Post-flare Formation of the Accretion Stream and a Dip in Pulse Profiles of LMC X–4

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Abstract

We report here a pulse profile evolution study of an accreting X-ray pulsar LMC X–4 during and after the large X-ray flares using data from the two observatories \textit{XMM-Newton} and \textit{RXTE}. During the flares, the pulse profiles were found to have a significant phase offset in the range of 0.2-0.5 compared to the pulse profiles immediately before or after the flare. Investigating the pulse profiles for about $10^5$ seconds after the flares, it was found that it takes about 2000-4000 seconds for the modified accretion column to return to its normal structure and formation of an accretion stream that causes a dip in the pulse profile of LMC X–4. We have also carried out pulse phase resolved spectroscopy of LMC X–4 in narrow phase bins using data from EPIC-pn and spectroscopically confirmed the pulsating nature of the soft spectral component, having a pulse fraction and phase different from that of the power-law component.

Keywords: X-ray: Neutron Stars - accretion, pulsars, individual: LMC X–4

LMC X–4 is a persistent, disk-fed, X-ray binary pulsar which consists of a 1.25 $M_{\odot}$ neutron star and a 14th magnitude O-type star of mass $\sim 15 M_{\odot}$ (Kelley et al., 1983; van der Meer et al., 2007) in the Large Magellanic Cloud. This high-mass system exhibits pulse period and an orbital period of $\sim 13.5$ s, and $\sim 1.4$ days respectively (Kelley et al., 1983). A periodic superorbital intensity modulation at $\sim 30.5$ day during which the X-ray intensity varies by the factor of $\sim 60$ between high and low states has also been observed in this source (Lang et al., 1981; Paul & Kitamoto, 2002).

LMC X–4 is one of the few X-ray binaries that shows large X-ray flares (Levine et al., 1991; 2000; Moon & Eikenberry, 2001; Moon et al., 2003b). X-ray flares in LMC X–4 are believed to occur due to increased mass accretion because of Rayleigh-Taylor instability of plasma in the accretion disk (Moon et al., 2003b).

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Sometimes the flare X-ray luminosity reaches up to $\sim 10^{39}$ ergs/sec (Levine et al., 2000; Moon et al., 2003b). This super-Eddington emission is understood to be due to inhomogeneous accretion columns during the flares (Moon et al., 2003b). During the LMC X–4 flares, pulse profiles are broad and sinusoidal in shape (Levine et al., 1991, 2000; Moon et al., 2003b). Moon et al. (2003b) suggested that during flares most of the flare emission is transported via a fan beam in the direction perpendicular to the magnetic field. However, this is in contrast to the pulse profiles observed outside the X-ray flares. Pulse profiles of LMC X–4 in a soft energy band show complex structures with dips in it (Levine et al., 1991, 2000; Paul et al., 2002; Naik & Paul, 2004). Significant changes in the pulse profiles of LMC X–4, during large flares suggest that it is a rare source to allow study of evolution of pulse profile during the transition between flaring and non-flaring states and to understand accretion flow in the system. During X-ray flares, the accretion column and the beaming of X-ray emission could be altered.

Dips are the sharp drops in intensity over a narrow phase range of $\Delta \phi \approx 0.1$ (see e.g., Greenhill et al., 1998; Giles et al., 2000; Galloway et al., 2001; Devasia et al., 2010, 2011a; Devasia et al., 2011b; Usui et al., 2012; Naik, 2013). The depth of a dip can attain a very high value, 80-100% of the pulse maximum (Giles et al., 2000). These are often attributed to the eclipse of the emitted radiation by the optically thick material in the accretion column (Cemeljic & Bulik, 1998). Certain viewing angle configurations of the systems can allow the passage of the accretion column through our line of sight at some pulse phases, giving rise to reprocessing of the emitted radiation from the column, where the softer low energy photons can either get absorbed or scattered out of our line of sight.

Dips in the pulse profiles are often predominant at energies below 15 keV (Devasia et al., 2011b; Maitra et al., 2012; Maitra, 2013; Devasia, 2014). However, there exist a few exceptions such as GX 1+4 (Giles et al., 2000), EXO 2030+375 (Naik et al., 2013) and GS 1843–02 (Devasia, 2014) in which dips are observed even at energies above 15 keV. Pulse profiles of a particular source may have more than one such features and these multiple dips are understood as the indication of more than one accretion stream (Devasia, 2014). They may also provide a unique opportunity to investigate the timescale required for the formation of the accretion stream that causes a dip in its pulse profiles after the accretion region and the beaming etc. is disturbed during the flares.

