Black Holes from Stars to Galaxies – Across the Range of Masses
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Variability of ultraluminous X-ray sources in the Cartwheel Ring

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Abstract. The Cartwheel is one of the most outstanding examples of a dynamically perturbed galaxy where star formation is occurring inside the ring–like structure. In previous studies with *Chandra*, we detected 16 Ultra Luminous X-ray sources lying along the southern portion of the ring. Their Luminosity Function is consistent with them being in the high luminosity tail of the High Mass X-ray Binaries distribution, but with one exception: source N.10. This source, detected with *Chandra* at $L_X = 1 \times 10^{41} \mathrm{erg\,s^{-1}}$, is among the brightest non–nuclear sources ever seen in external galaxies. Recently, we have observed the Cartwheel with *XMM-Newton* in two epochs, six months apart. After having been at its brightest for at least 4 years, the source has dimmed by at least a factor of two between the two observations. This fact implies that the source is compact in nature. Given its extreme isotropic luminosity, there is the possibility that the source hosts an accreting intermediate–mass black hole. Other sources in the ring vary in flux between the different datasets. We discuss our findings in the context of ULX models.

Keywords. Accretion, accretion disks – black hole physics – galaxies: individual (Cartwheel) – galaxies: stellar content – X-rays: binaries – X-rays: galaxies

1. Introduction

Very luminous off-nuclear X-ray sources in nearby galaxies are known since the *Einstein* satellite times. They have been named Ultra-Luminous X-ray sources (ULXs) because their isotropic X-ray luminosity is significantly higher than the Eddington limit for a solar mass black hole ($L_X \sim 1.4 \times 10^{38}$ $\mathrm{erg\,s^{-1}}$). The name itself is only a phenomenological description of their L_X, since their nature is not clear yet. They do not appear to have an equivalent among Galactic sources, and this may be related to the low Star-Formation rate of the Milky Way since ULXs are mostly found associated with Star-Forming regions. Explanations of their nature involve beamed emission from an accreting stellar mass compact object, or super-Eddington emission, or isotropic accretion onto an intermediate–mass black hole.

An extraordinary example of ULX is the source N.10 detected in the narrow, gas-rich star–forming ring of the Cartwheel galaxy with isotropic luminosity of $L_{0.5-10\mathrm{keV}} \sim 1.3 \times 10^{41}$ $\mathrm{erg\,s^{-1}}$ (Wolter *et al.* 1999; Wolter & Trinchieri 2004 - hereafter WT04; Gao *et al.* 2003). This is the brightest of a number of very bright individual sources that also appear to reside in the ring, with isotropic luminosities in excess of $L_{0.5-10\mathrm{keV}} = 3 \times 10^{39}$ $\mathrm{erg\,s^{-1}}$ (WT04).

Source N.10 is one of the brightest ULXs known, with observed L_X comparable with the peak L_X of the best studied example of the class, source X-1 in M82 (Ptak & Griffiths 1999; Matsumoto *et al.* 2001; Kaaret *et al.* 2001; Strohmayer & Mushotzky 2003; Dewangan *et al.* 2006). The spectral and temporal variability of X-1 (typically

