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Chapter 7

Canonical timing and spectral behavior of LMC X–3 in the low/hard state

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Abstract

We present results from three observations with the Rossi X-ray Timing Explorer (RXTE) of LMC X-3, obtained while the source was in an extended 'low/hard' state. The data reveal a hard X-ray spectrum which is well fit by a pure power law with photon index $\Gamma=1.69\pm0.02$, with a source luminosity at 50 kpc of $5-16\times10^{36}$ erg s$^{-1}$ (2–10 keV). Strong broad-band (0.01-100 Hz) time variability is also observed, with fractional rms amplitude 40±4%, plus a quasi-periodic oscillation (QPO) peak at 0.46±0.02 Hz with rms amplitude ~14%. This is the first reported observation in which the full canonical low/hard state behavior (pure hard power law spectrum combined with strong broad-band noise and QPO) for LMC X–3 is seen. We reanalyze several archival RXTE observations of LMC X-3 and derive consistent spectral and timing parameters, and determine the overall luminosity variation between high/soft and low/hard states. The timing and spectral properties of LMC X-3 during the recurrent low/hard states are quantitatively similar to that typically seen in the Galactic black hole candidates.

7.1 Introduction

Galactic X-ray binaries harboring a black hole candidate (BHC), such as Cygnus X–1 and GX 339–4, exhibit a number of distinguishable states characterized in terms of total luminosity, energy spectral parameters, and time variability (see e.g. reviews by van der Klis 1995; Tanaka & Lewin 1995; Nowak 1995, and references therein). During the high/soft state, the
2–10 keV spectrum can be modeled with a significant thermal component, and the rms time variability of the power spectral density is only a few percent. The more typical (for Galactic systems) low/hard state is well described by a non-thermal spectrum, represented by a power law with photon index \( \sim 1.7 \), and significant time variability with rms amplitudes of 30–50%. QPOs seen in this state have typical frequencies of 0.2–3 Hz (Wijnands & van der Klis 1999).

LMC X–3, a bright (up to \( 3 \times 10^{38} \text{erg s}^{-1} \)) BHC in the Large Magellanic Cloud, is highly variable on time scales from days to years. It is typically observed in the high/soft state, with an X-ray spectrum qualitatively similar to that of other BHCs in the soft state: an "ultra-soft" component and a hard (>10keV) tail (White & Marshall 1984). The ultrasoft component is well represented by an optically-thick accretion disk model (Shakura & Sunyaev 1973) with \( kT = \sim 1.1 \text{keV} \) and a variable mass accretion rate. The B3 V (V \( \sim 16.7-17.5 \)) optical counterpart shows a large velocity range with semi-amplitude K=235 km s\(^{-1}\) through its 1.7-day orbital period. The lack of eclipses implies an orbital inclination of <70° and a compact object mass of \( \sim 7M_{\odot} \) (Cowley et al. 1983; Paczynski 1983; Ebisawa et al. 1993, but see also Mazeh et al. 1986). Cowley et al. (1991) presented evidence for a long-term periodicity of \( \sim 198 \) (or perhaps \( \sim 99 \)) days based on HEAO1 and Ginga observations. This variability was attributed to the precession of a bright, tilted, and warped accretion disk. Later ASM observations reveal a much more complex, and less periodic, behavior (Nowak et al. 2001; Paul et al. 2000; P. T. Boyd, in preparation).

LMC X–3 has been the subject of two monitoring campaigns with RXTE, spanning 1996 February 2 through 1999 August 31. The first consisted of short \( \sim 1 \text{ks} \) pointings, separated by several days; the second used longer (\( \sim 8-10 \text{ks} \)) pointings separated by 3–4 weeks. Based on these data, Wilms et al. (2001) report the discovery of transitions from the high/soft to the low/hard state; during the observation with lowest count rate, the disk component vanishes and the spectrum can be fit by a pure power law. This implies that a state transition, rather than the periodically changing absorption column arising from a tilted, precessing disk, may be responsible for the low-flux episodes of LMC X–3. Wilms et al. (2001) suggest a model in which a wind-driven limit cycle gives rise to the long term variability.