The X-ray spectrum of LMC X–4 in 0.1–100 keV band is described by a power law with a high-energy cutoff, a soft X-ray excess, and an iron emission line (La Barbera et al., 2001; Naik & Paul, 2003). The soft X-ray excess is believed to originate from the reprocessing of hard X-rays from the neutron star by the inner accretion disk and is detectable only in those sources which have low value of hydrogen column density like SMC X–1, HerX–1, LMC X–4 (Paul et al., 2002; Hickox et al., 2004). Pulse Phase Resolved Spectroscopy performed using data from the ROSAT, Ginga, ASCA and BeppoSAX observatory revealed some
evidence that the soft spectral component of LMC X–4 is pulsating with a different pulse phase with respect to the power law component (Woo et al., 1996; Paul et al., 2002; Naik & Paul, 2004). However, this can be better investigated using data from the EPIC-pn instrument aboard XMM-Newton.

In this paper, we report a very detailed pulse profile evolution study of LMC X–4, using data from two observatories, XMM-Newton and RXTE. The results obtained from pulse phase resolved spectroscopy of LMC X–4 using data from EPIC-pn are also presented. The paper is organized as follows: Section-2 gives the details of the observations used in this work, section-3 describes pulse profile studies performed during flaring and non-flaring states using data from EPIC-pn and RXTE-PCA. We describe spectral studies of this source in section-4, where we investigate the behavior of soft excess in narrow phase bins. The last section discusses the results obtained from the analysis.

1. Observations and Data Reduction

We have selected those observations which include several large flares and a large continuous stretch of persistent emission after the flares. (We refer to the persistent emission in this paper as a state which has no flares and eclipse.)

We have used data from the EPIC-pn onboard XMM-Newton and the PCA of RXTE for this work. Table-1 shows the log of observations used in this work. Here, we would like to mention that these observations have been used before, but have never been analyzed for the purpose of pulse profile evolution study. Neilsen et al. (2009) used the same XMM-Newton observation for performing spectroscopic studies while the other two PCA observations were used for the detailed examination of flares (see Moon et al., 2003b). Very recently, the same observations were used by Molkov et al. (2017) for the spin period measurements.

The European Photon Imaging Camera (EPIC), and the Reflection Grating Spectrometer (RGS) are two X-ray instruments aboard XMM-Newton which operate in the energy range of 0.1-15 keV. The EPIC consists of two MOS (Turner et al., 2001) and one pn (Strüder et al., 2001) CCD arrays having moderate spectral resolution and a time resolution in the range of micro-seconds to 2.6 seconds depending on the instrument and the mode of observation. An optical Monitor (OM) performs simultaneous optical/UV observations. EPIC-pn data were collected in the small window mode with thick filter. Frame time of these observations was 6 ms. This observation belongs to the high state of the ~ 30.5 days superorbital cycle (Neilsen et al., 2009).

For the reduction and extraction purposes, we have used HEASOFT 6.12 and SAS-12.0.1. Standard filters were applied to the extraction of the cleaned EPIC-pn events. To check whether the data was affected with soft proton flaring, a light curve was extracted by selecting events with PATTERN=0 and
energy in the range of 10-12 keV. Thereafter, a good time interval (gti) with rate \( \leq 0.4 \) was created. This gti was then used to obtain the filtered events. The SAS tool `evselect` was used to perform the particle background check and for filtering out background flares prior to analysis. A circular region of 40 arcsecond radius was selected around the source centroid for the extraction of source events. The SAS tool `epatplot` was used to detect presence of any possible pile-up in the data. For the persistent emission, the count rate was slightly higher than the maximum count rate limit for EPIC-pn with a small window mode (25 counts/s), while for the case of flaring events, data were heavily piled up. Therefore, we have performed a pile-up correction by removing a radius of 7.5 arcseconds from the core of the PSF. This annular source region file was then used for light curve extraction during the flares. However, we have used all the pixels of source events for extraction of light curves during the persistent emission. We have used the annular source region file for extraction of source spectra during the persistent emission. PATTERN \( \leq 4 \) and FLAG=0 were used as selection criteria. Two off-source regions were used with a radius of 40 arcseconds for the background spectra and light curve extraction. An updated version of the current calibration files was used for reprocessing of the data and creation of the response files.

