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Spectral Properties of the X-ray Binary Pulsar LMC X-4 during Different Intensity States

S. Naik & B. Paul *Tata Institute of Fundamental Research, Mumbai, 400 005, India.*

Abstract. We present spectral variations of the binary X-ray pulsar LMC X-4 observed with the RXTE/PCA during different phases of its 30.5 day long third period. Only out-of-eclipse data were used for this study. The 3–25 keV spectrum, modeled with high energy cut-off power-law and iron line emission is found to show strong dependence on the intensity state. Correlations between the Fe line emission flux and different parameters of the continuum are presented here.

Key words. Stars: individual: LMC X-4—stars: neutron—X-rays: stars.

1. Introduction

LMC X-4 is an eclipsing high-mass disk-fed accretion-powered binary X-ray pulsar in the Large Magellanic Cloud. A spin period of 13.5 s was discovered in LMC X-4 by Kelley *et al.* (1983) and X-ray eclipses with a 1.4 day recurring period was discovered by Li *et al.* (1978) and White (1978). The X-ray intensity varies by a factor of $\sim$ 60 between high and low states with a periodic cycle time of 30.5 day (Lang *et al.* 1981; Paul & Kitamoto 2002). Flux modulation at super-orbital period in LMC X-4 is believed to be due to blockage of the direct X-ray beam by its precessing tilted accretion disk, as in the archetypal system Her X-1. Flaring events of duration ranging from $\sim$ 20s to 45 minutes (Levine *et al.* 1991 and references therein) are seen about once in a day during which the source intensity increases by factors up to $\sim$ 20.

Broad band spectroscopy using GINGA and ROSAT data shows that the continuum can be modeled with a high energy cut-off power-law (Woo *et al.* 1996). The spectrum also shows a soft excess and a broad iron emission line. The soft excess detected with ROSAT was modeled as a combination of thermal bremsstrahlung and very soft black-body by Woo *et al.* (1996), while the same observed with Beppo-SAX (La Barbera *et al.* 2001) was modeled as black-body emission from accretion disk at magnetospheric radius Comptonized by moderately hot electrons. La Barbera *et al.* (2001) also reported the presence of a cyclotron absorption line at $\sim$ 100 keV.

In this paper we present the spectral variations of LMC X-4 during the 30.5 day long period using the archival data from RXTE observations.

2. Observation, analysis and results

To study the super-orbital phase dependence of various spectral parameters, we have analyzed 43 RXTE/PCA observations of LMC X-4 at different phases of the 30.5 day third period. The data used for analysis are out-of-eclipse and free from the flaring state. Energy spectra in 129 channels were generated from the Standard 2 mode PCA data. The standard procedures for data selection, and response matrix generation were followed. Background estimation was done using both bright and faint models of RXTE/PCA according to different intensity states of the source at different phases. We restricted our analysis to 3–25 keV energy range. Data from all five PCUs are added together. We have fitted the energy spectrum of the source using a model consisting of blackbody, power law and a high energy cutoff as model components. We have included a Gaussian line near the expected K_α emission from iron and absorption edge due to iron. The value of equivalent hydrogen column density N_H was set to have a lower threshold of $0.055 \times 10^{22} \mathrm{cm}^{-2}$ which is the Galactic column density towards this source. The blackbody temperature was kept fixed at $kT = 0.2$ keV, while the center and width of the iron emission line was fixed at 6.4 keV and 0.65 keV respectively with free normalization. The variation in 3–25 keV source flux during the RXTE/PCA observations are shown in the left panel of Fig. 1 whereas the right panel of Fig. 1 shows the energy spectrum for one of the observations at high intensity state. The variation of iron line flux and iron equivalent width with the source flux in 7–25 keV energy range are shown in the left and right panels of Fig. 2 respectively.

The results obtained from this work are summarized as follows.

