TIMING AND SPECTRAL STUDIES OF LMC X-4 IN HIGH AND LOW STATES WITH BeppoSAX: DETECTION OF PULSATIONS IN THE SOFT SPECTRAL COMPONENT

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ABSTRACT

We report here detailed timing and spectral analysis of two BeppoSAX observations of the binary X-ray pulsar LMC X-4 carried out during the low and high states of its 30.5 day long superorbital period. Timing analysis clearly shows 13.5 s X-ray pulsations in the high state of the superorbital period, which allows us to measure the mid-eclipse time during this observation. Combining this with two other mid-eclipse times derived earlier with ASCA, we have derived a new estimate of the orbital period derivative. Pulse-phase–averaged spectroscopy in the high and low states shows that the energy spectrum in the 0.1–10 keV band comprises a hard power law, a soft excess, and a strong iron emission line. The continuum flux is found to decrease by a factor of \(\sim 60\) in the low state, while the decrease in the iron-line flux is only by a factor of \(\sim 12\), suggesting a different site for the production of the line emission. In the low state, we have not found any significant increase in the absorption column density. The X-ray emission is found to come from a very large region, comparable to the size of the companion star. Pulse-phase–resolved spectroscopy in the high state shows a pulsating nature of the soft spectral component with some phase offset compared to the hard X-rays, as is known in some other binary X-ray pulsars.

Subject headings: pulsars: individual (LMC X-4) — stars: neutron — X-rays: stars

1. INTRODUCTION

LMC X-4 is an eclipsing, accretion-powered, binary X-ray pulsar in the Large Magellanic Cloud orbiting around a 20 \(M_\odot\) O7 III–V companion with an orbital period of \(\sim 1.4\) days (Kelley et al. 1983; Ilovaisky et al. 1984) and a pulse period of \(\sim 13.5\) s (White 1978; Li, Rappaport, & Epstein 1978; Lang et al. 1981). X-ray eclipses with a 1.4 day recurring period were discovered by Li et al. (1978) and White (1978). X-ray pulsations with a period of 13.5 s were first detected in LMC X-4 from SAS 3 observations in 1976 and 1977 only during the infrequent flaring events by Kelley et al. (1983), who also derived the orbital solution from pulse arrival delay measurements. During a high state in 1983, EXOSAT observations detected the pulsations during both flaring and nonflaring episodes (Pietsch et al. 1985). Using subsequent pulse timing measurements with GINGA, ROSAT (Levine et al. 1991; Woo et al. 1996), and RXTE (Levine, Rappaport, & Zojchowski 2000), an orbital period decay with a timescale of \(\sim 10^6\) yr\(^{-1}\) was measured, which is similar to the period decay rate in other high-mass accreting binary pulsars (Cen X-3, SMC X-1, etc.).

Analogous to the well-known X-ray pulsar Her X-1, LMC X-4 exhibits a periodic long-term intensity variation of 30.5 days (Lang et al. 1981). The superorbital period has recently been found to be decreasing (Paul & Kitamoto 2002). In the case of LMC X-4, the X-ray flux varies by 2 orders of magnitude between the high and low intensity states of the superorbital period. Varying obscuration by the accretion disk due to precession provides a good explanation for the long-term periodic intensity variations. The 13.5 s X-ray pulsation is not yet detected during the low state of the superorbital period, indicating that most of the radiation observed in low state is probably reprocessed emission from the stellar wind of the companion star. The X-ray spectrum during eclipse of the neutron star, which consists only of scattered/reflected radiation, was found to be nearly identical in shape and strength throughout the superorbital period, supporting the disk-obscuration hypothesis (Woo, Clark, & Levine 1995). However, observations with RXTE (Heindl et al. 1999) did not detect any significant change in the absorption column density in different phases of the superorbital period. One possibility that was pointed out is that in low state, part of the X-ray emission from the central source is completely blocked by the disk and the rest is observed with the Galactic absorption. It should be noted that for sensitive measurements of absorption column density, observations with good soft X-ray spectral capability are required.