The PCA instrument on board RXTE consists of five Proportional Counter Units (PCUs) covering an energy range of 2–60 keV with an effective area of 6500 cm\(^2\) (Jahoda & PCA Team 1996; Jahoda et al., 2006). Both the RXTE observations (given in Table-1) have 6 pointings. For screening of data, the following filtering criteria were applied: time since South Atlantic Anomaly (SAA) was greater than 10 minutes, pointing offset was less than 0.02 degrees, and the earth elevation angle was greater than 10 degrees. Only the data obtained with two or more active Proportional Counter Units (PCUs) were used. PCA data collected in Good Xenon1 and Good Xenon2 modes were used to generate the source light curves. The tool `runpcabackest` was used to estimate the background, assuming a source model as suggested by RXTE GOF and subsequently background light curves were generated.

The arrival times of photons from both EPIC-pn and PCA were first converted to the solar system barycenter. Due to the short orbital period of LMC X–4, pulses may lose coherence within a relatively short timescale of a few thousand seconds. Therefore, the arrival time of each photon was corrected for the binary motion considering the semiamplitude to be 26.3 seconds and the mid-eclipse time as per its orbital evolution rate (Naik & Paul, 2004). The orbital parameters used for this correction are given in Table 2.

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1 [http://xmm2.esac.esa.int/external/xmm_sw_cal/calib/ecf.shtml](http://xmm2.esac.esa.int/external/xmm_sw_cal/calib/ecf.shtml)

2 [http://heasarc.gsfc.nasa.gov/docs/xte/pca_news.html](http://heasarc.gsfc.nasa.gov/docs/xte/pca_news.html)
Table 1: Log of observations

| Observatory   | Year | Observation ID | Total Exposure (ks) |
|---------------|------|----------------|---------------------|
| XMM-Newton    | 2003 | 0142800101     | 113                 |
| RXTE          | 1996 | P10135         | 170                 |
|               | 1999 | P40064         | 150                 |

Table 2: Orbital Parameters of LMC X–4 [Naik & Paul, 2004] used for the correction due to its orbital motion.

| Parameter                  | Units     | Value                  |
|----------------------------|-----------|------------------------|
| $a_x \sin i$               | lt-secs   | 26.33 ± 0.02           |
| $P_{\text{orb}}$           | days      | 1.40839 ± 0.00002      |
| $P_{\text{orb}}'/P_{\text{orb}}$ | yr$^{-1}$ | (9.69 ± 0.07)$\times 10^{-7}$ |
| $T_{\text{mid eclipse}}$ (pn) | MJD       | 52892.4844(17)         |
| $T_{\text{mid eclipse}}$ (P10135) | MJD       | 50315.1225(14)         |
| $T_{\text{mid eclipse}}$ (P40064) | MJD       | 51531.9727(25)         |

2. Timing Analysis with EPIC-pn and PCA

2.1. Light Curves

The time series obtained from the observation made with the EPIC-pn has flares, persistent emission and an eclipse (top panel of Figure-1). The flares lasted for nearly 20 ks. The light curve extracted in the 2-10 keV band, excluding the piled up pixels showed an average count-rate of ~ 9 counts/s during the persistent emission and a peak count rate during the flares up to 20 times the mean count rate during the persistent emission. An exponential decay timescale for each of the flares (2, 4, 6) (Figure 1) is 470 s, 880 s and 700 s respectively.

Light curves in the 2-10 keV band were created using the PCA data of the observations mentioned in the Table-1. Light curves created using the observation with ID P10135 showed four flares, persistent emission and an eclipse (see bottom panel of Figure-1). The flares lasted for about 40 ks. The average count rates per PCU observed during the persistent emission is 30 counts/s and the flares reached a peak count rate of about 650 counts/s/PCU. An exponential decay timescale measured for the four flares (2, 4, 6 & 8) seen in observation P10135 are about 160 seconds, 140 seconds, 540 seconds and 300 seconds respectively.

