We report the spectral analysis of the X-ray pulsar LMC X–4 in its high state out of eclipse observed by BeppoSAX. During this observation no coherent pulsations are detected. The primary continuum is well described by a power law with a high energy cutoff \( E_{\text{cutoff}} \sim E_{\text{fold}} \sim 18 \text{ keV} \). The addition of a cyclotron absorption line at \( \sim 100 \text{ keV} \) improves the fit significantly. The inferred magnetic moment is \( 1.1 \times 10^{31} \text{ Gauss cm}^3 \), in agreement with the value estimated assuming that the neutron star is at the spin equilibrium, as it has been proposed for this source. The remaining excess at low energies can be fitted by a Comptonization of soft photons by moderately hot electrons \( (kT \sim 0.9 \text{ keV}) \), with an optical depth \( \tau \sim 16 \). The seed photons for this Comptonization are consistent with black body emission from the accretion disk at the magnetospheric radius. Another possibility is to fit the soft excess with black body and thermal bremsstrahlung. In this case the black body would originate from cold plasma at the magnetosphere while the bremsstrahlung component may be produced by the strong stellar wind from the companion star, ionized by the X-ray emission from the pulsar.

Subject headings: stars: individual: LMC X–4 — stars: magnetic fields — stars: neutron — X-rays: stars

1. Introduction

LMC X–4 is an eclipsing high-mass X-ray binary pulsar in the Large Magellanic Cloud. Its optical counterpart was identified with a 20 \( M_\odot \) O7 III-V star (Sanduleak & Philip 1977). The orbital period of the system is 1.4 days (Li, Rappaport & Epstein 1978; White 1978). The X-ray intensity varies by a factor \( \sim 60 \) between high and low states with a cycle of 30.3 days (Lang et al. 1981). This long-term variation is attributed to a periodic blockage of the direct X-ray beam by a precessing accretion disk, which is tilted with respect to the orbital plane of the binary (Lang et al. 1981; Ilovaisky et al 1984, Priedhorsky & Holt 1987; Woo, Clark & Levine 1995, and references therein). Flaring episodes occur about once per day, lasting from \( \sim 20 \text{ s} \) to 45 minutes, during
which the intensity increases by factors up to $\sim 20$ (Epstein et al. 1977; White 1978; Skinner et al. 1980; Kelley et al. 1983; Pietsch et al 1985; Dennerl 1989; Levine et al. 1991).

Coherent pulsations with a period of 13.5 s were discovered by Kelley et al. (1983) during flares events. Later, the 13.5 s periodic pulsations were also detected in EXOSAT observations during non-flaring out-of-eclipse state (Pietsch et al. 1985). Nevertheless, while the periodic pulsations have been revealed several times during flaring events (Levine et al. 1991, Woo, Clark & Levine 1995, Woo et al. 1996), only once periodic pulsations have been observed during non-flaring state.

The orbital period decreasing rate is $\dot{P}_{\text{orb}}/P_{\text{orb}} = (-5.3 \pm 2.7) \times 10^{-7}$ yr$^{-1}$. This value is smaller than that measured for Cen X–3 and SMC X–1 placing a lower limit on the rate of orbital energy dissipation by tidal forces. This fact, together with the relatively large radius of the companion ($14 \leq R \leq 20 \, R_\odot$), suggests that the companion is expanding rapidly, still burning hydrogen into a shell (Levine et al. 1993). In fact the resulting increase of the moment of inertia could acts to reduce the rotation rate of the companion star producing a relatively large difference between stellar rotation period and orbital period. This enhances the tidal friction effects producing a large orbital decay.

Pulse-phase resolved spectroscopy from Ginga and ROSAT observations in the energy range 0.2–30 keV shows that the phase dependent spectrum can be modeled as the sum of three component (Woo et al. 1996): a high energy component represented by a power law with photon index $\alpha \sim 0.7$ with a high energy cutoff at 16.1 keV and a folding energy of 35.6 keV, a thermal bremsstrahlung component with temperature of 0.35 keV and a pulse-phase independent black body ($kT \sim 0.03$ keV). An iron line is also present at $E \sim 6.6$ keV.

Several observations of the spin period evolution showed both spin up and spin down episodes. This suggests that the pulsar has reached a spin equilibrium state, wherein its spin period approximately equals the Keplerian period at the inner edge of the accretion disk. Because of the high X-ray luminosity of LMC X–4 and the relatively slow spin period, a very strong magnetic dipole has to be present ($\geq 10^{31}$ G cm$^3$) (Woo et al. 1996; Naranan et al. 1985).

