X-ray spectral evolution of the extragalactic Z source LMC X-2

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ABSTRACT

We present the results obtained by a detailed study of the extragalactic Z source LMC X-2, using broad-band Suzaku data and a large (∼750 ks) data set obtained with the proportional counter array (PCA) onboard the Rossi X-ray Timing Experiment (RXTE). The PCA data allow the study of the complete spectral evolution along the horizontal, normal and flaring branches of the Z track. Comparison with previous studies shows that the details of spectral evolution (like the variation of Comptonizing electron temperature) are similar to those of GX 17+2 but unlike those of Cyg X-2 and GX 349+2. This suggests that Z sources are a heterogeneous group, with perhaps LMC X-2 and GX 17+2 being members of a subclass. However, non-monotonic evolution of the Compton y parameter seems to be generic to all sources. The broad-band Suzaku data reveal that the case in which the additional soft component of the source is modelled as disc blackbody emission is strongly preferred over the one where it is taken to be a blackbody spectrum. This component, as well as the temperature of seed photons, does not vary when the source goes into flaring mode, and the entire variation can be ascribed to the Comptonizing cloud. The bolometric unabsorbed luminosity of the source is constrained to be ∼2.23 × 10^{38} \text{ erg s}^{-1}, which, if the source is Eddington-limited, implies a neutron star mass of 1.6 M_\odot. We discuss the implications of these results.

Key words: accretion, accretion discs – X-rays: binaries – X-rays: individual: LMC X-2.

1 INTRODUCTION

Low-mass X-ray binaries containing accreting weakly magnetized neutron stars exhibit luminosity and spectral variations on timescales of hours to days, and are usually divided into two classes: Z sources and atoll sources (Hasinger & van der Klis 1989). This classification relies upon the path traced out by individual sources in the X-ray colour–colour diagram (CD) or hardness-intensity diagram (HID). The CD is constructed by plotting the hard colours (ratio of count rates in the two highest energy bands) against the soft colours (ratio of count rates in the two lowest energy bands). The HID is constructed by plotting hard colour against intensity. Z sources trace out an approximate ‘Z’ shaped path in the CD and HID, with the three branches named as the horizontal branch (HB), normal branch (NB) and flaring branch (FB). Spectral analysis of UV data, which is modelled as reproduced X-ray emission from an outer disc, indicates that the bolometric luminosity and hence the mass accretion rate increases along the Z track from HB to FB through NB (Hasinger et al. 1990; Vrtilek et al. 1990). However, more direct estimation of the bolometric luminosity has proved to be difficult since that requires both broad-band data and a reliable distance estimate. Nevertheless, there are indications that Z sources have luminosities comparable to the Eddington limit. There are nine Z sources known, including the recent discovery of a transient Galactic X-ray binary (Homan et al. 2007). Two of them – LMC X-2 (Smale & Kuulkers 2000; Smale, Homan & Kuulkers 2003) and RX J0042.6+4115 (Barnard, Kolb & Osborne 2003) – are extragalactic ones.

The radiative processes that produce the X-ray spectra of neutron star LMXBs are not well-constrained. While there have been attempts to create a detailed theoretical model based on the accretion flow (e.g. Psaltis, Lamb & Miller 1995), in general two different phenomenological approaches have been adopted to model their spectra. In both these approaches, the spectrum is modelled as the sum of two main components, one arising from an accretion disc and the other from the boundary layer between the disc and the neutron star surface. In the first approach (sometimes referred to as the ‘Western’ approach), the accretion disc is considered to be a standard cold disc emitting a soft component, while the boundary layer radiates the harder Comptonized component (Mitsuda et al. 1984, 1989; Di Salvo et al. 2002; Agrawal & Sreekumar 2003). In the second approach (called the ‘Eastern’ approach), the boundary layer emits cool blackbody emission while the harder Comptonized component arises from a hot inner disc (White et al. 1986; Di Salvo et al. 2000, 2001). There is also evidence for a variable hard
power-law component in the spectra of five Z sources (Asai et al. 1994; Di Salvo et al. 2000, 2001, 2002; D’Amico et al. 2001). The two approaches are difficult to distinguish, primarily due to the absence of good-quality low-energy (0.1–1.0 keV) data and the uncertainty in the absorption column density.