The RXTE ASM light curve of LMC X–3 showed that a possible low/hard state that began around 2000 April 10 was lasting longer than typical. We therefore arranged Target of Opportunity RXTE observations to search for the characteristic time variability of BHCs in the low/hard state (Boyd & Smale 2000; Homan et al. 2000). We present the first analysis in which the full canonical low/hard state behavior for LMC X–3 is seen. This is the first time such behavior has been observed for a BHC outside our Galaxy, as well as being the first detection of QPO in LMC X–3. Our analysis of archival data shows that such low/hard states are recurrent in LMC X–3.

### 7.2 Observations and Analysis

Observations were performed with the RXTE satellite (Bradt et al. 1993) on 2000 May 3, 10 and 13 for a total on-source good time of 10.4 ksec (see Table 7.1). The PCA instrument
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<table>
<thead>
<tr>
<th>Date</th>
<th>Exposure (s)</th>
<th>Rate (counts s⁻¹ PCU⁻¹)</th>
<th>$\Gamma$</th>
<th>$A_{pl}$ (x10⁻³)</th>
<th>$\chi^2$/dof</th>
<th>$L_x$ (ergs/s) (x10⁶)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996 Jun 29</td>
<td>1056</td>
<td>2.25</td>
<td>1.83+0.08</td>
<td>6.30+0.97</td>
<td>26.8/32</td>
<td>6.3+0.9</td>
</tr>
<tr>
<td>1996 Jul 04</td>
<td>976</td>
<td>0.76</td>
<td>1.57+0.22</td>
<td>1.29+0.03</td>
<td>23.8/32</td>
<td>1.9+0.7</td>
</tr>
<tr>
<td>1996 Jul 10</td>
<td>896</td>
<td>0.76</td>
<td>1.80+0.16</td>
<td>2.52+0.80</td>
<td>30.6/32</td>
<td>2.6+0.8</td>
</tr>
<tr>
<td>1998 May 29</td>
<td>6400</td>
<td>2.15</td>
<td>1.82+0.03</td>
<td>6.06+0.30</td>
<td>21.7/32</td>
<td>6.1+0.3</td>
</tr>
<tr>
<td>1998 May 29</td>
<td>3568</td>
<td>2.20</td>
<td>1.72+0.05</td>
<td>4.86+0.40</td>
<td>26.0/32</td>
<td>5.8+0.5</td>
</tr>
<tr>
<td>2000 May 05</td>
<td>1712</td>
<td>2.56</td>
<td>1.60+0.04</td>
<td>6.01+0.45</td>
<td>36.7/52</td>
<td>8.6+0.6</td>
</tr>
<tr>
<td>2000 May 10</td>
<td>2024</td>
<td>1.5</td>
<td>1.60+0.05</td>
<td>3.30+0.34</td>
<td>32.6/52</td>
<td>4.7+0.4</td>
</tr>
<tr>
<td>2000 May 13</td>
<td>6656</td>
<td>4.86</td>
<td>1.69+0.01</td>
<td>12.7+0.26</td>
<td>65.2/55</td>
<td>15.7+0.3</td>
</tr>
</tbody>
</table>

Table 7.1: LMC X-3 RXTE Low/Hard State Observations

on RXTE consists of five Xe proportional counter units (PCUs), with a combined effective area of about 6500 cm² (Jahoda et al. 1996). In each of the three observations, 4 PCUs were collecting data. We present results using the Standard 2, E₅₀₀us₆₄M₀₅₊, and Good Xenon data modes, with effective time resolutions of 16 s, 500μs and < 1μs respectively.

The spectral data were analyzed using FTOOLS 5.0. Background subtraction was performed using the faint source model ("L7-240", v19991214). We analyzed data from the top layer only, to increase signal to noise. Response matrices were generated using PCARSP 2.43 with the latest energy-to-channel relationship (e04v01). Spectral fitting was performed using XSPEC 11.0. We ignored data below 2.5 keV and above 25 keV.