Up to date no clear evidence of a cyclotron absorption feature has been reported. This is in line with the fact that the value of the cyclotron line energy deduced from the spin equilibrium ($\sim 100$ keV) is out of the energy range (typically up to 30 keV) of most X-ray satellites which antedate BeppoSAX. In fact the centroid of the line is related to the magnetic moment by the relation $E_{\text{cycl}} = 11.6\mu_{30}/R_6^3(1+z)$ where $\mu_{30}$ is the magnetic dipole moment in units of $10^{30}$ G cm$^3$, $R_6$ is the neutron star radius in units of $10^6$ cm, and $(1+z) = (1 - 2GM_{\text{NS}}/Rc^2)^{-1/2}$ is the gravitational redshift factor. Adopting a standard neutron star mass of 1.4 $M_\odot$ with a standard radius of $10^6$ cm and $\mu \geq 10^{31}$ G cm$^2$, we obtain $E_{\text{cycl}} \geq 90$ keV. The broad spectral band of the BeppoSAX satellite, extending up to 200 keV, gives us the possibility of studying the spectrum up to the energies where the cyclotron absorption feature is expected.

In this paper we report the spectral analysis of LMC X–4 out of eclipse in high state observed by BeppoSAX in the 0.12–100 keV energy range. We confirm the complex multicomponent nature
of the spectrum of LMC X–4. Moreover we find that there are evidences of the presence of a cyclotron line, with the centroid around 100 keV, at a high degree of confidence.

2. Observations and Light Curves

BeppoSAX observed LMC X–4 with its narrow-field instruments (NFI; Boella et al. 1997a) in 1998 from October 20th 22:40 to October 22th 08:05 (UT) corresponding to the phase interval 0.66–0.70 of the 30.3 days cycle, when the source was in its high state. The ephemeris (period: 30.3 ± 0.05 days, epoch: 50087 MJD, corresponding to the beginning of the low-state phase) has been obtained by using the observations of LMC X–4 performed by the ASM on board RXTE.

The BeppoSAX observatory covers more than three decades of energy, from 0.1 to 200 keV. The payload is composed by four coaligned instruments: the Low-Energy Concentrator Spectrometer (LECS, 0.1–10 keV; Parmar et al. 1997), the Medium-Energy Concentrator Spectrometer consisting of two units (MECS, 1–10 keV; Boella et al. 1997b), the High-Pressure Gas Scintillation Proportional Counter (HPGSPC, 4–120 keV; Manzo et al. 1997), and the Phoswich Detection System (PDS, 15–300 keV; Frontera et al. 1997). The fields of view (FOV) of the instruments is approximately 1°. Since LECS and MECS have imaging capabilities, we extracted the data from circular regions in the LECS and MECS FOVs of 8’ and 4’ radius, respectively, centered on the maximum of the point-spread function (PSF). The background subtraction is obtained using blank-sky observations and extracting the background spectra from a circular region corresponding to that one used for the source. The HPGSPC and PDS do not have imaging capabilities. In this case the subtraction of the background is obtained using off-source data collected during the rocking of the collimators. The effective exposure during the observation are so summarized: ∼28 ks for the LECS, ∼66 ks for the MECS, ∼29 ks for the HPGSPC, and ∼39 ks for the PDS.

In Figure 1 (upper panel) we show the light curve of LMC X–4, binned at 300 s, in the energy band 1.5–10.5 keV (MECS data). The light curve shows that the X-ray source is eclipsed for about 20 ks. No important flaring episodes are observed in this light curve. The corresponding hardness ratio, i.e. the ratio of the counts in the 4.5–10.5 keV energy band to the counts in the 1.5–4.5 keV energy band, is also shown in Figure 1 (lower panel). Although the source flux increases by ∼20–30% during the pre-eclipse phase, the hardness ratio appears to be quite constant during our observation. Actually the hardness ratio decreases from ∼2.5 to ∼1 in a short time interval just after the eclipse. In the following analysis we considered only data out of eclipse, i.e. we excluded the time interval from 8.74 s to 1.1 × 105 s, containing both the eclipse and the short interval where the hardness ratio varies significantly.

The average flux out of eclipse in the high state is 9.7×10−10 ergs cm−2 s−1 in the 0.1–100 keV band. Adopting a distance to the source of 50 kpc, the resulting luminosity is ∼3×1038 ergs s−1. In this paper we concentrate our analysis on data out of eclipse.