To understand the phenomenology of these sources, it is important to study their complete spectral evolution in order to confirm any generic behaviour and to see whether there are subclasses of sources that have similar spectral evolution. There is already some evidence that Z sources may not be a homogeneous group. This was first indicated by Kuulkers & van der Klis (1996) and Kuulkers et al. (1997), who classified them into ‘ Sco’- and ‘ Cyg’- like sources. Detailed study of spectral evolution along the Z track has been carried out for GX 349+2 (Agrawal & Sreekumar 2003), Cyg X-2 (Di Salvo et al. 2002), GX 17+2 (Di Salvo et al. 2000) and GX 340+0 (Church, Halai & Blaucinska-Church 2006). In general, there is considerable variation of the spectral parameters as a source moves along the Z track, and the variations are not always similar in all sources, indicating that Z sources are not a heterogeneous group. For example, as Cyg X-2 moves from the HB to the NB, the optical depth of the Comptonized component decreases while the electron temperature increases dramatically from 3 to 8 keV. A more modest increase in electron temperature from 2.7 to 3.2 keV is seen in GX 349+2. On the other hand, for GX 17+2 the temperature decreases along the same track. Along the flaring branch, a detailed spectral evolution study has only been undertaken for GX 349+2 (Agrawal & Sreekumar 2003), where the temperature increases along the track. While these results indicate that the physical parameters and conditions for these sources are different, what seems to be generic is that the effect of Comptonization decreases along the normal branch while it increases along the flaring branch. This is revealed by the variation of the Comptonization parameter $y = 4(kT_e/m_ec^2)\tau$, where $kT_e$ is the electron temperature, $m_e$ is the rest mass of an electron, $c$ is the speed of light and $\tau$ is the optical depth of the corona. The Comptonization parameter $y$ decreases along the normal branch and increases along the flaring one, a behaviour clearly seen in GX 349+2.

The temporal properties of Z sources are also known to correlate with the position of the source in the Z track. Three different kinds of quasi-periodic oscillations (QPOs) have been seen in these sources. QPOs with frequency 15–100 Hz, which appear in the horizontal branch (but are sometimes seen up to the upper part of the normal branch), are called horizontal branch oscillations (HBO). The frequency of a HBO increases from top left to bottom right of the horizontal branch (Wijnands et al. 1997; Homan et al. 2002). QPOs with frequency 5–15 Hz are observed in the normal and flaring branches, and are called normal–flaring branch oscillations (Homan et al. 2002). These low-frequency oscillations have been seen in all the Galactic Z sources except GX 349+2, where instead broad peaked noise is observed (Agrawal & Bhattacharyya 2003; O’Neill et al. 2002). The third class of QPOs is kHz ones (300–1200 Hz), which are observed in all the branches. The frequency of kHz QPOs increases along the Z track from the HB to the FB (van der Klis 2000).

Early observations of LMC X-2 showed that its luminosity varies from 0.6 to $3 \times 10^{37}$ erg s$^{-1}$ (Markert & Clark 1975). LMC X-2 was identified as a Z source when it traced out a complete Z track during 2001–2002 Rossi X-ray Timing Experiment (RXTE) observations (Smale et al. 2003). Its optical counterpart is a faint blue star (Pakull 1978) typical of other LMXBs. Simultaneous optical and X-ray observations of this source have revealed that X-ray and optical emission are correlated with a time delay of ~20 s (McGowan et al. 2003). A brief (~10 ks) XMM–Newton observation of this source can be described by a disc blackbody with inner disc temperature $T_{in} \sim 0.5$ keV and a blackbody component with temperature $T_{bb} \sim 1.5$ keV (Lavagetto et al. 2008). However, the source is bright enough to cause a pile-up in XMM–Newton observations, making such spectral analysis difficult. No QPO has been detected in LMC X-2, perhaps due to lack of statistics data.

LMC X-2 provides a unique opportunity to understand the spectral evolution of Z sources and the radiative processes that occur in such sources. The distance ($\sim 5\pm 2$ kpc) to the source (Freedman et al. 2001; McClintock & Remillard 2003) is much less uncertain than those of Galactic sources, enabling a more accurate estimation of its intrinsic luminosity. The Galactic column density along the line of the source is $6.3 \times 10^{20}$ cm$^{-2}$. This provides a firm lower limit to the absorption, which can provide constraints on spectral models. The source has been extensively observed by RXTE for a good time duration of ~750 ks. This allows the construction of elaborate CCD and HID diagrams and a detailed study of its spectral evolution. In addition, a ~50 ks observation by Suzaku reveals the broad-band spectrum (0.3–30 keV) of this source, which allows models to be differentiated between and the bolometric luminosity to be estimated.

In this paper, we report the results of spectral analysis of RXTE data in Section 2 and Suzaku data in Section 3. In Section 4, we summarize the main results and discuss the implications.