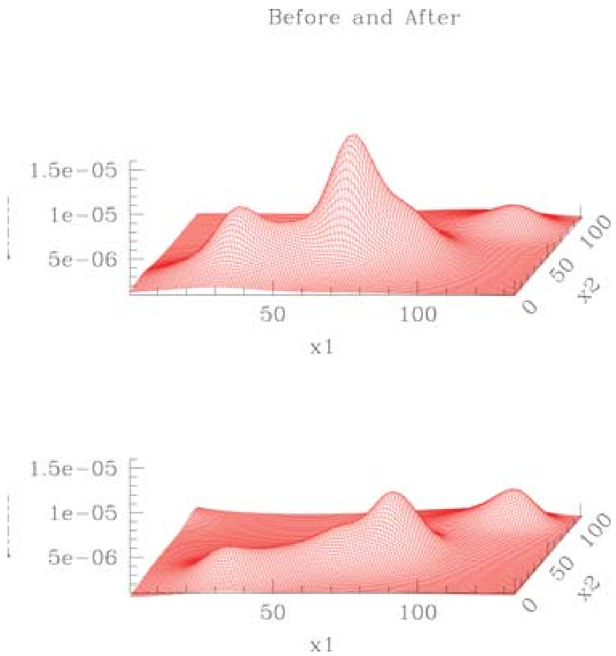

Figure 1. A 3-d representation of the two *XMM-Newton* pn observations [101] (top) and [201] (bottom) with a six months time separation. The smoothed images have been normalized to the respective exposure time. It is evident that the peak located at the position of source N.10 is very less prominent in the second epoch.

bursts of about a month duration) have led to the estimate of 200$M_\odot$ for the accreting object responsible for the X-ray emission (Dewangan *et al.* 2006).

The lack of detailed information on variability for source N.10 in the Cartwheel has instead prevented up to now the exclusion of an extended nature. We present here new *XMM–Newton* observations which have now confirmed its compact nature.

2. *XMM–Newton* observations

We have observed the source with *XMM-Newton* in two epochs (December 2004 and May 2005). A detailed description of the results obtained for source N.10 is presented in Wolter, Trinchieri & Colpi (2006). A 3-d representation of the two smoothed datasets is plotted in Figure 1.

The detection of variability is important because it is our strongest proof that we are detecting a single source, namely an accreting binary, and not a collection of less luminous unresolved X-ray sources. It is also relevant because it can provide essential information about the details of the accretion process and, most important, about the masses involved in the process (donor and accretor), giving the possibility to infer the presence of an intermediate-mass black hole.

The spectrum in the two different *XMM-Newton* observation (the first, [101] of 24 ksec, and the second [201], of 42 ksec exposure) is shown in Figure 2. The *XMM-Newton* PSF is such that the extraction radius (even if we used a smaller than customary value of 10″) contains part of the ring emission, which is described by the sum of a diffuse gas component (thermal spectrum) and the contribution from the unresolved point-like sources (X-ray binaries; power law spectrum. See WT04 for details). Even if the statistics is low, therefore, a multicomponent spectrum has been used to fit the emission: we have

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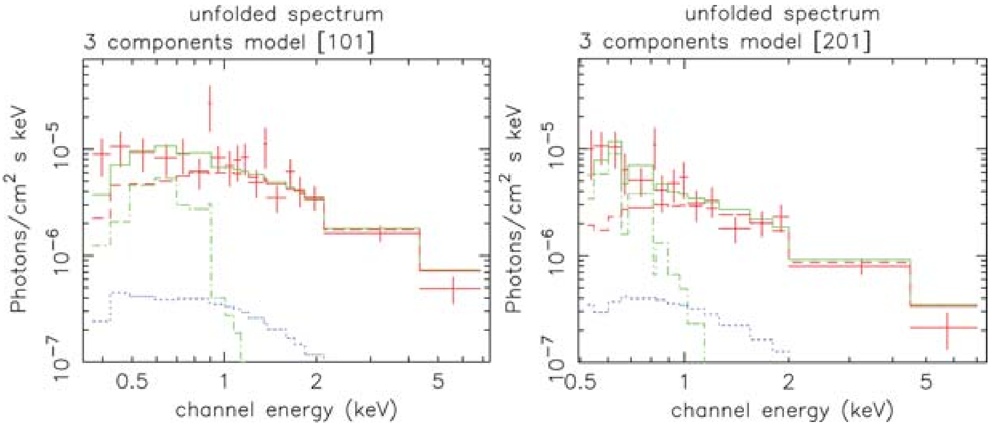

Figure 2. Unfolded spectrum, from pn data only for clarity, showing the three components (green dot-dashed line = gas; blue short dashed line = unresolved binaries; red long dashed line = ULX) at the best fit values. The difference between the left [101] and the right [201] datasets is only the normalization of the 'ULX' component [besides the binning scheme due to the different statistics at the two epochs].

added a power law describing the ULX power law emission (as seen in *Chandra*) to the two ring components. The spectra of the two observations 6 months apart clearly show that the thermal component (gas in the ring) is constant in time and that the factor of 2 variability of the ULX is quite evident.

