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Spectral Analysis of LMC-X2 with XMM/Newton

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Abstract We present the results of the analisys of an archival observation of LMC X–2 performed with XMM/Newton. The spectra of this source has never been analyzed with a high precision instrument before. The spectrum of the source can be fitted with a blackbody with a temperature 1.5 keV plus a disk blackbody at 0.8 keV. We argue that the emission of this source can be straightforwardly interpreted as a sum of the emission from a boundary layer between the NS and the disc and a blackbody component coming from the disc itself. The detection of the O VIII emission line (and the lack of detection of lines in the iron region) can be due to the fact that the source lies in the Large Magellanic Cloud.

1 INTRODUCTION

LMC X–2 has been the first extragalactic source to be classified as a Z-source. Z sources are a peculiar class of Low Mass X-ray Binaries (LMXBs), with luminosities close to the Eddington luminosity, $L_{\rm edd}$, and with some peculiar correlated X-ray spectral and timing properties, namely the pattern traced out by individual sources in the X-ray color-color diagram (CD, Hasinger & van der Klis 1989). The seven known (Galactic) Z sources usually describe a complete Z-track in the CD on timescales of a few days.

An extensive study of the correlated spectral and timing variability of LMC X–2, using data taken with the PCA on board RXTE, has allowed to observe the complete Z-track in the CD which is completed in about 1 day (Smale, Homan & Kuulkers 2003). Analyzing the same data, it was also found evidence of an orbital period of ~ 8.3 hours. Smale et al. (2003) went on to classify LMC X–2 as a "Sco-like" Z-source by looking at the shape of the Z-pattern described in the CD. LMC X–2 has a very high luminosity ($\sim 0.5 - 2L_{\rm edd}$; Markert & Clark 1975; Johnston, Bradt & Doxsey 1979; Long, Helfand & Grabelsky 1981; Bonnet-Bidaud et al. 1989; Smale & Kuulkers 2000), which makes it the brightest LMXB known together with Sco X–1. Other similarities with Sco X–1 include the nature of the optical counterpart, that is a faint, $M_V \sim 18.8$, blue star (similar to the optical counterpart of Sco X–1), and the correlation between the optical and the X-ray lightcurve during flares (McGowan et al. 2003). In some ways, we can consider LMC X–2 an extragalactic twin to Sco X–1.

Oddly enough, there has been no recent spectral study of this source in recent times: the latest spectral study has been carried out by Smale & Kuulkers (2000) that studied RXTE/PCA data of the source and found that the data can be well described by a cutoff power-law (e.g. a completely Comptonized component) with a cutoff temperature of 2.8 keV, or by a blackbody plus bremsstrahlung model with $kT_{\rm bb} \sim 1.5$ keV, $kT_{\rm brems} \sim 4.5$ keV. This result agrees with the spectral analysis carried out by Schulz (1999) using ROSAT data in the 0.1–2.4 keV band, where the data could be fitted using a blackbody with a temperature $kT = 1.5$ keV plus a thermal bresstrahlung model with a temperature of $kT = 5$ keV. Also, a gaussian emission line at 0.9 keV was evident in the spectrum. As the authors point out, however, this model is not physically realistic given the enormous emitting volumes required for the bremsstrahlung emission.

These low-resolution spectra differ noticeably from the X-ray spectra of other Z-sources, which are usually described in terms of a two-component model. The spectral models of Z-sources usually follow one

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of two main paradigmas: the Eastern model (Mitsuda et al. 1989), in which the spectrum of the source is interpreted as a sum of an emission coming directly from the compact object (Comptonized or not) plus a blackbody emission from the disc, and the Western model (White et al. 1986), where the emission is due to a hot blackbody coming from the central source, plus a Comptonized component that is due to the emission from an accretion disc corona surrounding the disc (no direct thermal emission from the disc is seen as photons emitted there are reprocessed and Comptonized in the corona). Moreover, all galactic Z-sources, with the exception of GX 5-1 (Asai et al. 1994), show broad features in the range 6.4 – 6.7 keV, which are identified as the Kα radiative transitions of iron at different ionization states. Sometimes an iron absorption edge at energies ~ 8 keV has been detected (see e.g. Di Salvo et al. 2001).