### 2 RXTE OBSERVATIONS

#### 2.1 Colour–colour and hardness intensity diagrams

LMC X-2 was observed by RXTE during 2001–2002 for a total good time of 750 ks. The observation log is shown in Table 1. We have analysed the data collected by the Proportional Counter Array (PCA), which operates in the 2–60 keV energy band and consists of five proportional counter units with a total effective area of ~6500 cm$^2$ (Jahoda et al. 1996). The analysis was done using PCA standard-2 mode data. Since only two of the five proportional counter units (PCU0 and PCU2) were reliably on all through the observation, only data from these PCUs were selected for analysis. We define soft colour as the ratio of count rates in the 4.5–6.5 and 2.5–4.5 keV energy bands and hard colour as that for the 9.8–18.5 and 6.5–9.8 keV bands. The CDs generated using 512-s average counts for different observations are plotted in Fig. 1. In Fig. 2(a), the combined CD for all the observations is plotted. The result is similar to that obtained by Smale et al. (2003), except that the present analysis is for a larger data set. We define the overall colour as the ratio of count rates in the 6.5–18.5 and 2.5–6.5 keV bands. The HID was constructed by plotting the overall colour against the 2.5–18.5 keV count s$^{-1}$ per two PCUs and is plotted in Fig. 2(b).

Since there were no gain changes after 2000, there was no need to normalize the intensities and colours.

| OBSID | Start Date | End Date | Duration (ks) |
|-------|------------|----------|---------------|
| 50041-01-01-** | 2001 Feb 10 | 2001 Feb 14 | 145 |
| 60027-01-01-** | 2001 Aug 30 | 2001 Sep 3 | 144 |
| 60027-01-02-** | 2001 Dec 13 | 2001 Dec 16 | 122 |
| 60027-01-03-** | 2002 Feb 01 | 2002 Feb 06 | 148 |
| 70017-01-** | 2002 Aug 22 | 2002 Oct 30 | 185 |

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As seen in Fig. 2(a), the HB for this source is neither horizontal nor distinct. The classification requires the study of other spectral relationships like the HID that is shown in Fig. 2(b). The HID of LMC X-2 is quite similar to that seen for another well-studied Z source, GX 17+2 (see fig. 1 of Homan et al. 2002). In the HID of GX 17+2, the slanted branch (almost vertical) at the top left is called the horizontal branch and we perform a similar identification for LMC X-2. We divide the HB in the HID into two regions, HB1 and HB2, and mark the corresponding location in the CD. The normal and flaring branch are distinct in the CD. Thus, we are able to identify all three branches for LMC X-2. For spectral studies, the Z curve has been divided into eight regions: two for the horizontal branch (HB1 and HB2), two for the normal branch (NB1 and NB2), a normal/flaring branch vortex point (N/FBV) and three regions for the flaring branch (FB1, FB2 and FB3). All eight regions have been marked out in Fig. 2(a).

### 2.2 Spectral evolution

We extracted spectra corresponding to the eight regions in the CD to carry out a detailed spectral evolution study. We added 1 per cent...
A single-component Comptonization model (compTT in XSPEC; see Titarchuk 1994) with absorption provided an adequate fit to all the PCA spectra in the energy range 3–20 keV. Since the data are for energies >3 keV, the absorbing column density is not well constrained. Hence we adopt a constant value of $N_{\text{H}} \sim 9 \times 10^{20}$ based on the Suzaku analysis reported in Section 3. An iron emission line centred at $\sim 6.4$ is also required to improve the fit. In the top panel of Fig. 3 we show the observed count rate spectrum for HB1, along with the best-fitting model. The residuals (in units of $\sigma$), with and without the inclusion of systematic error, are shown in the middle and bottom panels respectively. The PCA data suggest that the soft component, originating either from the disc or from the boundary layer, is absent above 3 keV.

The spectral parameters of the compTT component evolve significantly as the source moves along the Z track. The best-fitting parameters at different parts of the Z track have been listed in Table 2, and evolution along the track has been plotted in Fig. 4. The electron temperature decreases as the source evolves from the HB to the lower part of the FB. This variation is different from that seen in GX 349+2 (Agrawal & Sreekumar 2003) and Cyg X-2 (Di Salvo et al. 2002), where the opposite behaviour was found. On the other hand, it is similar to that observed in GX 17+2 (Di Salvo et al. 2000). As LMC X-2 moves along the flaring branch, the temperature increases, which again is in contrast to the behaviour observed for GX 349+2 where the temperature decreases. However what seems to be generic is that the effect of Comptonization decreases along the normal branch while it increases along the flaring branch. This is revealed by variation in the Comptonization parameter $y = 4(kT_{e}/m_{e}c^{2})\tau^{2}$, which decreases along the normal branch and increases along the flaring one (Fig. 4), a behaviour also seen in GX 349+2. In the flaring branch, as $y$ increases the spectrum is that of saturated Comptonization with a peak $\sim 3kT_{e} \sim 6$ keV.