We created power spectra using the high time resolution data modes in three energy bands: 3–20 keV, 3–10 keV and 10–20 keV. No background and dead time corrections were applied. The power spectra were generated from 256s data segments, using a Nyquist frequency of 1024 Hz. The individual power spectra were averaged and rms normalized (Belloni & Hasinger 1990; Miyamoto et al. 1991). The Poisson level, determined by taking the unweighted average of all powers between 500 and 1000 Hz, was subtracted from the power spectrum. The resulting power spectrum was rebinned logarithmically (to 60 frequency bins per decade) and fitted in the 1/256–256 Hz range. Errors on the fit parameters were determined using $\Delta \chi^2 = 1$ (1σ for a single parameter of interest). For observations with low count rates (<5 counts/s/PCU) the uncertainty in the background estimation introduces an additional fractional error of 5–10% in the rms amplitudes. The errors quoted here are only the statistical ones.

7.3 Spectral Results

The long-term light curve of LMC X–3 as measured by the All-Sky Monitor (ASM) aboard RXTE is shown in Figure 7.1. Locations of the low/hard and high/soft state PCA observations
discussed below are indicated with vertical dashes.

For each of the three 2000 May observations, the spectra were well modeled with a pure power law, with photon index $\Gamma=1.6-1.7$. The derived 2–10 keV flux, on the other hand, varies by a factor $\sim3$, between $4.7$ and $15.7 \times 10^{36}$ erg s$^{-1}$ (at 50 kpc). Table 7.1 summarizes the observations and spectral fitting results; the single-component power law model is sufficient to describe the spectrum, without the need for a second continuum component or a line feature. (Wilms et al. (2001) and Nowak et al. (2001) formally include such a line in their fits but quote only upper limits on its detection. We derive an upper limit of 90 eV (90% confidence) for a Gaussian line with a width of 0.1 keV centered at 6.4 keV, comparable to the upper limit of 60 eV quoted by Wilms et al. (2001)).

In Figure 7.2 we show the data and derived model for the three observations from 2000 May. We also include for comparison a spectrum of LMC X–3 taken at the relatively high ASM rate of 3 counts/s on 1996 April 28. The high/soft spectrum is well described by the power-law plus black body model with $\Gamma=4.95$ and a disk inner-edge temperature of $kT=1.34$ keV.

During the 3.5-yr period covered by previous RXTE monitoring campaigns, LMC X–3 has displayed seven episodes where the count rate decreased to levels comparable to those seen in 2000 May (Fig. 7.1). To compare with the current observations, we extracted PCA pointings

Figure 7.1: Long term variation of LMC X–3 as observed by the RXTE All-Sky Monitor. One-day averages are shown. PCA observations discussed in this paper are indicated with vertical lines. Target of Opportunity Observations occurred near the minimum of the most recent ASM minimum.
Figure 7.2: The PCA spectra from our three observations in 2000 May, together with the pure power law fits. The flux varies from 4.7 to $15.7 \times 10^{36}$ erg s$^{-1}$ while the spectra are fit with a constant photon index $\Gamma = 1.69 \pm 0.01$. A typical high/soft state spectrum from 1996 April 28 is shown for comparison. Here, the disk + black body model is an acceptable fit, with photon index of 4.95 and a disk inner-edge temperature of 1.34 keV. The flux for this observation is $2.95 \times 10^{38}$ erg s$^{-1}$.

from the RXTE archive obtained near low ASM count rates. Many of the data sets are either too short for good statistics, or are not centered in the minimum of the low/hard state. In addition, the observations span all four gain epochs of the PCA instrument. We restricted ourselves to observations containing at least 600s of good data, from PCA gain epochs 3 and 4 (1996 April 15 and following) where the calibration is best understood. We further limited ourselves to those minima where the 1-day ASM count rate was $<0.5$ counts/sec for more than 10 days.