The X-ray spectrum of LMC X-4 consists of, in addition to a hard power-law component, a soft excess below 1 keV and an iron emission line at 6.4 keV (Woo et al. 1996). Iron K-shell emission lines in X-ray pulsars are usually narrow, but the equivalent width can sometimes be as large as \(\sim 1\) keV or more. These lines are produced by illumination of neutral or partially ionized material in the accretion disk, the stellar wind of a high-mass companion star, material in the form of a circumstellar shell, material in the line of sight, or an accretion column. As expected, the iron emission line parameters are often found to be correlated to the continuum hard X-ray flux, absorption column density, etc. Using a large number of RXTE/PCA observations of LMC X-4 made in different phases of the superorbital period, a correlation was found between the line flux and the continuum flux, along with the highly variable nature of the equivalent width of the line during low state (Naik & Paul 2003).

It is known that X-ray pulsars that do not suffer from strong absorption by material in the line of sight show the presence of soft X-ray excess above the extrapolated hard power-law component (Paul et al. 2002 and references therein). In some pulsars, the soft excess is also found to pulsate, often with a phase difference with respect to the hard component. The origin of the pulsating soft component is not yet understood.

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clearly, at least for the bright pulsars in the LMC and SMC. In LMC X-4, a small Galactic absorption column density and a lack of local absorbing material allow us to probe the soft X-ray emission with some detail. Observations of LMC X-4 with ASCA detected the soft excess but were found to be inconclusive regarding the nature of the soft component (Paul et al. 2002). This was due to a small pulse fraction of this pulsar and also to the fact that the ASCA spectrometers are not sensitive at energies where the soft excess dominates the power-law component in LMC X-4.

We have carried out detailed timing and spectral analysis of two observations of LMC X-4 with the narrow-field instruments of BeppoSAX during one high and one low intensity state of LMC X-4. We aim to detect pulsations in the BeppoSAX observation carried out in the high state and to determine the mideclipse time during this observation. From pulse-phase–averaged spectral studies in the two states, we investigate relations of the iron-line parameters to the continuum flux. To investigate the nature of the soft excess, pulse-phase–resolved spectral analysis has been carried out for the high-state observation. In the subsequent sections we give details of the observations and the results obtained from the timing and spectral analysis. These are followed by a discussion of the results obtained from these two BeppoSAX observations.

2. OBSERVATIONS

The 2–12 keV X-ray light curve of LMC X-4 taken with RXTE/ASM for the last 6 years is shown in Figure 1, folded at the present superorbital period of 30.276 days (Paul & Kitamoto 2002). Two observations of LMC X-4 were made with the BeppoSAX narrow-field instruments from 1997 March 13 10:48 to March 15 08:17 (UT) and from 1998 October 20 22:39 to October 22 08:05 (UT) in the low and high states of the source, respectively. The durations of these two observations with respect to the phase of the long period are also shown in Figure 1. We have used archival data from these two observations in the present work.

For the present study, we have used data from the Low and Medium Energy Concentrator Spectrometers (LECS and MECS) and the Phoswich Detector System (PDS) on board the BeppoSAX satellite. In the 1997 observation, the hard X-ray instrument PDS with a larger field of view contained mostly photons from a nearby transient source EXO 053109–6609.2, which is only 0.75 away from LMC X-4 (Burderi et al. 1998). The broadband spectrum (0.1–100 keV) from the 1998 BeppoSAX observation has been reported by La Barbera et al. (2001). To obtain energy-resolved pulse profiles in hard X-rays, we have used PDS data from the 1998 observation.

The MECS consists of two grazing incidence telescopes with imaging gas scintillation proportional counters in their focal planes. The LECS uses a concentrator system identical to that of the MECS but utilizes an ultrathin entrance window and a driftless configuration to extend the low-energy response to 0.1 keV. The time resolution of the instruments during these observations was 15.25 μs, and the energy resolutions of the LECS and MECS are 25% at 0.6 keV and 8% at 6 keV, respectively. The PDS consists of a square array of four independent NaI(Tl)/CsI(Na) phoswich scintillation detectors. The energy resolution of the PDS instrument is 15% at 60 keV. The time resolution of the PDS instrument during the 1998 observation was 0.25 ms. For a detailed description of the BeppoSAX mission, we refer the reader to Boella et al. (1997).