Because of the better statistics, we used MECS data to investigate for periodicities. We
searched for periodic pulsations in a large interval (12.5-14.5 s) around the value of the spin period reported in the literature, 13.5 s, by using folding techniques. No pulsations have been found. In fact the maximum excess that we have found had $\chi^2 = 93.82$ for 63 degrees of freedom, which is not significant.

3. Spectral Analysis

Spectral analysis was performed on the average photon spectrum of LMC X–4, out of eclipse, in the energy range 0.12–100 keV. The energy ranges used for each NFI are: 0.12–3 keV for LECS, 1.8–10 keV for MECS, 9–30 keV for HPGSPC, and 15–100 keV for PDS. Different normalizing factors for the four instruments were included, fixed to 1 for the MECS and kept free for the other instruments.

The continuum is described by a power law with a high energy cutoff corrected by photo-electric absorption. Indeed, by using the XSPEC models, POWERLAW and HIGHECUT, an evident residual remains at the cutoff energy. Since it just appears at the cutoff energy, where the fitting function shows a cusp, this residual probably is an artifact of the model. To verify this hypothesis we changed the XSPEC HIGHECUT function, whose mathematical form is:

$$H(E) = \begin{cases} 1 & \text{for } E \leq E_{\text{cutoff}} \\ \exp\left(\frac{E_{\text{cutoff}} - E}{E_{\text{folding}}}\right) & \text{for } E > E_{\text{cutoff}} \end{cases}$$

with a function $F(E)$ that avoids the cusp. In fact $F(E)$ has a smoothed region of width $W$, between the low energy range ($E \leq E_{\text{cutoff}} - W/2$) and the high energy range ($E \geq E_{\text{cutoff}} + W/2$) described by a third degree polynomial function, in order to obtain a function that is continuous with its derivatives (see also Burderi et al. 2000); The mathematical form of our function is:

$$F(E) = \begin{cases} 1 & \text{for } E \leq E_{\text{cutoff}} - W/2 \\ AE^3 + BE^2 + CE + D & \text{for } E_{\text{cutoff}} - W/2 < E < E_{\text{cutoff}} + W/2 \\ \exp\left(\frac{E_{\text{cutoff}} - E}{E_{\text{folding}}}\right) & \text{for } E \geq E_{\text{cutoff}} + W/2 \end{cases}$$

where $A$, $B$, $C$, $D$ are constants calculated imposing continuity conditions for the function $F(E)$ and its derivatives while $W$ is left as a free parameter of the fit. Using this model, the residuals at the cutoff energy disappear, and the fit improves significantly.

An evident soft excess remains at low energies below $\sim 2$ keV. A simple black body model is not a good description of the soft excess, giving $\chi^2/d.o.f. \sim 727/537$. Following the literature (Woo et al. 1996) we fit this feature with a thermal bremsstrahlung emission plus a black body. The resulting parameters describing the model are reported in Table 1 (model 3 and 4) and can be so summarized. The photon index of the power law is $\sim 0.6$, the cutoff energy is $\sim 18$ keV and the folding energy is $\sim 17.5$ keV. The photo-electric absorption corresponds to an hydrogen column of $\sim 5 \times 10^{20}$ cm$^{-2}$. The temperature associated to the bremsstrahlung is 0.85 keV while that of the black body is $\sim 6 \times 10^{-2}$ keV.
An alternative way of fitting the soft excess is to model it with a Comptonization model (see Table 1, model 1 and 2). We used the COMPST model of XSPEC (v.10). We preferred COMPST to COMPTT because COMPST needs less free parameters. In addition, using COMPTT, the temperature of the seed photons obtained by the fit is less than 0.1 keV, i.e. it is out of the spectral range, making this estimate unreliable. The temperature associated with the hot electrons is $\sim 1$ keV and the relative optical depth is $\sim 16$. The parameters of the other model components remain substantially unchanged.

The presence of a gaussian emission line at $\sim 6.5$ keV is evident. Indeed the $\chi^2$ reduces significantly if we model it with two gaussians centered at the energies 6.1 and 6.6 keV (equivalent width $\sim 200$ and 65 eV, respectively). Comparing the model with one gaussian and that with two gaussians, the F-test gives a probability greater than 0.997 that the improvement is not casual. The simultaneous presence of a narrow line at 6.6 keV and a broader one at 6.1 keV implies two different iron ionization stages. In addition an absorption edge is observed at about 1.25 keV with a very large statistical evidence (the F-test probability of chance improvement is less than $1 \times 10^{-6}$). This feature could be attributed to the absorption edge of Fe XVII (1266 eV).