Another PCA observation with ID-P40064 also showed four flares in addition to the persistent emission. These four flares were, however, not continuous but had a time gap between the first and the other three (see middle
Figure 1: The top panel shows the light curve of LMC X–4, obtained using data from EPIC-pn after removing piled-up pixels, the middle panel shows the light curves created using the observation made with RXTE-PCA with ID-P10135 while the bottom panel shows the light curves obtained using PCA data with observation ID-40064. The 2-10 keV band was used for creating these light curves. The plotted light curves have been binned with a bin size equal to the pulse period of LMC X–4, $\sim$13.5 s.
panel of Figure1. The average count rate per PCU observed during persistent emission is 26 counts/s in 2-10 keV band. Flares reached the maximum of 400 counts/s/PCU for a light curve with binsize 13.5 seconds. In the observation P40064, an exponential decay timescales measured for the two high intensity flares (2 and 5) are 480 seconds and 500 seconds, respectively.

2.2. Energy-Resolved Profiles

We have used the light curves during persistent emission for the spin period measurement. For the EPIC-pn observation, persistent emission commenced about 5000 seconds after the end of last flare (segment 6). For the PCA observation with ID P10135, we have used data 2000 seconds after the end of last flare (marked as 8 in the second panel of Figure1). We have included all segments of the persistent emission excluding the intermediate flares (segments: 2, 5, 6, 7) for the other PCA observation with ID P40064.

The spin period was measured to be 13.49624(7), 13.50912(1) and 13.49642(2) seconds using the pulse folding $\chi^2$ maximization technique applied to the light curves during persistent emission from the EPIC-pn and the two PCA observations, P10135 and P40064 respectively. 1 $\sigma$ uncertainties in the pulse periods were estimated opting the same technique as used by Naik et al. (2005). We notice that spin-periods measured are consistent with those reported by Molkov et al. (2017). The respective period of each observation was used to create energy resolved pulse profiles using both the flaring and persistent emission data, using the FTOOL task efold.

Phase zero for each observation was determined with respect to the sharp, deep dip observed in the pulse profiles during persistent emission (deep dip which settled in phase after large flares). In Figure2 we show representative energy resolved pulse profiles, created using the EPIC-pn data. The phases of the pulse profile for all the three observations are adjusted with the dip appearing at phase zero. In the 0.3-2 keV band, the pulse profile during persistent emission is single peaked with a shoulder type structure. The dip feature is seen only at energies above 2 keV. These pulse profile shapes are quite similar to the previously reported profiles created using observations made with Ginga, RXTE, ASCA, BeppoSAX and Suzaku (Levine et al., 1991, 2000; Paul et al., 2002; Naik & Paul, 2004; Hung et al., 2010). Similar dips were also observed in the pulse profiles during the persistent emission, created using data from the other two PCA observations. Pulse profiles during the flares, on the other hand, exhibit simple sinusoidal shapes in all the energy bands (Figure2). This is consistent with the known facts of energy resolved pulse profiles during flares of LMC X–4 (Levine et al., 1991, 2000; Moon et al., 2003b).
Figure 2: Left: Energy resolved pulse profiles created using the EPIC-pn data during the persistent state, binned into 64 phasebins. Right: Energy resolved pulse profiles created using data during the flares of same observation.

2.3. Evolution of dips in the pulse profiles

We divided the data into narrow time segments to separate the flares and the periods in between the flares, labelled as 1, 2, 3, 4 and so on (see Figure-1). We have performed a pulse profile evolution study in the 2-10 keV band because the dips appeared in the pulse profiles above 2 keV, created using the persistent state data (refer Figure 2).

Figure 3 shows the evolution in the pulse profiles, created using data from the EPIC-pn. The most important and interesting observations from Figure-3 (EPIC-pn data) are described below:

- Pulse profiles during the flares (segments 2, 4, 6) and just before and after the flares (segments 1, 3 and 5) are nearly sinusoidal, but the peak of the profiles was found to have a significant phase offset (of about 0.23 ± 0.02). In particular, we note that the time segments around the flares do not have the dip feature even though the mean photon count rates in segments 1, 3 and 5 are similar to those of the persistent emission.

- Near the end of last flare and the beginning of persistent emission (segment 8), broad dip like features began to emerge.