The selected observations are included in Table 7.1, and their times marked on Figure 7.1. The data from 1998 May 29 are presented in Wilms et al. (2001) as evidence for the low/hard state in LMC X–3, reanalyzed here with the latest backgrounds and response matrices; the remainder of the observations are previously unpublished. For each observation, the spectrum is well described by a featureless power law, with photon index $\leq 1.8$. We conclude that these low count-rate episodes have all the spectral characteristics of the low/hard state. The spectrum of the low/hard state is characterized by a pure power law with nearly constant
7.4 Timing Results

The combined 3-20 keV power spectrum for the three 2000 May RXTE observations is shown in Figure 7.3 (crosses). A QPO peak is evident in the data, centered at $\sim$0.5 Hz.

We experimented with two models for the band-limited noise: a single power law, and a broken power law (the most commonly used model for Galactic BHCs in their low/hard state). The QPO was modeled with a Lorentzian. The broken power law fit yielded a break frequency of $0.15^{+0.14}_{-0.03}$ Hz, and power law indices of $0.0^{+0.5}_{-0.3}$ ($\nu < \nu_{\text{break}}$) and $0.77^{+0.07}_{-0.27}$ ($\nu > \nu_{\text{break}}$). The strength of the broken power law was $18.3^{+1.3\%}_{-1.1\%}$ rms in the 0.01–1 Hz range, and $40^{+4\%}_{-3\%}$ rms in the 0.01–100 Hz range. We measured a central QPO frequency of $0.46^{+0.02}_{-0.02}$ Hz, a FWHM of $0.14^{+0.06}_{-0.04}$ Hz, and a strength of $14.0^{+2.1\%}_{-1.9\%}$ rms. The $\chi^2$ for this model is 1.1 (for

Figure 7.3: The combined 3-20 keV power spectra of LMC X-3 for the three 2000 May (crosses) and the November 30/December 2 1996 (bullets) RXTE/PCA observations. For plotting purposes additional rebinning was applied to the power spectra. The solid line represents the best fit with a Lorentzian and a broken power law (see Section 4 for parameters). The arrows are 1 sigma upper limits to the power density. The lower power spectrum is mostly due to background fluctuations and should be regarded as an upper limit to the intrinsic source variability in the high/soft state.

photon index of $\sim1.7^{+0.2}_{-0.2}$, over a broad range of flux corresponding to $L_x=(2-16)\times10^{36}$ erg s$^{-1}$ at 50 kpc.
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210 d.o.f.) and the fit is shown as a solid line in Figure 7.3. The significance of adding the QPO component to the broken power-law model was assessed using the standard F-test. For this case, the F-statistic $F_s$ is 3.92, with probability $P(F > F_s) = 0.009$.

The single power law fit yielded an index of $0.58 \pm 0.04$ and strengths of $13.9 \pm 1.2\%$ rms (0.01–1 Hz) and $39 \pm 4\%$ rms (0.01–100 Hz) for the noise. With this as the underlying model, we determined a QPO frequency of 0.46$^{+0.07}_{-0.06}$ Hz, a FWHM of $23^{+4}_{-3}\%$, and an rms amplitude of $18.4^{+2.2}_{-1.8}\%$. The $\chi^2$ for this model is 1.15 (for 212 d.o.f.). For this case, adding the QPO results in an F-statistic of 16.8, with $P(F > F_s) = 8 \times 10^{-10}$.

To study the energy dependence of the band-limited noise and the QPO, we analyzed the power spectra in the 3–10 keV and 10–20 keV energy bands. We adopted the single power law for simplicity, fixed the index, QPO frequency, and QPO FWHM to values obtained in the 3–20 keV range, and allowed the other parameters to float. In the 3–10 keV band the rms amplitudes were $13.4 \pm 1.1\%$ (0.01–1 Hz), $38 \pm 3\%$ (0.01–100 Hz), and $15.2 \pm 1.2\%$ (QPO); in the 10–20 keV band they were $17 \pm 4\%$ (0.01–1 Hz), $50 \pm 12\%$ (0.01–100 Hz), and $<24\%$ (QPO).