Large residuals also appear in the hard part of the LMC X–4 spectrum starting from 40 keV and extending up to 100 keV (see figure 2, upper panel). We interpreted this feature as a cyclotron absorption line and modeled it with a gaussian profile, i.e. we used a multiplicative function given by: $f(E) = 1 - A_{cycl} \exp[-(E - E_{cycl})^2/(2\sigma^2)]$, with the condition that $f(E) = 0$ when it assumes negative values. Since the width of cyclotron lines is most probably of thermal origin (see e.g. Mihara 1995; Dal Fiume et al. 1999; Burderi et al. 2000), we preferred to use a gaussian profile, instead of a lorentzian profile, to fit this feature. Using this model the residuals disappear (see Figure 2, lower panel). The centroid energy of the line is $\sim 100$ keV and the sigma is $\sim 50$ keV. The addition of this component reduces the $\chi^2$ significantly, as it is evident comparing models 1 and 3 with respect to models 2 and 4 in Table 1. The F-test gives a probability of $4 \times 10^{-4}$ for a chance improvement of the fit.

Summarizing the whole 0.1–100 keV spectrum of LMC X–4 can be described as follows:

$$S(E) = WABS \times EDGE \times CYCL \times (SOFT + 2 \text{ GAUSS} + F(E) \times POW)$$  \hspace{1cm} (3)$$

where WABS is the photo-electric absorption, EDGE is the absorption edge, CYCL is the cyclotron absorption feature modeled as a gaussian, SOFT is the component that can be modeled as a bremsstrahlung plus a black body or as a Comptonization, 2 GAUSS represents the two iron emission features at about 6.5 keV, F(E) is the cutoff function above described and finally POW is the power law component. The fit corresponding to the model with bremsstrahlung and relative residuals are plotted in Figure 3, while the fit corresponding to the model with Comptonization and relative residuals are plotted in Figure 5. In both cases the cyclotron absorption line is present. The unfolded spectra corresponding to the two scenarios are drawn in Figure 4 and 6, respectively.
4. Discussion

We have found evidence, with a high degree of confidence, of a high energy cyclotron absorption feature in the broad band (0.1-100 keV) spectrum of LMC X–4. Modeling this feature as a gaussian in absorption, we have found the centroid energy at \( \sim 100 \) keV with sigma \( \sim 50 \) keV, corresponding to a magnetic moment of \( 1.1 \times 10^{31} \) Gauss cm\(^3\). The addition of this new component to our model significantly reduced the \( \chi^2 \), with a probability of chance improvement of \( 4 \times 10^{-4} \). This is in line with the expectation that LMC X–4 should have a very strong magnetic field.

There are some evidences that LMC X–4 have reached its spin equilibrium wherein its spin period is close to the Keplerian period at the inner edge of the accretion disk, which is probably the magnetospheric radius of the system. In fact several observations show both spin-up and spin-down regimes (see e.g. Woo et al. 1996). The average values of \( \dot{P}_{\text{pulse}} \) range from \( -4.0 \times 10^{-3} \) s/yr between the HEAO 2 and the first of the EXOSAT observations to \( +1.9 \times 10^{-3} \) s/yr between EXOSAT and the most recent Ginga and Rosat observations. The radius \( R_{\text{eq}} \) at which the Keplerian period of the orbiting matter in the disk equals the pulsation period \( P_{\text{pulse}} \) is simply

\[
R_{\text{eq}} \sim 1.5 \times 10^8 m^{1/3} P_{\text{pulse}}^{2/3} \text{ cm,}
\]

where \( m \) is the neutron star mass in units of solar masses and \( P_{\text{pulse}} \) is the spin period in seconds. For \( P_{\text{pulse}} = 13.5 \) s, \( R_{\text{eq}} \) results \( \sim 9 \times 10^8 \) cm. In addition we know that, for an accreting magnetized neutron star, the magnetosphere radius, \( R_m \), is (see, e.g., Burderi et al. 1998):

\[
R_m \sim 4.3 \times 10^8 \phi \mu_{30}^{4/7} L_{37}^{-2/7} m^{1/7} R_6^{-2/7} \text{ cm}
\]