- The iron emission line flux is found to be directly correlated with the source flux in 7–25 keV energy range.
- The source spectrum is found to be flat with power-law photon index in the range 0.5–0.7 during low intensity state (source flux $\leq 3 \times 10^{-10}$ ergs cm^{-2} s^{-1} at 3–25 keV energy range) whereas during high intensity state, the spectrum is steep with power-law photon index in the range 0.7–0.9.
- Equivalent width of the iron emission line is found to be highly variable in the range 0.25–1.1 keV during low intensity state (source flux $\leq 2 \times 10^{-10}$ ergs cm^{-2} s^{-1} in 7–25 keV energy range), whereas it remains almost constant (0.2–0.35 keV)

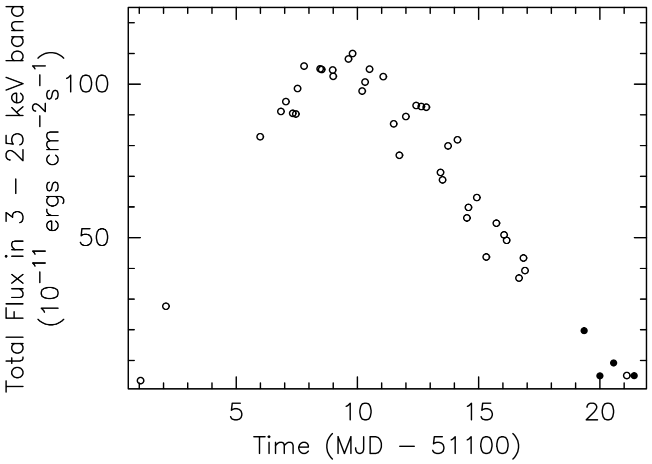

Figure 1(a). Average background-subtracted X-ray flux in 3 - 25 keV energy range obtained from the RXTE/PCA observations of LMC X-4 in 1998. The points marked by "•" are for the observations which were made outside the selected time range and have been included here based on the phase of the super-orbital period. These observations are used to get a better coverage of low intensity state.

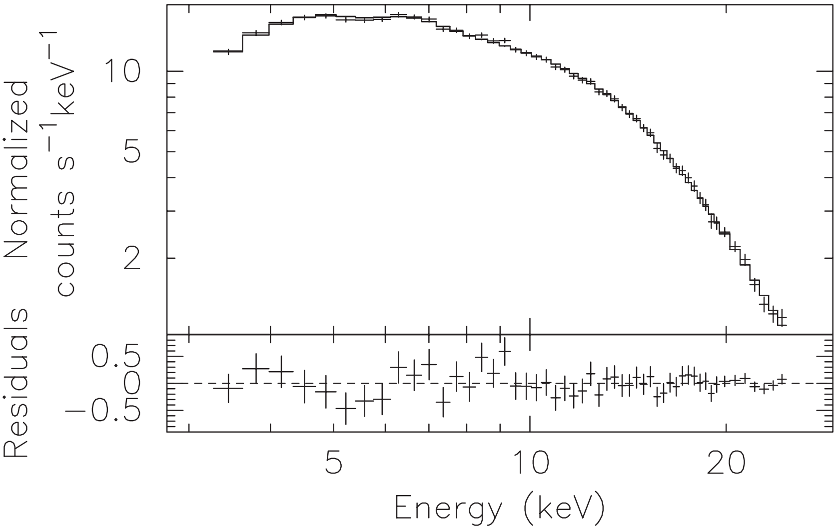

Figure 1(b). The figure shows the observed count rate spectrum of LMC X-4 on 1998 October 22nd. The best fit model consists of a blackbody (kT = 0.2 keV), a power law and a high energy cutoff. The iron emission line was kept fixed at 6.4 keV with width of 0.65 keV.