- Data during the segment 9 showed further development of the dip near phase 0.9, though the dip is not very deep and narrow in comparison to the dip seen in the profiles created using later segment 10 of the persistent emission. Moreover, some other dip-like features are also observed in the profiles created using data of segment 10.
Figure 3: The left-hand plot shows the pulse profiles created with EPIC-pn data in short segments as marked in the top panel plot of Figure 1. Each panel is marked with the time offset relative to the start of the observation. The profiles are created using time series in the 2-10 keV band and binned into 64 phasebins while the plot on the right shows the pulse profiles created using the sub-segments of segment 9, binned into 32 phasebins, in order to demonstrate the time required for the evolution of dips after the flares. Segment 9 was divided into 6 short segments, each with 5 ks of exposure.
**Figure 4:** This figure illustrates the emergence and evolution of the dip phase and depth with time. Top panel: Plotted light curve binned with a binsize of 135 seconds. The bottom panel shows the evolution of dip phase and dip depth in the pulse profiles. To notice a change in phase depth with time each circle is scaled by a factor of 20. The x and y-axis is in log scale. For details see text.
• Pulse profiles of segment 11 (the region after the eclipse) exhibited many
  dip-like structures in it. The most prominent dips were observed near
  phases 0.2 and 1.0 with the rest of the profile also showing some structures
  in it.

From the above-mentioned sequence, we infer that dips are formed in the pulse
profile after all the flares are completed, and it takes several thousand seconds
for the dips to settle in phase. Therefore, in order to measure the timescale
required for the formation of the dip, we further divided segment 9 into nar-
row segments, each with 5 ks of exposure time (see right plot of Figure 3). It
is evident from the figure that for the first five thousand seconds of segment 9
there are several evolving structures in the profile with the most prominent ones
near phase 0.8 and 1.0. Profiles created using the next five thousand seconds of
the segment 9 show a sharp dip near phase 0.8. During later times of the 9th
segment the profiles show the appearance of a clear dip near phase 1.0.

For a quantitative estimation of the timescale of formation of a dip, the lo-
cation of dip phase and its depth, we created pulse profiles using the data in
short segments starting from the segment 8. Dips observed in the phase range
of 0.8 – 1.1 in each of these profiles were fit to a constant and a negative Gaus-
sian. This robust method of finding the exact location of the dip phase and its
depth allowed us to study the dip evolution more accurately. Figure 4 shows
the evolution of dip phase and depth with time, where the top panel shows the
light curve starting 100 seconds after the peak of the last flare while the bottom
panel gives the measure of the dip phase and its depth as observed in the profiles
at the corresponding times. After the flares observed during this XMM-Newton
observation, it took nearly 4000 seconds starting from the peak of the last flare
for dip feature to emerge. However, it took more than 30,000 seconds for the
dip to settle in phase. The depth of the dip which is represented by the size of
circle in the lower panel of Figure 4 indicates that for about 9000 seconds dips
were quite shallow in comparison to the rest of the dips seen in the pulse profiles.

It is interesting to notice that although the flare decay timescale varies from
flare to flare, the time difference between the consecutive flares is approximately
4 ks.

Pulse profiles created with short segments of the other two PCA observa-
tions - P10135 and P40064 are shown in a left hand plot of Figures 5 and 6
respectively. In both these observations profiles during the flares are simple and
exhibit sinusoidal shapes. However, it is interesting to notice that the low inten-
sity flares (segments 6 and 7) seen in the observation with ID-P40064 exhibits
a signature of a shallow dip near the peak of the profiles (Figure 6). The phase
offset of 0.21 ± 0.01 is also observed between the peak of the pulse profiles of
segments 1, 3, 5 and 7 (just before and after the flares) and the flare pulse
profiles (Figure 5).
Figure 5: The left-hand plot shows the pulse profiles created using PCA data (OBSID-P10135) in short segments as marked in middle panel of Figure. Each panel is also marked with the time range for each segment. These profiles are created using the time series in the 2-10 keV band and are binned into 64 phasebins while the plot on the right shows the pulse profiles created using the sub-segments of segments 8 and 9. The duration of segment 8(a), 8(b) is 2000 and 800 seconds, respectively. Segment 9 is divided into 4 each having 500 seconds of exposure time. Pulse profiles of the sub-segments of segment 9 are binned into 32 phasebins.
Figure 6: Left hand side plot shows the pulse profiles created in short segments of PCA data with OBSID-P40064, as marked in the bottom panel of Figure 1. Each panel is also marked with the time range used. These profiles are created using the time series in the 2-10 keV band and are binned into 64 phasebins. The plot on the right side shows the pulse profiles created using the sub-segments of segments 1, 2 and 3. The pulse profiles of the sub-segments of segment 3 are binned into 32 phasebins.
The plot on the right hand side of Figures 5 and 6 shows a detailed investigation of the evolution of the dip in the pulse profiles after the end of flares. From Figure 5, we observe that near the decline of the last flare (b) of P10135, the profiles showed some emerging features in comparison to the flare profile (a). The pulse profiles created using the subsegments of the segment 9 (each with 1200 seconds time) also showed the evolution of a dip near phase 1.0 with time. This result is consistent with that obtained using the EPIC-pn data. For the observation-P40064, we again noticed that the dip near phase 1.0 is evolving with time and this feature became deep and narrow in the last subsegment of 3. Since flares are not continuous for this particular PCA observation, we could not measure the exact time difference between the two consecutive high intensity flares. Hence, structures seen in the profiles near the beginning of the flare 2 could not be explained with this observation.