where \( \mu_{30} \) is the magnetic moment in units of \( 10^{30} \) Gauss cm\(^3\), \( L_{37} \) is the intrinsic luminosity in units of \( 10^{37} \) erg/s, \( R_6 \) is the neutron star radius in units of \( 10^6 \) cm, and finally \( \phi \) (\( \leq 1 \)) is the correction to the Alfvén radius for the presence of the accretion disk. Equaling \( R_{\text{eq}} \) and \( R_m \) it is possible to estimate the strength of the magnetic moment. Taking into account the intrinsic high luminosity of LMC X–4 (\( \sim 3 \times 10^{38} \) ergs/s in the 0.1-100 keV band), we derive a high magnetic dipole moment, of the order of \( 2 \times 10^{31} \) Gauss cm\(^3\). If this is correct, any cyclotron spectral feature in this source has to be expected at energies around 150 keV. Indeed we find evidences of an absorption feature in the hardest part of spectrum of LMC X–4 centered at 100 keV which is consistent with the expected value.

The width (gaussian \( \sigma \)) of the cyclotron line that we found is \( \sim 57 \) keV. If the broadening is caused by thermal Doppler effects, the relationship among the folding energy of the exponential cutoff, \( E_{\text{fold}} \), that is a measure of the temperature close to the neutron star, the centroid energy of the cyclotron line, \( E_{\text{cycl}} \), and its width, \( \sigma \), is: \( \sigma \approx E_{\text{cycl}} (E_{\text{fold}}/m_e c^2)^{1/2} \). Adopting this relationship the expected width of the line would be \( \sim 26 \) keV that is almost half the measured broadening of the line. However, note that the width of the cyclotron line might be not well constrained since the centroid energy of the line is at the end of the energy range of PDS, and therefore only the left wing of the line is visible.

The whole 0.12-100 keV spectrum of LMC X–4 is complex. The primary continuum is well fitted by a power law with a high energy cutoff, smoothed at the cutoff energy. This component
could be produced by Comptonization of the radiation coming from the hot spots on the neutron
star by the plasma in the accretion column, very close to the neutron star surface. Anyway, at
low energies, an evident soft excess remains. We fitted this excess with two different models: 1)
bremsstrahlung emission with the addition of a black body, 2) Comptonization.

In the first scenario, the black body component is probably emitted by the accretion disk,
whereas the bremsstrahlung component comes from an optically thin plasma surrounding the sys-
tem. In fact, considering that the luminosity and the temperature of the black body component,
obtained by the fit, are $1.3 \times 10^{37}$ ergs s$^{-1}$ and $6.3 \times 10^{-2}$ keV, respectively, the typical radius
associated with emitting region of the black body component is $\sim 2.5 \times 10^8$ cm. This value is in
agreement with that found for the magnetospheric radius under the spin equilibrium hypothesis.
With regard to the bremsstrahlung component, the calculated luminosity is $2.2 \times 10^{37}$ ergs s$^{-1}$.
This give us the possibility to estimate the radius of the bremsstrahlung emitting region. The
luminosity of the bremsstrahlung component, $L_{\text{brems}}$, can be expressed as:
\begin{equation}
L_{\text{brems}} \sim 5.8 \times 10^{-24} T^{1/2} N_e^2 V \text{ erg/s} \tag{5}
\end{equation}
where $T$ is the electron temperature in keV, $N_e$ is the electron density and $V$ is the volume of
the emission region in cm$^3$. Considering the relationship between the optical depth $\tau$ and $N_e$:
$\tau \sim \sigma_T N_e R$, where $\sigma_T$ is the Thomson cross section and $R$ is the radius of the emission region, and
supposing a spherical geometry, we obtain:
\begin{equation}
L_{\text{brems}} \sim 5.5 \times 10^{25} T^{1/2} R \tau^{-2} \text{ erg/s} \tag{6}
\end{equation}
Adopting the electron temperature of 0.86 keV obtained by the fit, the radius of the emission region
is $\sim 4.9 \times 10^{11} / \tau^2$ cm. For an optical depth associated to the bremsstrahlung not greater than 1,
the resulting radius of the emitting region is larger than the radius of the Roche lobe containing the
neutron star. Therefore, in this scenario the black body component could be emitted by optically
thick plasma at the magnetosphere, and the bremsstrahlung component could be produced by
plasma of the stellar wind from the companion star, ionized by the X-ray emission from the pulsar.