3. TIMING ANALYSIS

The light curves of LMC X-4 during these two BeppoSAX observations obtained with the LECS and MECS detectors are shown in Figure 2 with respect to the orbital phase (mideclipse time = orbital phase 0.5). During the 1997 observation, which was during a low state, a smooth intensity variation is observed throughout the orbital period and the eclipse is not clearly seen. Near the end of the low-state observation, an increase in count rate is noticed that is similar to the flares observed earlier in the low state with ROSAT (Woo et al. 1995). Similarly to the other high-state observations of LMC X-4, the 1998 observation clearly shows an eclipse during which the X-ray intensity decreases sharply to a very low level.

For timing analysis, the arrival times of the photons were first converted to the same as at the solar system barycenter. Light curves with time resolution of 0.25 s were extracted from circular regions of radius 4′ around the source. The pulses from LMC X-4 lose coherence within a relatively short timescale of a few thousand seconds due to the short orbital period of 1.4 days, while the semiamplitude of the arrival time delay due to orbital motion is 26.3 s. In addition, the relatively small effective area of the BeppoSAX telescopes and the small pulse fraction of LMC X-4 makes it difficult to detect pulse arrival times from small segments of the light curve. Therefore, to detect the pulsations and also the mideclipse times during these observations, we have first corrected the light curve for the binary motion. Regarding the orbital parameters, the semiamplitude was taken to be 26.31 s and the mideclipse time was derived from the quadratic solution given by Levine et al. (2000). The binary arrival time delay correction was applied with a range of trial mideclipse times around the value extrapolated from Levine et al. (2000). A pulse-folding and χ^2 maximization method was applied to all the corrected light curves. The distribution of maximum χ^2 against the trial mideclipse times obtained from each pulse-folding analysis is shown in Figure 3 for the high-state observation in 1998. The maximum χ^2 distribution has a
Gaussian profile around the expected value of the mideclipse time, the center of which gives the correct value. Using the same method, we did not detect any pulsations in the low state. The result of the pulse-folding analysis corresponding to the peak of the curve in Figure 3 is shown in Figure 4, which clearly shows the detection of pulsations in this observation, contrary to La Barbera et al. (2001). In the high state, the pulsations were in fact detected independently in light curves of the LECS, MECS, and PDS detectors. The pulse profiles obtained from the high-state light curves of the LECS, MECS, and PDS in different energy bands are shown in Figure 5.

From this analysis, we have derived the pulse period of LMC X-4 as 13.50260(12) s and the mideclipse time as MJD 51,106.6399(25), corresponding to orbit number 5877.

Combining the new determination of the mideclipse time with the previous measurements (Levine et al. 2000 and references therein; Paul et al. 2002), we fitted a second-order polynomial to derive the orbital decay rate. Residuals of the orbital mideclipse time history of LMC X-4 relative to a constant period are shown in Figure 6. The solid line in the figure shows the quadratic nature of the mideclipse time history. We derive a period decay rate of $P_{\text{orb}}/P_{\text{orb}} = (9.89 \pm 0.05) \times 10^{-7}$ yr$^{-1}$.

The pulse profiles in the different energy bands are shown in Figure 5. In the low energy band (0.1–1.0 keV of LECS; top), the profile is nearly sinusoidal, and there is a complex structure in the energy band 4.0–10.0 keV (MECS; bottom), with multiple dips superposed on a smooth sinusoidal profile. A phase difference between the sinusoidal pulse components of the two energy bands is also visible in the figure. At intermediate energies (1.0–4.0 keV; both LECS and MECS), the pulse profile is a mixture of the above two. The pulse fraction is less than 10%, and these features are similar to the known pulsation properties of LMC X-4. Although the pulsations are seen in the PDS light curves in the 15.0–60 keV energy band (Fig. 5, right, top three panels), the pulse profiles do not show the complex dipping feature, as seen in the MECS profiles, and are similar to those obtained from the LECS light curves with certain phase differences. The light
curve above 60 keV is mainly background-dominated, and we did not detect pulsations in the 60–200 keV range. The transient X-ray pulsar EXO 0531–66, which has a pulse period of 13.7 s, close to that of LMC X-4, was in the field of view of the PDS instrument. This source was detected in the LECS and MECS instruments at an intensity level about 0.2% that of LMC X-4. From a period search of the PDS light curve in a range covering the pulse periods of both LMC X-4 and EXO 0531–66, we have verified that contamination of the PDS folded light curve of LMC X-4 was minimal.