### Table 2. The best-fitting parameters obtained by fitting the RXTE PCA data with XSPEC model compTT. The electron temperature $kT_{e}$ and seed photon temperature $kT_{W}$ are measured in keV. $\tau$ is the optical depth of central corona and y is the Compton $y$ parameter. The division N/FBV means normal–flaring branch vertex.

|       | HB1          | HB2          | NB1          | NB2          | N/FBV        | FB1          | FB2          | FB3          |
|-------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| $kT_{W}$ | 0.47$^{+0.03}_{-0.06}$ | 0.55$^{+0.04}_{-0.06}$ | 0.61$^{+0.03}_{-0.04}$ | 0.62$^{+0.03}_{-0.04}$ | 0.59$^{+0.03}_{-0.03}$ | 0.59$^{+0.03}_{-0.03}$ | 0.61$^{+0.03}_{-0.03}$ | 0.62$^{+0.03}_{-0.04}$ | 0.58$^{+0.04}_{-0.05}$ |
| $kT_{e}$ | 2.74$^{+0.04}_{-0.04}$ | 2.60$^{+0.04}_{-0.04}$ | 2.45$^{+0.03}_{-0.03}$ | 2.24$^{+0.02}_{-0.02}$ | 2.15$^{+0.03}_{-0.03}$ | 1.95$^{+0.02}_{-0.02}$ | 1.94$^{+0.02}_{-0.02}$ | 2.06$^{+0.02}_{-0.02}$ | 2.07$^{+0.02}_{-0.02}$ |
| $\tau$  | 13.37$^{+0.22}_{-0.25}$ | 12.90$^{+0.04}_{-0.04}$ | 12.59$^{+0.03}_{-0.03}$ | 12.99$^{+0.05}_{-0.05}$ | 14.47$^{+0.33}_{-0.34}$ | 15.71$^{+0.40}_{-0.40}$ | 15.61$^{+0.45}_{-0.46}$ | 18.13$^{+0.41}_{-0.33}$ |
| $y$    | 3.85$^{+0.14}_{-0.15}$ | 3.38$^{+0.14}_{-0.15}$ | 3.04$^{+0.13}_{-0.13}$ | 2.90$^{+0.12}_{-0.12}$ | 3.19$^{+0.15}_{-0.15}$ | 3.74$^{+0.19}_{-0.19}$ | 4.26$^{+0.24}_{-0.21}$ | 5.34$^{+0.25}_{-0.19}$ |
| $\chi^2$/dof | 17.7/29 | 17.2/29 | 15.5/29 | 12.7/29 | 30.1/29 | 15.6/29 | 16.2/29 | 19/29 |
3 SUZAKU OBSERVATIONS

3.1 Colour–colour diagram and light curves

Suzaku observed LMC X-2 for a good time duration of 119 ks on 2006 April 24 and 25. The observatory (Mitsuda et al. 2007) consists of two different types of instrument, the X-ray Imaging Spectrometer (XIS; Koyama et al. 2007) and Hard X-ray Detector (HXD; Takahashi et al. 2007).

There are four XIS units (named XIS0, XIS1, XIS2, XIS3); each of them is a 1024 × 1024 pixel CCD and covers an energy range of 0.3–12 keV. HXD consists of two types of detectors, the Si diode detector (PIN) and the Gadolinium silicate crystal (GSO). The PIN diode covers an energy range of 10–70 keV while the GSO scintillators are sensitive in the 40–600 keV band. The XIS data were collected in normal mode with 1/4 window option. The minimum bin time available in this mode is 2 s. The cleaned XIS event files were used to obtain the light curves and spectra. The XIS image is shown in Fig. 5. The source light curves were extracted using 4 arcmin radius centred at the source position.

For comparison with RXTE observations, we study the colour and intensity properties of the counts at energies >3 keV. Fig. 6 shows the colour–colour diagram for the Suzaku data using three energy bands defined as 3–4.5, 4.5–6.5 and 6.5–10 keV. The data points correspond to 512-s averages. Superimposed on the figure is the simulated colour–colour diagram obtained using the best-fitting PCA spectral parameters and XIS0 response matrix. In particular, eight fake X-ray spectra were created using the best-fitting RXTE model parameters (Table 2) using the Suzaku XIS response matrix. The count rates in three energy bands (3–4.5, 4.5–6.5, 6.5–10 keV) were calculated for these eight simulated spectra and the simulated colour–colour diagram was computed. The simulated CD is represented by a solid line connecting the eight points. While it is difficult to differentiate between the different branches, the Suzaku data points are consistent with simulated ones. Note that statistical errors for these data points are significantly larger than for RXTE data because the 3–10 keV count rate for Suzaku (~6 count s$^{-1}$) is smaller than that for RXTE, ~60–150 count s$^{-1}$ per two PCUs. Comparison with the hardness intensity plot generated using RXTE data is more difficult because, apart from the statistical uncertainty of Suzaku points, the absolute calibration between the PCA and Suzaku may differ.