It is also possible to model the soft excess with a Comptonization model. The corresponding
luminosity of this component is $5 \times 10^{37}$ ergs/s. Knowing the temperature of the seed photons
and that of the hot electrons, the luminosity of the emitting region and its optical depth, it would
be possible to infer the characteristic radius of the seed photons emitting region, where the seed
photons originate. The COMPST model does not give the possibility to obtain the temperature
of the seed photons from the fit, therefore we derived this temperature assuming that it is the
temperature at the inner radius of the accretion disk (assuming the standard model of Shakura
& Sunyaev 1973), under the hypothesis that the disk is truncated at the magnetospheric radius.
Using the value of the magnetic field corresponding to the cyclotron line, we obtain a temperature
of the seed photons of $1.8 \times 10^{-2}$ keV. From this we obtain that the radius of the region emitting
the seed photons is $36 \times 10^8$ cm. This value is in agreement within a factor 5 with that obtained
from equation 4 where we have adopted $\mu_{30} = 11$, as deduced by the fit of the cyclotron feature.
However, note this model might be inadequate to describe the whole emission mechanism, since at this cold temperatures and large optical depths, free-free absorption, that is not included in the COMPST model, could give a not negligible contribution.

An iron emission line is detected at about 6.5 keV. We find that it can be fitted by two gaussians at energies 6.1 and 6.6 keV, respectively. The gaussian at lower energy has a large sigma ($\sim 0.95$ keV), whereas the gaussian at higher energies is much narrower. We note that the width of the broad line component cannot be explained by the Doppler effect induced by the fast rotation at the magnetospheric radius. In fact considering a magnetic moment of $1.1 \times 10^{31}$ Gauss cm$^3$ (as estimated by the cyclotron line energy) we obtain $\Delta \nu \sim 0.1$ keV at 6.4 keV, that is much smaller than the measured width. Complex iron line features are not unusual in high mass X-ray binaries (see e.g. Audley et al. 1996, Ebisawa et al. 1996). The energy values that we obtained are consistent with the iron features expected at 6.4 and at 6.7 keV, within the associated errors. The usual interpretation is that the line at 6.7 keV is produced by highly ionized iron and probably is emitted in a hot corona, while the line at 6.4 keV corresponds to neutral iron and might come from the radiation reflected by the accretion disk. In this case we would expect the 6.7 keV line to be broad because of the Compton smearing in the hot corona, and the 6.4 keV line to be narrow given that the disk is truncated at a large radius by the presence of the magnetosphere. We observe that our data of LMC X–4 indicate an opposite behaviour, with a broad 6.4 keV line and a narrow 6.7 keV line. Probably this feature can be explained by line blending, for the presence of several iron line components with energies between 6.4 and 7 keV, or by the presence of a line with a narrow core but broad wings. Certainly other high resolution observations in the iron line region are needed to address this question.

All the models reported above need an absorption edge at about 1.25 keV. The nature of this feature is highly uncertain. The energy of the edge is close enough to the K-edge of high ionized Ne or neutral Mg, or to an L-edge of moderately ionized Fe. If we attribute this feature to FeXVII (edge at 1.266 keV), the optical depth corresponding to this feature is:

$$\tau = \sigma \int N \, dx = 1 - \frac{\phi_{\text{with-edge}}}{\phi_{\text{no-edge}}} \sim 0.1$$

where $\phi_{\text{with-edge}}$ and $\phi_{\text{no-edge}}$ are the flux with and without the absorption edge, respectively, calculated in the 1.25-3.0 keV range. Assuming that the cross section of this process is comparable with that of the ejection of electrons from the K-shell ($\sigma \sim 1.7 \times 10^{-16}$ cm$^2$) the corresponding iron column is $\sim 0.6 \times 10^{15}$ cm$^{-2}$. This value could be compared with that deduced from the hydrogen column obtained by the fit of the photoelectric absorption. In that case the hydrogen column is $\sim 5 \times 10^{20}$ cm$^{-2}$ so the deduced iron column (assuming solar abundances) could be of the order of $5 \times 10^{15}$ cm$^{-2}$. The good agreement between the two values indicates that the edge at 1.252 keV could be a real feature produced by the iron around the neutron star. Other authors have also reported similar features. Parmar et al. (2000) have found an absorption edge in the spectrum of the low mass X-ray binary X 1822–371 at about 1.33 keV and optical depth 0.26. Moreover Iaria et al. (2000) have observed the edge in the spectrum of the source 4U 1254–69 at 1.26 keV and
optical depth 0.15.

