXTE is sensitive in the soft X-ray regime (2−10 keV) is particularly useful for the studies of LMXBs, since their largest flux contribution comes from soft X-rays.

2.2 Data reduction

The full ASM light curves of all 44 significantly detected LMXBs (average flux of >0.5 counts s⁻¹) were considered for further analysis. Transients were excluded (Aql X-1, GRO J1655−40, GX 339−4, H1743−322, 4U 1543−47, 4U 1608−52, 4U 1630−47, XTE J1550−564, XTE J1701−462 and XTE J1859+226), since their outburst(s) is the only reason why these sources were detected above the 3σ level. 4U 1820−30 was excluded, since it is almost certainly a triple system (Chou & Grindlay 2001), which would have additional dynamics compared to the other LMXBs and is therefore not relevant in our analysis here. Cir X-1 was also excluded, since its highly eccentric orbit (Murdin et al. 1980) will introduce large phase-dependent changes in the donor’s Roche lobe.

ASM 1-d-average sum-band light-curve data were plotted on scales appropriate for showing long-term behaviour, and from visual inspection of these light curves, it became apparent that some sources display large amplitude, very long-term modulations that appear periodic or quasi-periodic in nature. They are GX 3+1, GX 9+1, GX 9+9, GX 354−0, 4U 1636−536, 4U 1708−40, 4U 1735−444, 4U 1746−37 and Ser X-1. These are all classified as Atoll sources, with the exception of the X-ray burster 4U 1708−40. Re-examining all the Atoll sources, there appear to be very long-term modulations in all of them, although to a lesser extent than those sources listed above. Furthermore, all the Z sources display remarkably steady light curves over the long term.

For the plots, the Liu et al. (2007) classifications for LMXBs were added in square brackets (see the caption of Fig. 1 for a description of these classifications). Our subsequent analysis focused on the Z and Atoll sources, since they appear to represent the two extremes in long-term periodic behaviour. Therefore, the remaining sources [4U 1254−69, 4U 1556−60, 4U 1624−49, Her X-1, 4U 1708−40, MXB 1730−335, KS 1731−260, 4U 1822−000, 2A 1822−371, GS 1826−238, GRS 1915+105, 4U 1957+11] were not considered further.

2.3 Variability analysis

The variability analysis was conducted on ASM dwell-by-dwell data, which were rebinned into 10 d bins, using the prescribed filters (see footnote 1) for constructing ASM averages. These are \( \chi^2 < 1.5 (<8 \, \text{for Sco X-1}) \), number of sources in the field of view <16, Earth angle of >75°, exposure time of >30 s, long-axis angle of \( -41.5 < \theta < 46^\circ \) and short-axis angle of \( -5 < \phi < 5^\circ \). Additional filters applied are: background counts of <10, hardness ratio \( -5 < \frac{B+C}{A} < 5 \), flux error of <3 and number of data points per bin >10 to give the most reliable data set. We include data up to 2009 August 13 (50100 < MJD < 55056).

\footnote{http://xte.mit.edu/ASM1c.html}
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Since the long-term modulations displayed in these light curves have time-scales that exceed or are comparable to the observational baseline, we cannot make use of the usual period analysis tools such as periodograms. In order to estimate the time-scale of these long-term variations, single sine waves were fitted to all the Atoll sources. The results for the eight Atoll sources, which display the most significant long-term modulations, are contained in Table 1 (and Fig. 1). The results for the remaining Atoll sources are included in Table 2 (and Fig. 2).

Although the Z sources appear to display remarkably steady light curves over the long term, they can also be fitted with single sine waves but with much lower amplitudes. The results of their fits are contained in Table 3 and Fig. 3.

Uncertainties in the values obtained are included in the tables in parentheses. The binned data flux errors were adjusted by a factor, so as to obtain fits for which \( \chi^2 \sim 1 \). This gives more sensible errors on the sine-wave parameters, since the error bars for the binned data are extremely small in comparison to the larger flux variations (which dominate). The factors applied to the sources that show the largest scale systematic variations were 43.4 for Cyg X-2, 36.8 for 4U 1705—44 and 32.9 for Sco X-1. The factors applied to the rest of the sources range from 1.5 to 14.7, which are comparable to the factor of 3.1 required for a constant fit to the Crab.