The XIS0 light curve created using the 3–10 keV energy band is shown in the top panel of Fig. 7. There is clear flaring-like activity where the rate increases by ~30 per cent. Moreover, the spectra harden during the flares, as revealed in the bottom panel of Fig. 7 where the overall colour is plotted as a function of time. The overall colour is the ratio of count rates in the 5–10 and 3–5 keV energy bands. Thus, we divided the data into two states, a flaring state where the count rate is >7 count s$^{-1}$ and a non-flaring one corresponding to rates <7 count s$^{-1}$. The low statistics of the data does not permit a more reliable division. We identify the flaring state with the flaring branch and the low-count-rate state as the normal branch.

3.2 Spectral evolution

We extracted source and background spectra for the flaring and non-flaring parts for each of the four XIS units. The latest calibration
data base was used to create the XIS response. The response matrix files were generated using the ftools task xisrmfgen and ancillary response files were generated using the ftools task xissimarfgen.

To analyse the HXD data, we first checked for the process version. Since the HXD process version was 2.0.6.13, we reprocessed the data as recommended by the Suzaku team. As a first step to reduction, we ran the command hxdtime to calculate the HXD event arrival-time correction. Then invariant pulse heights (PI) were determined using hxdpi. The HXD event grades were calculated using the task hxdgrade. We used standard screening criteria (given in the Suzaku ABC guide) to obtain the filtered PIN event files. We also excluded the telemetry saturation period while creating filtered event files. The filtered PIN files were used to create the source spectra for the different flux levels and dead-time correction was performed on the PIN spectra. As suggested by the HXD team, we used a version 1.2 (method = LCFFIT(bgd_d)) background file to create PIN background spectra. Since the PIN background was simulated with a 10 times scale level to decrease the Poisson noise, we modified the exposure keyword by entering a new exposure 10 times the original. Since we do not have enough counts above 30 keV, we restricted our analysis to <30 keV and did not use GSO data. We added the data, background and response matrices from the front-illuminated (FI) XIS CCDs. We used 0.5–10 keV FI CCD data, 0.3–10 keV back-illuminated (BI) CCD data and 10–30 keV for the PIN HXD for combined spectral fitting. We grouped the XIS data to obtain three channels per resolution and added 2 per cent systematic error to take into account the uncertainty in the XIS response matrix. While spectral fitting, we allow for calibration uncertainties between the FI CCDs, BI CCDs and PIN HXD.

The broad-band spectra of Suzaku allow for a two-component fit to the data. We use a blackbody and Comptonization model (the xspec model comptt) to represent the ‘Eastern’ model and fit both the flaring and normal branch data sets. A Gaussian representing the iron line was added to both the XIS and HXD data. The equivalent width of the iron line.

We repeat the spectral fitting using a disc blackbody (xspec model DISKBB) and the same Comptonization model to represent the ‘Eastern’ model. The best-fitting spectral parameters are shown in Table 4. Here, the column density turns out to be ~9 × 10^20 cm^-2 above the Galactic lower limit. For the normal branch χ^2/d.o.f = 380/375, which is significantly better than the value obtained for the ‘Western’ model, χ^2/d.o.f = 463/375. A similar trend is seen for the flaring branch, where the ‘Eastern’ model gives better results, χ^2/d.o.f = 356/373 compared with χ^2/d.o.f = 442/374. Thus spectral fitting of Suzaku data strongly favours the interpretation where the soft component is disc emission rather than a simple blackbody. Note that this distinction is possible because of the imposed lower limit on the absorption column density. If the column density is allowed to have any value, then a reasonable fit using the blackbody component is possible. For the model with blackbody emission, the best-fitting column density turns out to be NH = 0.013 × 10^22 cm^-2 with χ^2/dof = 367/375. For Galactic sources, the column density is more uncertain and hence such a distinction would not be possible even with broad-band data.