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REFERENCES


Table 1: Fit of LMC X–4 spectrum during the high state in the energy band 0.12-100 keV. Uncertainties are at 90% confidence level for a single parameter. $\tau_{\text{edge}}$ is the absorption depth of the edge at the threshold. $kT_{\text{BB}}$ is the temperature of the black body. The normalization of the black body, $N_{\text{BB}}$, is in units of $L_{36}/D^2_{50}$ where $L_{36}$ is the luminosity of the source in units of $10^{36}$ ergs/s and $D_{50}$ is the distance of the source in units of 50 kpc. $kT_{\text{Brems}}$ is the temperature of the plasma emitting for bremsstrahlung. The normalization of the bremsstrahlung, $N_{\text{Brems}}$, is in units of $(1.27 \times 10^{-59}/(4\pi D^2_{50})) \int N_e N_I dV$, where $N_e$ and $N_I$ are the electron and ion densities ($\text{cm}^{-3}$), respectively. $kT_{\text{comp}}$ is the temperature of the hot electrons Comptonizing cool photons. The COMPST normalization is in XSPEC (v.10) units. The power law normalization is in units of photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$ at 1 keV. The (emission lines) gaussian normalization is in units photons cm$^{-2}$ s$^{-1}$.

<table>
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<tr>
<th>Parameters</th>
<th>model 1</th>
<th>model 2</th>
<th>model 3</th>
<th>model 4</th>
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<td>$N_H (\times 10^{20} \text{ cm}^{-2})$</td>
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<td>$0.47^{+0.05}_{-0.1}$</td>
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<td>–</td>
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<td>$0.8 \pm 0.2$</td>
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<td>$(4 \pm 1) \times 10^{-2}$</td>
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<td>–</td>
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<tr>
<td>$\tau_{\text{comp}}$</td>
<td>$16 \pm 5$</td>
<td>$5^{+6}_{-2}$</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$N_{\text{comp}}$</td>
<td>$2.1^{+0.3}_{-0.2} \times 10^{-2}$</td>
<td>$1.7 \pm 0.2$</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Photon Index</td>
<td>$0.5^{+0.1}_{-0.2}$</td>
<td>$0.5 \pm 0.1$</td>
<td>$0.6 \pm 0.1$</td>
<td>$0.64^{+0.03}_{-0.04}$</td>
</tr>
<tr>
<td>$N_{\text{power law}}$</td>
<td>$(1.1 \pm 0.2) \times 10^{-2}$</td>
<td>$7^{+2}_{-1} \times 10^{-3}$</td>
<td>$1.0^{+0.2}_{-0.1} \times 10^{-2}$</td>
<td>$9.9^{+0.5}_{-0.8} \times 10^{-3}$</td>
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<tr>
<td>Smooth Width (keV)</td>
<td>$9 \pm 4$</td>
<td>$17 \pm 3$</td>
<td>$9 \pm 4$</td>
<td>$15 \pm 3$</td>
</tr>
<tr>
<td>$E_{\text{cut}}$ (keV)</td>
<td>$18 \pm 1$</td>
<td>$18 \pm 1$</td>
<td>$18 \pm 1$</td>
<td>$18.7 \pm 0.5$</td>
</tr>
<tr>
<td>$E_{\text{fold}}$ (keV)</td>
<td>$18 \pm 3$</td>
<td>$12.2 \pm 0.4$</td>
<td>$17^{+3}_{-4}$</td>
<td>$12.7 \pm 0.3$</td>
</tr>
<tr>
<td>$E_{\text{Fe}}$ (keV) 1st gaussian</td>
<td>$6.1 \pm 0.3$</td>
<td>$6.1^{+0.1}_{-0.3}$</td>
<td>$6.2^{+0.2}_{-0.8}$</td>
<td>$6.2^{+0.2}_{-0.7}$</td>
</tr>
<tr>
<td>$\sigma_{\text{Fe}}$ (keV)</td>
<td>$0.9^{+0.4}_{-0.2}$</td>
<td>$1.1^{+0.5}_{-0.2}$</td>
<td>$0.8 \pm 0.4$</td>
<td>$0.9^{+0.3}_{-0.5}$</td>
</tr>
<tr>
<td>$I_{\text{Fe}}$ (ph cm$^{-2}$ s$^{-1}$)</td>
<td>$9^{+150}_{-4} \times 10^{-4}$</td>
<td>$8^{+5}_{-3} \times 10^{-4}$</td>
<td>$6^{+10}_{-4} \times 10^{-4}$</td>
<td>$6^{+3}_{-4} \times 10^{-4}$</td>
</tr>
<tr>
<td>EW_{\text{Fe}} (eV)</td>
<td>169</td>
<td>183</td>
<td>215</td>
<td>267</td>
</tr>
<tr>
<td>$E_{\text{Fe}}$ (keV) 2nd gaussian</td>
<td>$6.6 \pm 0.1$</td>
<td>$6.6 \pm 0.1$</td>
<td>$6.6 \pm 0.1$</td>
<td>$6.6 \pm 0.1$</td>
</tr>
<tr>
<td>$\sigma_{\text{Fe}}$ (keV)</td>
<td>$(0.1 \pm 0.2) \times 10^{-2}$</td>
<td>$(0.1 \pm 0.1) \times 10^{-2}$</td>
<td>$7^{+30}_{-7} \times 10^{-2}$</td>
<td>$7^{+25}_{-7} \times 10^{-2}$</td>
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<tr>
<td>$I_{\text{Fe}}$ (ph cm$^{-2}$ s$^{-1}$)</td>
<td>$3^{+5}_{-1} \times 10^{-4}$</td>
<td>$(2 \pm 1) \times 10^{-4}$</td>
<td>$2^{+4}_{-0.4} \times 10^{-4}$</td>
<td>$2^{+1}_{-1} \times 10^{-4}$</td>
</tr>
<tr>
<td>EW_{\text{Fe}} (eV)</td>
<td>64</td>
<td>64</td>
<td>67</td>
<td>69</td>
</tr>
<tr>
<td>$E_{\text{cycl}}$ (keV)</td>
<td>$100^{+100}_{-20}$</td>
<td>–</td>
<td>$100^{+80}_{-15}$</td>
<td>–</td>
</tr>
<tr>
<td>$\sigma_{\text{cycl}}$ (keV)</td>
<td>$60^{+100}_{-20}$</td>
<td>–</td>
<td>$45^{+140}_{-20}$</td>
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<tr>
<td>$A_{\text{cycl}}$</td>
<td>$1.0^{+0.4}_{-0.2}$</td>
<td>–</td>
<td>$1.0^{+0.4}_{-0.3}$</td>
<td>–</td>
</tr>
<tr>
<td>$\chi^2/$d.o.f.</td>
<td>614/536</td>
<td>636/539</td>
<td>614/535</td>
<td>638/538</td>
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</tbody>
</table>
FIGURE CAPTIONS