The F-statistic was calculated for the two models of a constant fit and a single sine-wave fit to the data. For GX 9+9, the simpler model considered was a linear variation with time. The calculated F-values of \( > 99 \) per cent confidence. The F-values are highest in those sources where we could detect long-term variation by simple visual inspection. Even the lowest F-values determined \( \sim (2–10) \) are still highly significant, indicating that all the sources considered here were better fitted with a single sine wave than with a constant value.

Flux modulations of \( \sim 8–30 \) per cent of the average flux values are present in the Atoll sources, with the exception of the superburst 4U 1636—536 and the burster GX 13+1. It is possible that the modulation detected in 4U 1636—536 represents a superburst, rather than the long-term modulations we consider to be present in the other sources (which may also be the case for KS 1731—260). GX 13+1 is classified as an Atoll source, but it shares certain properties with Z sources (Liu et al. 2007). Indeed, we find that its amplitude for the very long-term modulation rather agrees with those found in the Z sources than with those obtained for the Atoll sources. Flux

\[ \text{Table 1. ASM properties of the eight significantly modulating Atoll sources.} \]

<table>
<thead>
<tr>
<th>Source</th>
<th>Average$^a$ flux (counts s$^{-1}$)</th>
<th>Amplitude$^a$ (per cent of flux)</th>
<th>Period$^a$ (yr)</th>
<th>F-stat.</th>
</tr>
</thead>
<tbody>
<tr>
<td>4U 1636—536</td>
<td>10.2(2)</td>
<td>49(4)</td>
<td>17.6(7)</td>
<td>1.336</td>
</tr>
<tr>
<td>GX 9+9</td>
<td>20(4)</td>
<td>8(2)</td>
<td>3.95(3)</td>
<td>2.111</td>
</tr>
<tr>
<td>GX 354—0</td>
<td>6.8(1)</td>
<td>31(7)</td>
<td>7.9(2)</td>
<td>0.49</td>
</tr>
<tr>
<td>4U 1735—444</td>
<td>14.14(7)</td>
<td>28(1)</td>
<td>10.3(1)</td>
<td>0.491</td>
</tr>
<tr>
<td>GX 3+1</td>
<td>20.8(2)</td>
<td>29(4)</td>
<td>6.07(7)</td>
<td>1.133</td>
</tr>
<tr>
<td>4U 1746—37</td>
<td>2.70(5)</td>
<td>27(9)</td>
<td>4.36(8)</td>
<td>0.35</td>
</tr>
<tr>
<td>GX 9+1</td>
<td>38.0(1)</td>
<td>12.5(2)</td>
<td>12.0(2)</td>
<td>0.391</td>
</tr>
<tr>
<td>Ser X-1</td>
<td>16.27(8)</td>
<td>9(2)</td>
<td>7.3(2)</td>
<td>0.58</td>
</tr>
</tbody>
</table>

$^a$The numbers in parentheses are 1σ errors on the fits as described in the text and refer to the last decimal place quoted.

\[ \text{Table 2. ASM properties of the remaining Atoll sources.} \]

<table>
<thead>
<tr>
<th>Source</th>
<th>Average$^a$ flux (counts s$^{-1}$)</th>
<th>Amplitude$^a$ (per cent of flux)</th>
<th>Period$^a$ (yr)</th>
<th>F-stat.</th>
</tr>
</thead>
<tbody>
<tr>
<td>4U 0614—091</td>
<td>3.03(5)</td>
<td>16(7)</td>
<td>10.4(7)</td>
<td>0.26</td>
</tr>
<tr>
<td>4U 1702—429</td>
<td>3.23(7)</td>
<td>23(11)</td>
<td>6.9(3)</td>
<td>0.19</td>
</tr>
<tr>
<td>4U 1705—44</td>
<td>13.3(4)</td>
<td>13(10)</td>
<td>9(1)</td>
<td>0.3</td>
</tr>
<tr>
<td>4U 1724—307</td>
<td>2.4(1)</td>
<td>21(28)</td>
<td>12(3)</td>
<td>0.6</td>
</tr>
<tr>
<td>GX 13+1</td>
<td>22.61(7)</td>
<td>2(1)</td>
<td>6.7(4)</td>
<td>0.10</td>
</tr>
</tbody>
</table>