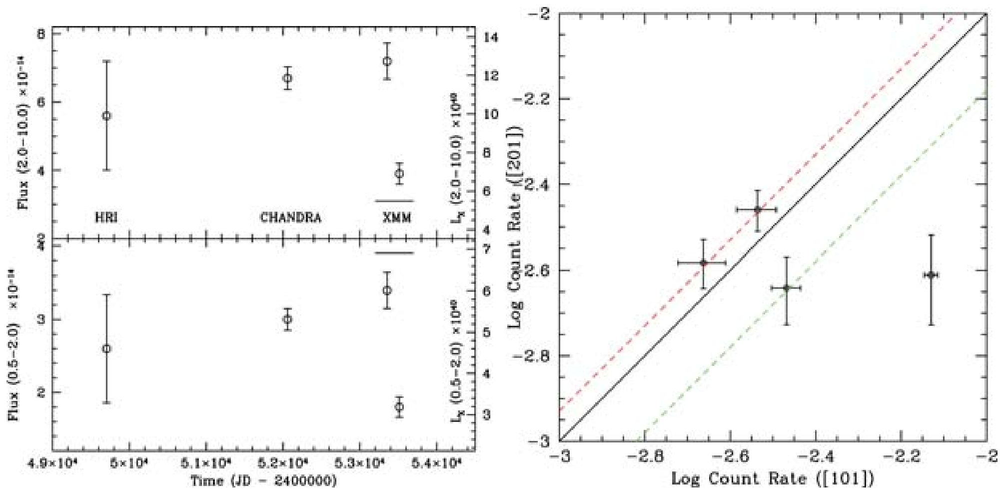

Figure 3. Left: long term light curve in the soft (lower panel) and hard (upper panel) energy band, over an interval of about 10 years. The two *XMM–Newton* points that define the variation are not subject to cross-calibration uncertainties. All fluxes are computed with the same spectral shape, i.e. power law with $\Gamma = 1.6$ and $N_H = 3.6 \times 10^{21}$ cm^{-2}; see fit to *Chandra* data in WT04. Right axis reports luminosities computed assuming the Cartwheel distance. From Wolter *et al.* 2006. Right: flux comparison of the brightest sources in the first and second epoch.

The long term behavior of N.10 shows a nearly constant luminosity for about 10 years (see Figure 3 – left), and then a rapid dimming of at least a factor of 2 in 6 months. This is quite different from the variability pattern observed in the best studied bright ULX, namely X–1 in the starburst galaxy M82 (Dewangan *et al.* 2006).

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We compared count rates for the brightest source neighboring N.10. The comparison is shown in Figure 3 (Right). We have determined that the source next to it, which corresponds to *Chandra* sources N.13 & N.14, has not varied between the two observations (the count rate in the second observation is at most 15% higher than in the first one). If we assume that this is constant, then the source to the NW, corresponding to N.16 & N.17, is also constant (the same 15% increase in the count rate), but the SE source (N.7 & N.9) has faded to about half its strength in the second observation.

3. Conclusions

The whole ring of the Cartwheel consists of bubbles and condensations (Struck *et al.* 1996) and the neighborhood of N.10 is no exception; the association with an environment of massive and young stars is almost certain. The most appealing interpretation for the emission of source N.10 is that it is powered by an intermediate–mass black hole. We cannot rule out the presence of Super-Eddington accretion. Other sources have been observed to vary in the same time frame of N.10. Further studies on variability will help us in distinguishing between different accretion modes. It is evident that the Cartwheel ring is an excited (and exciting!) environment, in which star formation is violently at work. The low metallicity measured for the optical gas might be a key ingredient for the formation of sources capable of emitting very high X-ray luminosity, whatever the mechanism is.

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