The spectral fit to the non-flaring state is shown in Fig. 8. Also plotted are the residuals with and without the addition of a systematic error of 2 per cent. The column density is well constrained to 9 × 10^20 cm^-2 and it is this value that has been used for fitting RXTE data (Table 2). The inner disc temperature, kT_in, the inner disc radius, R_in, as well as the soft photon input temperature, kT_w, remain invariant between the flaring and normal branches. A broad iron line is significantly detected for both branches. The electron temperature decreases during the flare, which is consistent with the behaviour seen by RXTE, although Suzaku data require a higher temperature. More significantly, it is the Compton y parameter that is seen to increase during the flare, which is again consistent with the RXTE observations. Using a distance of 50 kpc, the unab sorbed luminosities of the flaring and normal branch turn out to be

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**Table 3.** The best-fitting parameter obtained by fitting Suzaku data with blackbody (BBODY), Comptonization (COMPTT) and broad Gaussian iron line models. kT_BB is the blackbody temperature. kT_W, kT_e and τ are the seed photon temperature, the electron temperature and the optical depth of the Comptonization model. E_Fe and σ_Fe are the centroid energy and the width of the iron line Gaussian.

| Parameter | NB | FB |
|-----------|----|----|
| N_H \[^{10^20 \text{cm}^{-2}}\] | <6.3 | <6.3 |
| kT_BB (eV) | 213±3 | 215±4 |
| kT_W (eV) | 528±4 | 530±4 |
| kT_e (eV) | 2180±90 | 2190±70 |
| τ | 14.05±0.04 | 14.75±0.20 |
| E_Fe (keV) | 6.4 (fixed) | 6.4 (fixed) |
| σ_Fe (keV) | 0.27±0.14 | 0.27 (fixed) |
| Eq. width (eV) | 20 | 9 |
| Ftest prob | 7×10^{-3} | 0.11 |
| Fline | 0.74 ± 0.35 | <0.9^a |
| χ^2/dof | 463/375 | 442/374 |

\[^{1}\text{The column density N_H was restricted to be larger than the Galactic value of 6.3} \times 10^{20} \text{cm}^{-2}.

\[^{2}\text{The equivalent width of the iron line.}

\[^{3}\text{The F-test probability for the presence of the Gaussian iron line.}

\[^{4}\text{The flux of the iron line in units of 10^{-12} erg s^{-1} cm^{-2}.}

\[^{5}\text{90 per cent confidence upper limit on the iron-line flux.}
Table 4. The best-fitting parameter obtained by fitting Suzaku data with disc blackbody (DISKBB), Comptonization (COMPTT) and broad Gaussian iron line models. \( kT_{in} \) and \( R_{dbb} \) are the inner disc temperature and radius. \( kT_w \), \( kT_e \) and \( \tau \) are the seed photon temperature, the electron temperature and the optical depth of the Comptonization model. \( E_{Fe} \) and \( \sigma_{Fe} \) are the centroid energy and the width of the iron line Gaussian. The luminosities are computed using the best-fitting model in the energy range 0.01–50 keV and are in units of 10^{38} \text{ erg s}^{-1}.

| Parameter                  | NB     | FB     |
|----------------------------|--------|--------|
| \( N_H \times 10^{20} \text{ cm}^{-2} \) | \( 8.0_{-0.7}^{+0.2} \) | \( 8.35_{-0.91}^{+0.5} \) |
| \( kT_{in} \) (eV)            | 394_{-1}^{+1} | 397_{-13}^{+3} |
| \( R_{dbb} \) (km)            | 99 ± 3   | 95 ± 5  |
| \( kT_w \) (eV)               | 660 ± 20 | 670 ± 20|
| \( kT_e \) (eV)               | 2600_{-10}^{+10} | 2490_{-50}^{+10} |
| \( \tau \)                    | 11.30_{-0.20}^{+0.20} | 12.40_{-0.15}^{+0.15} |
| \( E_{Fe} \) (keV)            | 6.4 (fixed) | 6.4 (fixed) |
| \( \sigma_{Fe} \) (keV)       | 0.56_{-0.15}^{+0.15} | 0.44_{-0.10}^{+0.11} |
| Eq. width\( ^d \) (eV)        | 72      | 36     |
| \( F \)-test prob\( ^b \)     | 7.1 \times 10^{-9} | 2.5 \times 10^{-4} |
| \( L_{dbb}^{\text{comptT}} \) | 1.83 ± 0.11 | 1.95 ± 0.12 |
| \( L_{T}^{\text{compT}} \)    | 2.10 ± 0.13 | 2.23 ± 0.12 |
| \( L_{\text{Fe}}^{\text{compT}} \) | 0.59 ± 0.04 | 0.60 ± 0.04 |
| \( L_{\text{compT}}^{\text{line}} \) | 1.51 ± 0.03 | 1.63 ± 0.03 |
| \( y^{\text{line}} \)         | 2.60_{-0.04}^{+0.08} | 2.98_{-0.09}^{+0.07} |
| \( \chi^{2}/\text{dof} \)     | 390/375 | 356/373 |

\( ^a \) The equivalent width of the iron line.