In this paper we report on the analysis of an archival XMM/Newton observation of LMC X–2, which gives us the opportunity to perform the first high resolution spectral study available to date on this source.

2 OBSERVATION AND DATA ANALYSIS

XMM has observed LMC X-2 between 2003-04-21, 20.21:03 and 2003-04-22, 03:03:58. The source was observed in High event rate mode with both the Reflection Grating Spectrometers (RGS1 and 2) for a common exposure time of ~ 19.5 ks. The EPIC-PN camera observed the source in Small Window mode with Medium filter, for a total exposure of 11.2 ks. Of the two MOS, only MOS2 data in Fast Uncompressed mode are available, for a mere 457 s of exposure.

The average count rates are 3.7, 4.6 and 120 cts s^{-1} for RGS1, RGS2 and Epic-PN, respectively. This means that, given the use of the small window mode, any pileup issue is avoided for this source.

We decided to extract a single spectrum from the whole dataset. In the PN, we selected photons coming from a circular region of $20''$ centered on the brightest pixel (the source coordinates), and for the background we selected photons from a region of the same shape and area in a blank sky region near the source. For RGS 1 and 2 the spectra were extracted using the standard pipeline, indicating the newly discovered refined position. All spectra were rebinned in order to have at least 25 counts per channel, so that we are allowed to use the χ^2 statistics.

We decided to use RGS data in the standard energy range $0.35 - 2.0$ keV, and PN data in the $0.6 - 10$ keV energy range. We fitted these spectra to a two-component model constituted by a blackbody plus a bremsstrahlung component. Both components were modified by photo-electric absorption from neutral matter. The model gave a fit that, although statistically acceptable ($\chi^2/\mathrm{d.o.f.} = 5916/5529$), is not satisfactory if one looks at its residuals: they show that there is a strong mismatch between the two RGSs and the EPIC PN below 1.3 keV. This is probably due to calibration issues of the PN for bright sources (see e.g. Boirin & Parmar 2003). We therefore decided to use PN data limiting ourselves to the $1.3 - 10.0$ keV range.

Using this reduced spectral range for the PN, we found a blackbody temperature of 1.4 keV and a bressstrahlung temperature of 7.7 keV. The resulting blackbody radius is 11 km, while the radius of the bremsstrahlung emitting region is $\sim 10^8$ km. This model gives a satisfactory fit to the data, it is not physically reasonable: the emission region for the bremsstrahlung component is presumably orders of magnitude larger than the whole system.

Data can be fitted by a conventional “Eastern model”. In particular, we fitted the data with a two-component model constituted by a blackbody and a disk blackbody, modified by photo-electric absorption from neutral matter and the O VIII Ly-α emission line. This model is statistically indistinguishable from the former. In this case, we find a blackbody temperature of 1.54 keV, a radius of 14.9 km and a luminosity of $1.6 \times 10^{38}\,\mathrm{erg\,s^{-1}}$, while the disk emission accounts for the remaining 33% ($8 \times 10^{37}\,\mathrm{erg\,s^{-1}}$) of the emission with an inner disk temperature of 0.815 keV and a lower limit on the inner radius of 27.5 km.

Recently, Church et al. (2006) applied the “Birmingham model” , where the emission of the central source is described by a blackbody and the rest of the emission comes from an accretion disc corona, to Z-sources. We tried to fit the data to a two-component model constituted by a blackbody and a cutoff powerlaw, to test if the Birmingham model was also acceptable. Although this model fits well the data, the cutoff powerlaw index is below 1, so that this powerlaw does not describe a Comptonized component: $\Gamma < 1$ implies $y = 4kT/m_e c^2 < 0$ which is impossible. If we try to fix the power-law index to values common in fits of spectra of other Z-sources, like 1.9 (Sco X–1, Barnard et al. 2003) or 1.7 (GX 340+0,

Table 1 Results of the fits to LMC X–2 data with the four spectral Models. Uncertainties are at 90% confidence level for a single parameter ($kT_{\rm bb}, R_{\rm bb}$ and $L_{\rm bb}$ are the blackbody temperature, radius of the emitting region and Luminosity. kT_2 is the temperature of the second thermal component, that is the bremsstrahlung temperature the disk blackbody inner temperature, and the cutoff temperature, respectively. $R_{\rm br}$ is the radius of the bremsstrahlung emitting region, $R_{\rm diskbb}$ is the radius of the disk blackbody, γ is the powerlaw photon index and the normalization of the powerlaw is in units of photons keV^{-1} cm^{-2} s^{-1} at 1 keV).