4. PULSE-PHASE–AVERAGED SPECTROSCOPY

For spectral analysis, we have extracted LECS spectra from regions of radius 6" centered on the object (the object was at the center of the field of view of both the instruments). The combined MECS source counts (MECS 1+2+3 in the 1997 observation and MECS 2+3 in the 1998 observation) were extracted from circular regions with a 4" radius. For spectral fitting, the 1997 September LECS and MECS 1 response matrices were used. Background spectra for both the LECS and MECS instruments were extracted from appropriate source-free regions of the field of view, with the extraction region on the detector similar to the source extraction regions. Some rebinning was done to allow the use of the $\chi^2$ statistic. Events were selected in the energy ranges 0.1–4.0 keV for LECS and 1.65–10.0 keV for MECS, where the instrument responses are well determined. Combined spectra from the LECS and MECS detectors, after appropriate background subtraction, were fitted simultaneously. All the spectral parameters, other than the relative normalization, were tied to be the same for both detectors, and the minimum value of hydrogen column density $N_H$ was set at the value of Galactic column density in the source direction.

4.1. Low State

In the low-state observation of 1997, the source count rate was about 2 orders of magnitude lower than in the high state. Therefore, spectral fitting required significant rebinning. The

![Fig. 5.—LECS and MECS pulse profiles of LMC X-4 in the high state are shown here in the left panels for different energy bands with 16 and 32 phase bins per pulse, respectively. Energy-resolved pulse profiles from the PDS are shown in the right panels. Two pulses are shown for clarity.](image)

![Fig. 6.—Residual orbital epochs of LMC X-4 relative to a constant orbital period $P = 1.40839374$ days. The new measurements, after Levine et al. (2000), are shown as filled circles. The best-fit quadratic function to the residuals is shown as a curve.](image)
spectrum, when fitted to a single power-law model with line of sight absorption, showed significant soft excess below 1 keV. The addition of a soft component to the model improves the spectral fit; we have tried two different components such as blackbody emission and a bremsstrahlung component to fit the soft excess. Results of the spectral fits are given in Table 1. From the spectral fitting, we are unable to distinguish between these two models of the soft component. The low-state photon spectrum, along with a spectral model comprising three components, a hard power law, a Gaussian emission line, and a bremsstrahlung emission, is shown in Figure 7. Two notable features of the low-state spectrum are that the power-law component is very hard, with a photon index of \(\gamma\approx 0.1\), and the iron-line equivalent width is large, \(\sim 1.3\) keV. Both of these have been observed earlier with RXTE (Naik & Paul 2003). The line-of-sight absorption during the low intensity state is found to be approximately \(\sim 5 \times 10^{20}\) atoms cm\(^{-2}\), similar to the Galactic column density, and the characteristic temperature of the soft component is lower than that in the high state.

### 4.2. High State

A power-law fit to the high-state spectrum shows a large soft X-ray excess. As with the low state, we tried to fit the soft excess with different single components: blackbody, thermal bremsstrahlung, and soft power law; none gave a satisfactory fit. Finally, we found that a combination of any two of these components for the soft excess improves the spectral fit to some extent. The best-fit model is the one comprising a hard power-law of photon index 0.65, an iron K\(\alpha\) emission line of equivalent width 240 eV, a blackbody component of temperature 0.15 keV, and a soft power law with photon index \(\sim 3\). The LECS and MECS count rate spectra are shown in Figure 8, along with contributions of individual components. Irrespective of the model chosen to fit the soft excess, the soft component starts dominating the spectrum at energies below 0.8 keV.