For a quantitative measurement of the dip phase and depth, we followed the same technique (as explained for EPIC-pn data) of fitting a dip (in the phase range of 0.9-1.35 for P10135 and 0.95-1.1 for P40064) with a constant and a negative gaussian model component (Figure 4). From the Figure 4, it was found that it took nearly 2500 seconds after the peak of a last flare for the dip to emerge. The time difference between two the flares is also nearly 2500 seconds. This is again consistent with the fact that no dip is seen in the persistent emission (3,5) between two flares. The dip-phase settle after about 20,000 seconds.

For the observation-P40064, it was found that dip occurred about 2000 seconds after the peak of first very high intensity flare (segment 2). Both the PCA observations also showed that it takes a few thousand of seconds for dip to develop after the end of the flares.

2.4. Phase Shift During Flare Profiles

To keep track of the phase shift observed between the peak of the pulse profiles during flares (segments 2, 4 and 6) and just before and after flare segments (segments 1, 3 and 5) in the EPIC-pn data, we further divided 1, 2, 3 and 4 segments in the short intervals, shown in the left panel of Figure 7. It was found that the pulses are in phase during intervals 1(a)−1(e). Then there is a sudden phase change at the beginning of the flare at interval 2(a), the pulse peak appears delayed (i.e., the beaming during the flare is away from the direction of rotation). The phase seems to be constant during all the segments of flare (2) and returns by a sudden jump to the original phase at 3(a). 3(a)−3(e) have a similar phase, just like in 1(a)−1(e). The same kind of sudden phase shift happens at 4(a). The phase shift observed between the flares and pre-flares measured using the location of the peaks in Figure 7 varies between 0.2 and 0.5.

For the PCA observation P10135, we divided segments 1, 2, 3, 4, 5, 6, 7, 8 into short intervals. Pulse profiles created using the sub-segments are shown in right hand side plot of Figure 7. The same range of phase shift between the
Figure 7: Left hand plot shows pulse profiles created using sub-segments of 1, 2, 3 and 4 intervals of the top panel of Figure 1 (PN data), while the right-hand plot shows the pulse profiles created using sub-segments of 1, 2, 3, 4, 5, 6, 7 and 8 shown in the middle panel of Figure 1 (PCA-P10135), each vertically shifted for ease of viewing. The profiles are binned into 16 phasebins.
peak of pulse profiles is also observed in this observation. This confirms the change in beaming pattern within flares.

3. Spectroscopy with EPIC-pn

3.1. Phase-Averaged Spectroscopy

Pulse-phase averaged spectral analysis was performed using the mean spectrum extracted using the persistent emission data (excluding flares and an eclipse). The spectrum was rebinned by factor of 4 between 1-10 keV using ftool *grppha*. The spectral fitting in the 0.3-10 keV band was done using Xspec Version: 12.8.0 ([Arnaud, 1996](#)). We have first tried to fit the continuum of the phase-averaged spectrum using as model components: bremsstrahlung for the soft excess and a powerlaw, each attenuated with line of sight absorption. The minimum of the interstellar absorption component was set at the value of the Galactic column density towards the source. A bremsstrahlung model component alone did not provide an acceptable fit, some soft excess was still seen in the residual. Therefore, we added an additional blackbody emission component ([Woo et al., 1996](#)) to fit the low energy excess.

Using only the continuum model still showed an excess in the form of an emission line features around 1.0 keV and 6.4 keV. The RGS data from the same observation was used by [Neilsen et al., 2009](#), where they have reported a broad emission feature near 1 keV. Therefore, considering this fact we added a gaussian component centered around 1 keV with a width of 0.080 ([Neilsen et al., 2009](#)). An additional gaussian feature was also added with the line energy centered around 6.4 keV (see Figure 8). The parameters obtained from the fitting are given in Table-2. These parameters are in good agreement with the values reported by [Neilsen et al., 2009](#) using the RGS data from the same observation (see Table-2). These authors also fixed the galactic neutral hydrogen column density at $5.78 \times 10^{20} \text{cm}^{-2}$.