\( ^b \) The \( F \)-test probability for the presence of the Gaussian iron line.

\( ^c \) Total absorbed luminosity.

\( ^d \) Total unabsorbed luminosity.

\( ^e \) Unabsorbed luminosity of the disc blackbody component.

\( ^f \) Unabsorbed luminosity of the Comptonized component.

\( ^g \) The Comptonization parameter.

\( ^h \) The flux of the iron line in units of 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}.

2.1 \times 10^{38} \text{ and } 2.2 \times 10^{38} \text{ erg s}^{-1}, \text{ which for a 1.4-M}_{\odot} \text{ neutron star corresponds to 1.1 and 1.15 of the Eddington value.}

4 DISCUSSION

A detailed spectral analysis of the extragalactic source LMC X-2 has been undertaken using broad-band data from Suzaku and from a large (~750 ks) data set obtained using the RXTE PCA.

From the PCA data the complete Z-track evolution was obtained and spectra at eight representative positions were analysed. In the energy band of the PCA (3–20 keV), a single-component Comptonization fit adequately represents the spectra from all the track branches. This is unlike other Z sources (GX 349+2: Agrawal & Sreekumar 2003; Cyg X-2: Di Salvo et al. 2002), where an additional soft component is required in the RXTE energy band. The temperature of the Comptonizing cloud, \( kT_w \), is found to decrease from the horizontal to the normal branch (see Fig. 4), similarly to what is observed for GX 17+2 (Di Salvo et al. 2000), but in contrast to the results from Cyg X-2 (Di Salvo et al. 2002) and GX 349+2 (Agrawal & Sreekumar 2003), where the opposite behaviour was found. Along the flaring branch, the temperature increases for LMC X-2, again differently from GX 349+2 where the temperature decreases. On the other hand, for LMC X-2 the Compton y parameter decreases along the horizontal and normal branches and increases along the flaring branch. This is consistent with what is observed for GX 349+2 and it seems to be a generic feature of Z sources.

These results confirm that while details of the spectral evolution are different for each source, generic behaviour like the evolution of the Compton y parameter seems to be similar in all Z sources. The hard-component evolution similarity between LMC X-2 and GX 17+2 suggests that there could be subgroups within Z sources where similar physical conditions are met. The observed similarity in the spectral evolution seen in these two sources is also suggested in the near-identical colour and hardness intensity diagrams of these sources. Similar diagrams are also observed in Sco X-1. Hence, our results are consistent with the idea that Z sources can be further divided into two subclasses, ‘Sco’- and ‘Cyg’-like sources (Kuulkers & van der Klis 1996; Kuulkers et al. 1997), with LMC X-2 being a member of the ‘Sco’-like class. While it was suggested earlier that the difference between ‘Sco’- and ‘Cyg’-like sources may be due to inclination angle (Kuulkers & van der Klis 1996), the spectral differences between LMC X-2 and other sources suggests instead a more intrinsic difference between the two classes. Analysis of Z source XTE J1701 – 462 reveals that the source evolves from a ‘Cyg’-like to a ‘Sco’-like Z source, suggesting that the difference between these two classes is not caused by a difference in the inclination angle (Homan et al. 2007; Lin, Remillard & Homan 2009).

The Suzaku data provide the broad-band spectral and luminosity evolution of the source from the NB to the FB. As expected, the data require an additional soft component. This additional component was represented as a blackbody (emitted from boundary layer) and as emission from a multicolour disc. The multicolour disc approach (sometimes called the ‘Eastern’ approach) provides a significantly better fit to the data. This spectral distinction is possible because the Galactic neutral hydrogen column density along the direction of the source is \( N_H = 6.3 \times 10^{20} \text{ cm}^{-2} \) and hence the fitted absorption column density was restricted to be larger than this value. Such a constraint is usually not available for Galactic sources.

The distance to LMC X-2 (50 ± 2 kpc) is better constrained than those of Galactic sources and hence the broad-band Suzaku
data provide a better estimate of the bolometric luminosity. The unabsorbed luminosity of the source for the normal branch is $2.1 \times 10^{38}$ erg s$^{-1}$ and for the flaring branch it is $2.23 \times 10^{38}$ erg s$^{-1}$. Taking into account the uncertainty in the spectral fitting ($\sim 5$ per cent), the distance ($\sim 5$ per cent) and calibration of different instruments ($\sim 10$ per cent), one can put a highly conservative error estimate of $\sim 15$ per cent on these luminosities. If the source reaches its Eddington limit on the normal branch, this would imply that the mass of the neutron star is $1.50 \pm 0.1 M_\odot$. If instead the source is Eddington-limited in the flaring branch, one obtains a slightly higher mass of $1.61 \pm 0.09 M_\odot$.