$^a$The numbers in parentheses are 1σ errors on the fits as described in the text and refer to the last decimal place quoted.

\[ \text{Table 3. ASM properties of the Z sources.} \]

<table>
<thead>
<tr>
<th>Source</th>
<th>Average$^a$ flux (counts s$^{-1}$)</th>
<th>Amplitude$^a$ (per cent of flux)</th>
<th>Period$^a$ (yr)</th>
<th>F-stat.</th>
</tr>
</thead>
<tbody>
<tr>
<td>LMC X-2</td>
<td>1.56(2)</td>
<td>12(7)</td>
<td>17(2)</td>
<td>0.67</td>
</tr>
<tr>
<td>Sco X-1</td>
<td>896(3)</td>
<td>4(1)</td>
<td>9.1(4)</td>
<td>0.27</td>
</tr>
<tr>
<td>GX 340+0</td>
<td>27.7(3)</td>
<td>12(6)</td>
<td>20(2)</td>
<td>0.75</td>
</tr>
<tr>
<td>GX 349+2</td>
<td>49.8(3)</td>
<td>6(5)</td>
<td>18(2)</td>
<td>0.53</td>
</tr>
<tr>
<td>GX 5—1</td>
<td>70.7(3)</td>
<td>4.8(4)</td>
<td>17(2)</td>
<td>0.46</td>
</tr>
<tr>
<td>GX 17+2</td>
<td>43.4(6)</td>
<td>7(5)</td>
<td>23(4)</td>
<td>0.97</td>
</tr>
<tr>
<td>Cyg X-2</td>
<td>37.2(3)</td>
<td>3(2)</td>
<td>4.6(4)</td>
<td>0.4</td>
</tr>
</tbody>
</table>

$^a$The numbers in parentheses are 1σ errors on the fits as described in the text and refer to the last decimal place quoted.

\[ \text{Figure 2. Remaining Atoll sources: binned 10-d-average RXTE/ASM light curves.} \]

\[ \text{Figure 3. Z sources: binned 10-d-average RXTE/ASM light curves.} \]
modulations are <13 per cent for the Z sources, with the brighter sources having the lower amplitudes.

3 DISCUSSION

Both Atoll and Z sources contain NS primaries, but Z sources have fluxes that are ∼0.5–1L_{Edd}, whereas Atoll sources and bursters have fluxes of ∼0.01–0.5L_{Edd} (van der Klis 2006). Once at the Eddington limit (L_{Edd}), Z sources are unlikely to show any X-ray flux modulation due to additional changes in the mass-transfer rate. However, Atoll sources would be expected to modulate their flux in response to overall changes in the mass-transfer rate. The results show that, in general, Atoll sources have larger amplitude in the very long-term modulations than Z sources, which occur on very long-term time-scales in both types.

3.1 Solar-cycle type time-scales in LMXBs?

A mechanism for modulating the mass-transfer rate over long time-scales has been proposed for CVs (Applegate & Patterson 1987; Warner 1988). Given the similarities between CVs and LMXBs, we decided to investigate whether this mechanism might also be applicable to LMXBs.

Our current X-ray observational baseline for LMXBs is too short to cover multiple cycles and thereby establish the stability of these variations. However, given the similarity of these time-scales to those exhibited by solar-type stars, we use the approach of R94 for CVs and see if it is also applicable to LMXBs.