### 5. PULSE-PHASE–RESOLVED SPECTROSCOPY

Since we did not detect any pulsations in the low-state observation of 1997, the pulse-phase–resolved spectroscopy was done only on the 1998 data set to understand the nature of the soft component. The photon arrival times in the LECS and MECS event files were corrected for the solar system barycenter and for the arrival time delays due to orbital motion. Following this, spectra were accumulated into 16 pulse phases by applying phase filtering in the FTOOLS task XSELECT. As in the case of phase-averaged spectroscopy, the background spectra were extracted from source-free regions in the event files and appropriate response files were used for the spectral fitting.

Each pulse-phase–resolved spectrum has a very inferior signal-to-noise ratio compared to the phase-averaged spectrum. Therefore, sometimes it is not possible to constrain all the model parameters, especially if a complicated spectral model is used. Since our aim is to investigate the nature of the soft excess (whether pulsating or not), we used only two models, in which a single component (either a soft power law or a bremsstrahlung) is used for the soft excess and a relatively
low reduced $\chi^2$ is obtained. For the phase-resolved spectra, the iron-line energy, line width, and $N_H$ were fixed to their phase-averaged values and all the other spectral parameters were allowed to vary. The continuum flux and the fluxes of the soft and hard components in the 0.1–10.0 keV energy range were estimated for all 16 phase-resolved spectra. The modulation in the X-ray flux for the hard and soft spectral components and the total flux are shown in Figure 9, along with the 1σ error estimates. Pulse-phase–resolved spectral analysis shows that modulation of the hard power-law flux is very similar to the pulse profile at higher energies. A pulsating nature of the soft-spectral component is clearly detected irrespective of the spectral model used. The pulsating soft component has a nearly sinusoidal profile, dissimilar to the complex profile seen at higher energies, with a certain phase difference with the hard component. These properties are very similar to what is seen in Her X-1 (Endo, Nagase, & Mihara 2000) and SMC X-1 (Paul et al. 2002).

6. DISCUSSION

6.1. Orbital Evolution

There are several ways to measure the orbital ephemeris of X-ray binaries from X-ray observations. Pulse frequency modulation or arrival time delay measurement of X-ray pulsars gives a very accurate measurement of the mideclipse time ($T_{\text{mideclipse}}$) of binary X-ray pulsars and has so far been used to measure the orbital parameters of a large number of binary X-ray pulsars. The quadratic nature of the mideclipse time history during the last two to three decades unambiguously establishes an orbital evolution with a timescale of about $10^5$–$10^6$ yr in several binary X-ray pulsars (Cen X-3, Nagase et al. 1992; LMC X-4, Levine et al. 2000; SMC X-1, Wojdowski et al. 1998, etc.). In the case of low-mass X-ray binary pulsars, the orbital evolution is mainly due to conservative mass transfer from the companion to the neutron star, whereas in the case of high-mass X-ray binaries, it is due to mass loss from the system and/or strong tidal interaction between the two stars. The measurement of one new mideclipse time of LMC X-4 with BeppoSAX and two with ASCA (Paul et al. 2002) allows us to determine the orbital period derivative of the source with better accuracy. It has been pointed out before that tidal interaction is probably the dominating effect in the orbital evolution of LMC X-4 (Levine et al. 2000).

6.2. The Iron Emission Line

Spectral analysis of the high and low states of LMC X-4 shows significant differences. The presence of a prominent iron emission line can be seen in the low intensity state of the source (Fig. 7). While the continuum flux in the 0.1–10 keV band in the two states differs by a factor of $\sim 5$, the iron-line flux differs only by a factor of $\sim 12$. This results in a much larger equivalent width of 1.26 keV in the low state compared to 200 eV in the high state. In view of an obscuring precessing accretion disk model for the superorbital period, it is interesting to note that the column density is very similar in the two states and is close to the Galactic value. It was suggested (Heindl et al. 1999) that if the low-state X-rays are due to Compton scattering by circumstellar material, significant obscuration by the accretion disk in the low state may still be true. Partial coverage of the hard X-ray emission could be a possible explanation for the low state. However, we found that the addition of a partial covering model component to the hard power law does not fit the low-state spectrum.