3.2. Phase-Resolved Spectroscopy

The pulsating nature of the soft spectral component during its high state has been studied by [Woo et al., 1996](#); [Paul et al., 2002](#); [Naik & Paul, 2004](#) using data of ROSAT, Ginga, ASCA and BeppoSAX. A significant difference in the pulse profile below and above 2 keV of the PN light curve (Figure 2) also indicates the soft component of spectrum to pulsate differently compared to the powerlaw component. We here present phase resolved studies performed at narrow phasebins.

The event file used for the extraction of phase resolved spectra was corrected for the binary motion as mentioned earlier in section-2. Phase resolved spectra were created using the 'phase' filter of ftools² task XSELECT with a phase bin

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²http://heasarc.gsfc.nasa.gov/ftools/
Table 3: Best-fitting parameters of Phase-averaged spectrum of LMC X–4.

| Parameter                  | Model Values                  |
|----------------------------|-------------------------------|
| $N_H$ ($10^{22}$ atoms cm$^{-2}$) | 0.06                         |
| $\Gamma$                  | 0.750 ± 0.005                 |
| $N_{PL}$                  | (5.65 ± 0.04) × 10$^{-3}$   |
| $kT_{\text{bbodyrad}}$ (keV) | 0.043 ± 0.001               |
| $kT_{\text{Bremss}}$ (keV)  | 0.400 ± 0.004               |
| $Fe_{E}^b$                | 6.62 ± 0.02                  |
| $Fe_{W}^c$                | 0.40 ± 0.02                  |
| $Fe_{\text{flux}}^d$      | 2.3 ± 0.1                    |
| $Fe_{\text{EW}}^e$        | 0.17 ± 0.01                  |
| Reduced $\chi^2$          | 1.2 (dof 1179)               |

Notes: Errors quoted are for the 68 % confidence range.

a → Powerlaw normalisation ($N_{PL}$) is in units of photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$ at 1 keV

b → Iron-line energy in units of keV.

c → Iron-line width in units of keV.

d → Gaussian normalisation is in units of 10$^{-4}$ photons cm$^{-2}$ s$^{-1}$

e → Iron-line equivalent width in units of keV.

Table 4: Best-fitting parameters obtained by [Neilsen et al. 2009]

| Parameter                  | Model Values                  |
|----------------------------|-------------------------------|
| $\Gamma$                  | 0.813 ± 0.007                 |
| $kT_{\text{bbodyrad}}$ (keV) | 0.043$^{+0.001}_{-0.002}$    |
| $kT_{\text{Bremss}}$ (keV)  | 0.455$^{+0.001}_{-0.001}$    |

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Figure 8: Data and folded model spectrum of LMC X–4 from XMM-Newton EPIC-PN.
Figure 9: Left: Variations of the continuum spectral parameters across the pulse phase. Powerlaw normalisation ($PL_{\text{norm}}$) is in units of photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$ at 1 keV. Right: variation of the flux ($f$) of the continuum. $f_{\text{total}}$, $f_{\text{Brems}}$, & $f_{\text{PL}}$ are measured in units of $10^{-10}$ ergs cm$^{-2}$ sec$^{-1}$. All the errors were estimated with 1$\sigma$ confidence.
of 0.05. We have used the same background spectrum and response files as were used for the phase-averaged spectrum. X-ray spectra in different phases were grouped using ftools task grppha with minimum 25 counts per bin. For fitting the phase-resolved spectra we followed exactly the same technique as we opted for the phase-averaged spectrum. However, we fixed all the line energies and line widths to the values obtained in the best fit of phase-averaged spectrum. It is interesting to observe the pulsations (pulse fraction 17%) of the soft component (thermal bremsstrahlung) in narrow phase bins (see right plot of Figure 9). The profile shapes were similar to those reported by Naik & Paul (2004). The powerlaw flux also exhibited variation across the pulse phase with some similarity with the pulse profiles in the 5-10 keV band. A dissimilar pulse profile between the low and high-energy bands is similar to the earlier results obtained from ASCA and BeppoSAX that indicated that the soft component may have a different origin of emission, or that the geometry of emission is different in different energy ranges (Paul et al., 2002; Naik & Paul, 2004). The continuum parameters like the bremsstrahlung temperature, its normalisation and powerlaw index also exhibit some variation across the pulse phases (Figure 9).