**Figure 1:** Upper panel: LMC X–4 light curve in the energy band 1.5-10.5 keV band (MECS data). The bin time is 300 s. Lower panel: Corresponding hardness ratio [4.5–10.5 keV]/[1.5–4.5 keV].

**Figure 2:** Upper Panel: Residuals in unit of $\sigma$ with respect to model 2 of Table 1 (without the cyclotron absorption line correction). Lower Panel: Residuals in unit of $\sigma$ with respect to model 1 of Table 1. In this case the cyclotron absorption line correction is taken into account. Different symbols have been used to distinguish between HPGSPC data (filled triangles) and PDS data (open triangles).

**Figure 3:** Pulse-averaged count spectrum (0.12-100 keV) of LMC X–4 and residuals in units of $\sigma$ corresponding to model 3 of Table 1. In this case the soft part of the spectrum is fitted with bremsstrahlung plus black body. The cyclotron absorption line is also included.

**Figure 4:** Unfolded energy spectrum and best fit model corresponding to model 3 of Table 1. The solid line with the data on top is the total spectrum, the dashed lines are the blackbody (left) and the bremsstrahlung component (right) respectively, the dot-dot-dot-dashed line is the power-law component, the dot-dashed line is the gaussian at 6.1 keV, and the dotted line is the gaussian at 6.6 keV.

**Figure 5:** Pulse-averaged count spectrum (0.12-100 keV) of LMC X–4 and residuals in units of $\sigma$ corresponding to model 1 of Table 1. In this case the soft part of the spectrum is fitted with a Comptonization. The cyclotron absorption line is included.

**Figure 6:** Unfolded energy spectrum and best fit model corresponding to model 1 of Table 1. The solid line with the data on top is the total spectrum, the dashed line is the comptonized emission component, the dot-dot-dot-dashed line is the power-law component, the dot-dashed line is the gaussian at 6.1 keV, and the dotted line is the gaussian at 6.6 keV.