The spectral results obtained from the present work are consistent with those obtained from the RXTE/PCA observations (Naik & Paul 2003). However, a much better sensitivity to weak sources and the better energy resolution of BeppoSAX LECS and MECS compared to RXTE/PCA gives improved confidence in the equivalent width measurements of the iron
emission line. A smaller iron-line flux in the low state indicates that most of the line emission is produced in a region comparable to or smaller than the size of the obscuring material, probably the accretion disk. But an increased equivalent width of the iron line in the low state also indicates that part of the emission line must originate in a region farther away from the neutron star. It is known that high-mass X-ray binary pulsars often show several iron-line components from different ionization species, probably produced in different regions of the system. The best example is the case of Cen X-3, where at least three components with different variability characteristics were resolved (Ebisawa et al. 1996). The flux evolution of different line components during eclipse egress suggests that the 6.4 keV line is emitted close to the neutron star, while the other components are probably emitted in a more extended highly ionized plasma (Nagase et al. 1992; Ebisawa et al. 1996). In the case of LMC X-4 also, La Barbera, A., Burderi, L., di Salvo, T., Iaria, R., & Robba, N. R. 2001, claimed detection of more than one component, with one of them being at 6.1 keV. High spectral resolution observations with Chandra or the future Astro-E mission will allow one to find out whether these two species of iron have different ionization states. High spectral resolution observations in different phases of the superorbital and orbital periods of LMC X-4, including during the eclipse, will finally help to settle the issue regarding the origin of the iron emission line in LMC X-4.

6.3. Pulsations of the Soft Excess and Its Origin

A soft excess above the hard power-law component is now known to be present in several accreting pulsars, and the soft component is also known to be pulsating in some of these sources. The soft excess has been modeled with several different types of emission, but no single model is applicable to all sources with soft excess. A blackbody-type pulsating soft excess can describe the emission from Her X-1 well (Endo et al. 2000); however, it runs into a problem in the case of the more luminous sources such as SMC X-1 and LMC X-4 (Paul et. al. 2002). In some sources, a bremsstrahlung type of soft emission describes the spectrum well. However, since the emission region has to be very large and the cooling timescale is also very large, such an emission is not expected to pulsate. The soft excess in LMC X-4 is more complex, and more than one component is needed to model the soft excess. However, when a bremsstrahlung component is included, it produces most of the soft excess, and the pulsating soft excess requires that this component pulsate. LMC X-4 has a very small pulse fraction, and the soft excess peaks at energies lower than the ASCA threshold. As a result, ASCA observations of LMC X-4 were inconclusive regarding the pulsations of the soft excess in LMC X-4. In the present work with BeppoSAX, we have obtained a definite detection of pulsations in the soft excess irrespective of the spectral model used.

In the low state, the LECS and MECS light curves (Fig. 2) show large amplitude but gradual intensity variation over the entire binary orbit. The sharp eclipse, which is easily detectable in the high state, is not clear in the low state at all. This indicates that in the low state, the observed X-rays are due to reprocessing from a scattering region that has a size comparable to that of the companion star. It is possible that in different orbital phases part of the scattering region is blocked from view by the companion star. The amplitude of variation, i.e., the ratio between the maximum and minimum in the low-state binary light curve, is larger in MECS compared to LECS. This is possible if the soft excess is produced in a larger region and the hard power-law component originating near the neutron star is heavily absorbed, with the absorption varying highly with orbital phase. Using a radius of 8.1 $R_\odot$ of the companion star (Woo 1993) and a binary separation of 26.31 It-s (Levine et al. 1991), the solid angle subtended by the companion star at the neutron star is calculated to be $\sim 4\pi/7$. In the present work, the soft excess flux in the low and high states of LMC X-4 is measured to be about 18% of the hard power-law flux. Therefore, one probable site for production of the soft excess is the surface of the companion star, which can work as a reprocessing agent. The different visibility of the stellar surface that is irradiated by the neutron star can cause the observed orbital soft X-ray intensity modulation in the low state.

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