4. Summary and Discussions

In this work, we have probed the pulse profiles of LMC X–4, during the flares and outside the flares. A study performed using the data from XMM-Newton and RXTE showed the existence of dips during persistent emission, after the flares. The narrow dips, observed in the pulse profiles, are believed to occur due to phase-locked absorption of the emitted radiation by the optically thick material in the accretion column (Cemeljic & Bulik, 1998; Galloway et al., 2001; Naik et al., 2011; Maitra, 2013; Devasia, 2014). Therefore, the dipping structures seen in the pulse profiles during persistent emission indicate the existence of an absorption stream in the accretion column that causes the drop in intensity. The observed broad pulse profiles during flares support their origin due to gravitational bending of the flare emission which is transported via fan beams. Thus, the observed differences in the pulse profiles during and after the flares suggest that significant change in the accretion stream happens during the transition between flares and the persistent state. The existence of the observations containing both flares and persistent emission allowed us to estimate the timescales required for the formation of accretion stream that causes dips, after the accretion region and beaming etc are disturbed during flares. If flares occur due to sudden infall of additional matter then the peak of a flare should indicate the time when this sudden inflow is coming to an end. Hence, the time since the last flare peak would indicate the time since it started getting back to persistent emission. From the analysis with EPIC-pn (Figure 4), we found that the time required for the formation of accretion stream that causes the dip is nearly 4 ks starting from the peak of last flare. Moreover, this observed time is nearly equal to the time difference between the two flares. The time estimated from the PCA observation with ID-P10135 is nearly 2500 seconds, this time is also consistent with
time difference between two flares. The second PCA observation used in this work with ID P40064 also indicated that the time required for the formation of a dip after the peak of flare is approximately 2000 seconds. Hence, we conclude that the formation of a dip in the pulse profiles is not abrupt, it takes a few thousand seconds for the formation of an accretion stream that causes the dip. To our knowledge, this is for the first time such a measurement has been made for any pulsar. The timescale of formation of the dips is significantly larger than the dynamical timescale of Keplerian motion of the inner accretion disk.

Another very interesting result we have found in this study is the existence of a significant phase shift between the pulse profiles from the persistent emission (just before and after the flares) and the flares, with the EPIC-pn data. This suggests an evolution of the beaming pattern as the flare evolves and decays. Similar behaviour was also observed in one of the PCA observations P10135.

Pulse profiles during flares in LMC X–4 are known to exhibit simple shapes (Levine et al., 1991, 2000; Moon et al., 2003b) and they are known to exhibit the same shapes in different energy bands (Levine et al., 2000). However, the profiles created using the PCA observation with ID P40064 provide evidence in support of intensity dependence of the flare pulse profiles. It was observed that low intensity flares (e.g., 6 and 7 segment) show the presence of a shallow dip near the peak of the profiles. However, this structure was not observed in high intensity flare pulse profiles.

Very complex changes in the pulse profiles with luminosity have also been observed in pulsars like EXO 2030+375 (Parmar et al., 1989), GX 1+4 (Paul et al., 1997), Cepheus X-4 (Mukerjee et al., 2000). Parmar et al. (1989) suggested one possible explanation for the luminosity dependence of profiles to be switching of the beaming mechanism from fan to pencil configurations and vice-versa. The same hypothesis was applicable for the change in the pulse shape observed for Cep X-4 during the IXAE observation (Mukerjee et al., 2000). As mentioned earlier, we observe simple sinusoidal profiles during flares and complex features like dips in the pulse profiles, using the data during persistent emission. Therefore, we think that the changes in the pulse profile during and after the flares indicate changes in the shape and beaming pattern of the accretion column / emission region. This behavior is, however, different from that observed in SMC X–1. Moon et al. (2003a) found simple and broad profiles during both the flares and non-flaring states of SMC X–1. The difference between SMC X–1 and LMC X–4 could be related to the difference in the strength of the magnetic field.

Pulse phase resolved spectroscopy carried out in narrow phasebins confirmed the presence of pulsations in the soft spectral component. The pulse profile shape is sinusoidal for the soft component and is different from that seen in the hard component. The pulsating nature of the soft component, though it was measured earlier with ASCA, BeppoSAX, is more clear in this XMM-Newton
observation due to its higher sensitivity. This indicates that the soft and hard emissions have different origins.

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