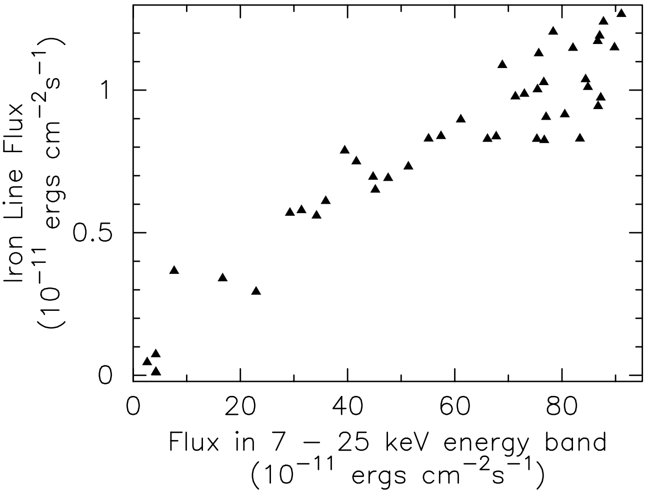

Figure 2(a). The figure shows the variation in iron line flux with the source flux in 7 − 25 keV energy band.

during the high intensity state with source flux $\geq 2 \times 10^{-10}$ ergs cm^{-2} s^{-1} in 7–25 keV energy range.

3. Discussion

According to the results of the present work, it is observed that iron intensity correlates very well with the continuum intensity in 7–25 keV energy range. The equivalent width

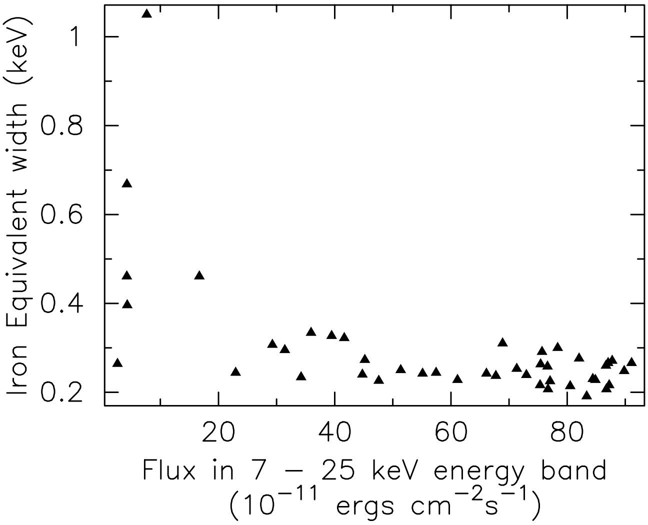

Figure 2(b). The variation in equivalent width of the iron emission line with the source flux in 7–25 keV energy range is shown. It is observed that the iron equivalent width is high when the source flux is low.

of the iron emission line is very high at low luminosity. Similar thing was found in Vela X-1 (Becker *et al.* 1979; White *et al.* 1983). In Vela X-1, it can be due to increase in absorption caused by the stellar wind of the primary.

Nagase *et al.* (1986) studied the change in equivalent widths of iron emission line against the column density of matter in the line of sight for Vela X-1. Similar studies were done for GX 301-2 by Makino *et al.* (1985) and for Her X-1 by Makishima (1986). These results suggest that the column density averaged over the whole direction does not change appreciably, whereas the absorption column density along the line of sight changes drastically with time and orbital phase. Inoue (1985) and Makishima (1986) estimated the equivalent widths of the fluorescence iron line emission from neutral matter in a sphere surrounding the X-ray source using a power law type incident spectrum. They found that, if the matter is located between the X-ray source and the observer, the continuum spectrum is absorbed by the matter resulting in increasing the equivalent width monotonically with the column density as observed in GX 301-2 (Makino *et al.* 1985). However, when the X-ray source is hidden by some thick material, the equivalent width remains almost constant ($\sim$ 1 keV) (as observed from Vela X-1 during the eclipse; Nagase *et al.* 1984). In case of accretion powered X-ray pulsars, if the compact object is hidden from direct view by the accretion disk and only X-rays scattered into the line of sight by an accretion disk corona or wind are visible, the iron equivalent width can be higher. This may explain the higher value of iron equivalent width during the low intensity states of LMC X-4.

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