The mechanism proposed in R94 to be responsible for long-term variations in CVs is due to magnetic-activity cycles in the donors. They calculate the variation in the mass-transfer rate (ΔM/Δt) which is associated with the observed orbital period variation (∆P/Δt) brought about by this mechanism in CVs.

R94 proposed that changes in the rotation of a thin outer shell (mass M₁) of the donor (mass M₂), rotating with angular velocity (Ω), will affect the orbital period. They calculate that

$$\frac{\Delta P}{P} = -0.04 \left( \frac{q}{1 + q} \right)^{2/3} \frac{M_1}{M_2} \frac{\Delta \Omega}{\Omega}$$

(1)

where q = M₂/M₁. They noted that the Applegate (1992) variable differential rotation rates follow the Hall (1990, 1991) differential rotation–orbital period relation and consequently applied this relation to the orbital periods for CVs to obtain ΔΩ/Ω ≈ 0.0015. They furthermore assume that ΔM/Δt ≈ 0.1 and calculate a ΔP/Δt which is consistent with the observed long-term flux variations in CVs, but consider the observed ΔP/Δt to be the best evidence for long-term cycles with a preferred time-scale of decades (5–30 yr), reminiscent of solar-like magnetic cycles (Warner 1988). They also find that CVs show quasi-periodic brightness fluctuations over that time-scale.

We apply equation (1) to the LMXB GX 9+9, which has P_{orb} = 4.1958 ± 0.0005 hr (Kong et al. 2006) and for which q = 0.25 has been found spectroscopically by Cornelisse et al. (2007). We consequently obtain ΔP/Δt = -2 × 10^{-9}.

Cornelisse et al. (2007) found no significant change in the orbital period over the ∼11 yr RXTE/ASM baseline. Considering the result for ΔP/Δt, we would not expect to detect a change in the orbital period in the RXTE/ASM dwell-by-dwell data, since the ΔP implied is ∼60 times smaller than the error in P_{orb}.

Such a change in P will cause a corresponding change in the size of the donor’s Roche lobe (R₂) and therefore modulate the mass-transfer rate M by an amount determined by R94:

$$\frac{\Delta M}{M} = \frac{1}{3} \left( \frac{a}{R_2} \right)^2 \frac{R_2}{H} \frac{M_2}{M} \frac{\Delta P}{P},$$

(2)

where H is the photospheric scaleheight of an MS donor. Assuming the standard Paczynski (1971) relation for the size of the donor’s Roche lobe gives $R_2/H = 0.27$ and if the donor in GX 9+9 also follows the CV secondary relation of $R/H = (M/M_\odot)^{0.88}$, then $\Delta M/M = 0.3$ for $R_2/H = 3200$ (see R94).

Therefore, a maximum flux modulation of ∼30 per cent is expected by virtue of the orbital period variation and we actually observe ∼8 per cent over a period $P_{long} \sim 4$ yr. In fact, this result regarding the expected maximum flux modulation will apply to all the LMXBs mentioned in this paper for the whole range of long-term periods determined from the fitted sine waves. The flux modulations determined from the fitted sine waves for the sources considered are ∼30 per cent. It is therefore quite plausible that the long-term modulations observed in the RXTE/ASM light curves of the LMXBs originate from magnetic-activity cycles in the donor, just as has been proposed for CVs.

4 CONCLUSIONS

Long-term variation in the mass-transfer rate due to the magnetic-activity cycle of the donor should translate into long-term quasi-periodic modulations of the X-ray flux for sources in which the additional material can be accreted on to the NS without violating the Eddington limit, such as Atoll sources and bursters. However, in Z sources very little (if any) of the additional material will be accreted and much lower amplitude (if any) long-term X-ray flux modulations are expected as a result of the magnetic-activity cycle of the donor.

Therefore, we conclude that RXTE/ASM light-curve data may now provide the first evidence for very long-term quasi-periodic modulations of the X-ray flux as a result of the modulation in the mass-transfer rate due to a solar-type magnetic-activity cycle in the donor star, similar to those proposed for CVs.

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