Model	blackbody + bremsstrahlung	blackbody + disk blackbody	Birmingham Model
$N_{\rm H}$ (10^{20} cm^{-2})	8.35 ± 0.12	$4.04^{+0.11}_{-0.12}$	$6.67 \pm +0.12$
$kT_{\rm bb}$ (keV)	1.411 ± 0.016	1.543 ± 0.009	1.66 ± 0.02
$R_{\rm bb}$ (km)	11.6 ± 0.3	14.9 ± 0.02	$10.1^{+1.2}_{-0.2}$
$L_{\rm bb}$ (erg s^{-1})	0.67×10^{38}	1.6×10^{38}	0.96×10^{38}
kT_2 (keV)	7.72±0.012	0.815 ± 0.002	3.18 ± 0.04
$R_{\rm br}$ (km)	3.7e+8	–	–
$R_{\rm diskbb}$ (km)	–	27.52 ± 0.05	–
γ	–	–	0.963 ± 0.007
PL norm	–	–	0.1047 ± 0.0004
$L_{\rm tot}$ (erg s^{-1})	2.3×10^{38}	2.24×10^{38}	2.26×10^{38}
$E_{\rm line}$ (eV)	653 ± 2	653 ± 2	653 ± 2
σ(eV)	5(fixed)	5(fixed)	5(fixed)
Eqw (eV)	2.53	2.9	2.86
$\chi^2_{\rm red}$ (d.o.f.)	5534 (5404)	5555 (5404)	5485 (5403)

Church et al. 2006), the fit we obtain to the data is unstable, as the high energy cutoff becomes larger than 15 keV and is unconstrainable.

The total luminosity ($0.3 - 10.0$ keV) of the source is, for all the models, $\sim 2.3 \times 10^{38}$ erg s^{-1}, that is about 1.3 times the Eddington luminosity for a $1.35\, M_\odot$ NS. In all our calculations we assumed a distance of 50 kpc (Feast 1999). Results of the fits to the data of the four models described above are reported in Table 1.

As can be seen from Figure 1, using the "eastern-like" model the fitting is good enough and no other significant local feature is present in the spectra.

3 DISCUSSION AND CONCLUSIONS

We have fitted the spectrum of LMC X–2 taken with the EPIC-PN and RGS instruments on board XMM/Newton with three different two-component models which describe completely different physical processes. Since they are all statistically acceptable, in order to choose a best-fit model we should inspect which one looks as the most physically reasonable.

The first model is constituted by blackbody plus a bremsstrahlung component. This model is clearly unphysical as the bremsstrahlung emission region is 3.6×10^8 km, which is more than one order of magnitude larger than the orbital separation for a system with an orbital period of 30 ks. We can therefore safely discard this model without any further discussion.

The Birmingham model, is not able to fit the data satisfactorily, since the component described by a cutoff power-law is incompatible with a Comptonized spectrum (the power-law index is below 1), and if we fix the value of the power-law index we cannot constrain the cutoff energy due to the narrow band of XMM/Newton.

Since the other models are physically unreasonable for one reason or another, the only model that fits satisfactorily the data consists of a blackbody at 1.5 keV and a cooler disk blackbody at 0.8 keV, and the emission is dominated by the radiation coming from the central source, plus a blackbody component due to the thermal emission of the disk. The hot component coming from the compact object is well described in this case by a blackbody emission. This blackbody is relatively hot, has a radius that approaches the neutron star radius and is the origin of the most part of the emission from the source ($\sim 70\%$ of the unabsorbed luminosity, see Table 1). The cooler disk blackbody that describes the emission from the accretion disc has