We also compared the strength of the noise in the three 2000 May observations with that of several archival RXTE/PCA observations during troughs and peaks in the ASM light curve (see Figure reffig:asm). The noise had strengths of 5–10% rms (0.01–1 Hz) and 10–40% rms (0.01–100 Hz) during the troughs, somewhat lower than during the 2000 May observations but still consistent with a low/hard state. In the peak observations values were found of $\sim 1\%$ rms (0.01–1 Hz) and $\sim 1.5\%$ rms (0.01–100 Hz). We compared the power spectra of the peak observations with power spectra calculated from $\sim 25$ ks randomly chosen background observations, and concluded that the power spectra of the peaks are consistent with those and should therefore be regarded as upper limits (see also Nowak et al. 2001). The upper limits are consistent with the source being in a high/soft state. An example of a power spectrum during high ASM count rate is included in Figure 7.3 (bullets). It is the combined power spectrum of the 1996 November 30 and December 2 observations (Nowak et al. 2001).

7.5 Discussion

The Galactic BHCs share many characteristics: (1) A mass function that implies a compact object mass in excess of $3 M_\odot$; (2) At least two distinct emission states; (3) Prominent time variability in the low/hard state, in the form of band-limited noise with rms amplitudes of 30–50%, in contrast to the weak ($<10\%$) variability seen in the higher states; and (4) QPO activity in the range 0.01–10 Hz. (Useful summaries and references to results from individual sources can be found in reviews by e.g. Tanaka & Lewin (1995); van der Klis (1995); Wijnands & van der Klis (1999).) Until the current work, the extragalactic binary LMC X–3 fulfilled only the first two of these criteria. Here, we have unambiguously determined the presence of the latter two characteristics in LMC X–3, which thus now joins the Galactic sources in showing the full range of canonical BHC behavior.

At low inferred accretion rates, observed QPO frequencies in GBHCs fall in the lower
range 0.2–3 Hz (Wijnands & van der Klis 1999, and references therein). A total of eight GBHC exhibit both strong band-limited noise and low-frequency QPO peaks at these moderate to low accretion rates; at frequencies >1 Hz, this noise component can be modeled as a power law with index \(~\sim 1\), with a break frequency at \(~\sim 0.02–0.4\ Hz, below which the spectral index flattens to \(~\sim 0\). For these sources, Wijnands & van der Klis (1999) find a monotonic relation between the QPO centroid frequency and the break frequency of the band-limited noise. Our measured values for the break frequency (0.15 Hz) and the QPO frequency (0.46 Hz) in LMC X–3 obey this relation, suggesting that the basic (and unknown) physical mechanism that underlies the fast aperiodic variability in the Galactic sources extends also to LMC X–3.

A total of ten GBHC sources with previously published QPOs and corresponding spectral states were investigated by di Matteo & Psaltis (1999), who conclude that the inner radii of the accretion disks around the black holes do not change significantly from one state to the next. This is contrary to the qualitative predictions of the ADAF models (Esin et al. 1998, and references therein), wherein the inner radius retreats quite dramatically from soft-to-hard state transitions. di Matteo & Psaltis (1999) find that the GBHCs occupy a fairly narrow, confined region when plotted in the photon index \(\Gamma\) versus QPO frequency plane. Our measured values for the photon index (1.69) and QPO frequency (0.45 Hz) in LMC X–3 fall in this region as well.

Below a critical source luminosity \(L \lt 5–10\% Eddington\), GBHCs have spectra described by a pure power law (Nowak 1995). Our observations, combined with the archival results presented here, show that LMC X–3 follows this trend, with the three low/hard states presented here corresponding to a luminosity of \(~\sim 2\%\) or less of \(L_{Edd}\).

For all low/hard state properties measured here—photon index, QPO frequency, band-limited noise, and luminosity—LMC X–3 falls squarely in the range measured for the GBHCs. This is significant, for it implies that the dominant mechanism responsible for the low/hard state and state transitions in BHCs is robust against variations in system parameters such as compact object mass, inclination, and initial chemical composition.

### 7.6 Acknowledgments

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### Bibliography

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73
Debi: You know what you need?
Martin: What?
Debi: Shakabuku.
Martin: You wanna tell me what that means?
Debi: It’s a swift, spiritual kick to the head that alters your reality forever.
Martin: Oh, that’d be good. I think.

From ‘Grosse Pointe Blank’ (1997)