The phenomenological spectral models used in this analysis, a single-temperature Comptonized component and multicolour disc emission, are adequate considering the statistics of the available data and the uncertainties regarding the theoretical models. However, considering that the system is a near-Eddington neutron star source, it is expected that the actual radiative processes would be considerably more complicated, with possibly quantitative and qualitative differences compared with the simple model adopted here. For example, detailed structural analysis of the boundary layer reveals a temperature- and density-stratified extended region (Popham & Sunyaev 2001).

A fairly detailed model for Z sources is one in which soft photons produced by electron cyclotron emission in the neutron star magnetosphere are Comptonized primarily in a hot central corona (Psaltis et al. 1995; Psaltis & Lamb 1997). The outer accretion disc gets converted into a radial flow, which also Comptonizes the outgoing photons. The phenomenological description in our analysis is broadly consistent with this picture, with the temperature and optical depth of the Comptonizing component identified as the average temperature and optical depth of the hot central corona. The source of seed photons for Comptonization, which is assumed to be a blackbody with temperature $kT_w$ in the xspec model compTT, will then be the electron cyclotron emission. Finally, the multicolour disc component is the outer disc. Note that, from Table 4, the seed photon temperature, $kT_w \sim 0.65$ keV, is different from the inner disc temperature, $kT_{in} \sim 0.4$ keV, and hence in this interpretation the seed photons are not produced by the outer disc. This is consistent with the above model, where the seed photons are produced in the magnetosphere.

A straightforward interpretation of the analysis is that the inner disc radius, $R_{abs}$, does not vary significantly when the source is in a flaring state, and at $\sim 100$ km it is about 10 times the neutron star radius. The radius may be larger if the colour factor is significantly greater than unity, as is assumed for the radius estimation. The luminosity of the disc emission is nearly 25 per cent of the total luminosity, and hence gravitational energy dissipation is not sufficient to power the disc. At 10 times the star radius, the gravitational energy dissipated should be only 10 per cent or less of the total dissipation. Instead the disc is probably heated by the inner corona and hence radiates such high luminosities. This is expected if the disc is truncated due to the radiation pressure of a near-Eddington inner corona. However, in contrast to what is seen in such a scenario, one would expect that the inner disc radius and its luminosity should vary as the source goes into a flaring mode. The large inferred inner disc radius argues against the possibility that the broad iron line detected arises from the disc. Instead, it may be speculated that it perhaps arises from the neutron star surface. Unfortunately, the line is weak (with equivalent width of $\sim 50$ eV) and hence the statistics are not sufficient to test these ideas by modelling the line profile.

It may also be that the phenomenological models used in this analysis do not sufficiently approximate the complex radiative process of the system. In particular, the soft seed photon input is assumed here to be a blackbody and this may not be the case. While the high-energy spectrum is largely independent of the shape of the seed photon spectrum, the low-energy spectrum will depend on its shape. In the framework of a model, the magnetosphere emission could be more complex than a blackbody. Moreover there could be an additional source of seed photons from the outer disc. Such complexities may vary the disc emission parameters or even eliminate the need for the additional component. However, an arbitrary seed photon spectral shape will not be falsifiable by spectral analysis, since some shape will always be a good representation of the data. A theoretically motivated spectral shape for the seed photon is required. Despite these caveats, the spectral analysis shown in this work does reveal the overall behaviour of the source. One can still conclude model-independently that the lower energy part of the spectrum (which in this case is the seed photon source and the disc component) does not vary as the source flares, and the entire variation can be ascribed to the Comptonizing cloud.

The low statistics of the Suzaku data did not allow for a detailed broad-band spectral study of the source as it evolves along the Z track. Instead the data were split into two broad parts representing the flaring and non-flaring periods. This is unfortunate, because such a broad-band evolution study would have been able to test whether the bolometric luminosity increases monotonically along the track as expected by theoretical models and inferred by UV observations. The two main flares observed by Suzaku seem to be of similar strength (Fig. 7); however, clearly this needs to be confirmed by longer duration observations. This will have important implications on whether the source is Eddington-limited during the flares or not. These deficiencies may be alleviated by longer duration Suzaku observations undertaken simultaneously with RXTE. The PCA data would distinguish the different track positions, while Suzaku would provide broad-band spectra for each position. Alternatively, such results could be obtained by a long-duration observation of the source by the forthcoming multiwavelength satellite ASTROSAT. The proportional counter array on board (LAXPC) would determine the Z track, while the UV and other X-ray instruments would give simultaneous broad-band coverage.

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