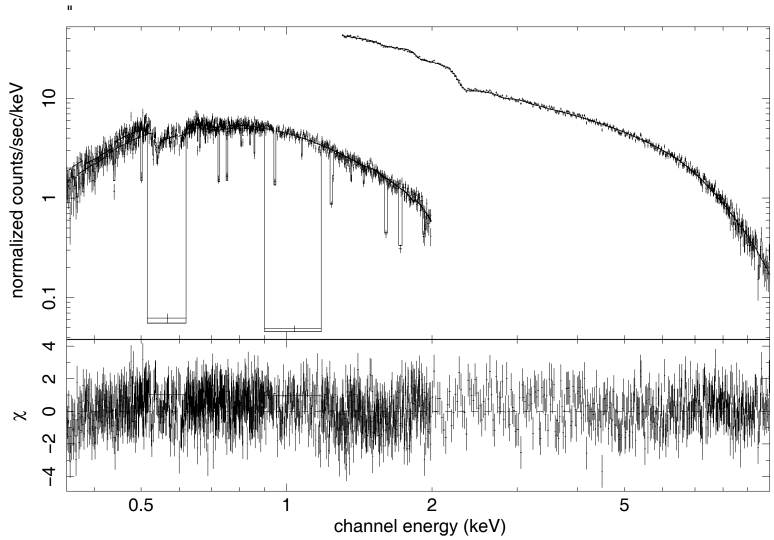

Fig. 1 Data with best fit model, consisting of a blackbody and a disk blackbody and relative residuals in units of σ for RGS1, RGS2 and PN, respectively.

an inner emission radius lower limit of $R_\infty \sim 30\,\text{km}$, which is almost surely larger than the inner disc radius given the extremely high luminosity (and thus accretion rate) of the source. This means that we do not see any emission from the innermost parts of the disc. This could be explained with the obscuration of that part of the disc due to ejection of matter at the Eddington limit that takes place, according to the standard picture of the accretion disk (Shakura & Sunyaev 1973), at the so-called *spherization* radius, that in this case in placed at 22 km from the compact object.

This model of the geometry of emission is often opposed to the Birmingham model, where the emission is described by a blackbody coming from the central powerhouse of the system, plus by a comptonized component describing the emission of an extended accretion disc corona, which is usually fitted with a cutoff powerlaw, where the cutoff energy is equal to the temperature of the scattering electrons cloud. We have shown that the Birmingham model, which has been used to fit the low-resolution spectra of several Z-sources (Sco X–1, Barnard et al. 2003; GX 340+0, Church et al. 2006), cannot give a good fit of the spectrum of LMC X–2. This could be due to the fact that at the high accretion rates that we have in LMC X–2, the thermal emission of the accretion disc dominates over any emission from an accretion disc corona, but we should keep in mind that the narrow energy range of XMM/Newton may well be the cause for our inability to apply this model.

3.1 Discrete Spectral Features

LMC X–2 is the second, among the 8 Z-sources, which does not show any emission feature in the Fe region (after GX 5-1, Asai et al. 1994). It could well be possible, in line of principle, that the short exposure time did not allow to accumulate the statistics required to show a significant iron line. To test this, we added to the best-fit models a gaussian emission line with a fixed energy of 6.7 keV and σ of 200 eV (which is quite typical of lines found in Z-sources). We found that, considering the upper limit on the line flux (at 90% confidence), the equivalent width of the line is $\leq 20\,\text{eV}$, which is about half of the lowest equivalent width found, for example, in BeppoSAX observations of Cyg X–2. The absence of this feature in the spectrum could be due to the lower metallicity of the stars in LMC ($Z \sim 0.008$) compared to the mean metallcity of the stars in our galaxy ($Z \sim 0.02$): if the donor is less abundant in heavy elements, so is the disc and thus any emission line will be fainter as well by roughly the same proportionality factor.

On the other hand, we detect for the first time in a Z-source, a O VIII Ly-α emission line with a significativity of 4.4 σ. The energy of the emission line is perfectly compatible with the rest-frame energy of the O VIII Ly α transition energy (653.4 eV).

This emission line could be present in most Z-sources as O is more abundant than heavier elements in the donor star, but is normally undetected due to the strong absorption by neutral matter that is present in all Galactic Z-sources, as they lie relatively near the galactic center. In the case of LMC X–2, the absorption due to neutral matter is more than an order of magnitude lower than for Galactic sources, and this can explain why we do detect this line and we do not detect any other emission line at higher energies.

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