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Published in:
E P J Web of Conferences

Link to article, DOI:
10.1051/epjconf/20136406010

Publication date:
2014

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Zhang, W. W., Stern, D., Craig, W. W., Parker, M., Risaliti, G., Boggs, S. E., ... Walton, D. J. (2014). The NuSTAR ULX program. E P J Web of Conferences, 64, [06010]. DOI: 10.1051/epjconf/20136406010

EPJ Web of Conferences **64**, 06010 (2014)
DOI: 10.1051/epjconf/20146406010

The NuSTAR ULX program

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Abstract. We present the results of the first large program of broadband ULX observations with *NuSTAR*, *XMM–Newton* and *Suzaku*, yielding high-quality spectra and timing measurements from 0.3–30 keV in 6 ULXs, providing powerful information for understanding the accretion modes and nature of the central BHs. In particular, we find that all ULXs in our sample have a clear cutoff above 10 keV. This cutoff is less pronounced than expected by Comptonization from a cold, thick corona. We confirm the presence of a soft excess at low energies in the brightest ULXs, with temperatures below ~ 0.5 keV. We make an estimates on the masses of several ULXs based on spectral variability and model fitting.

1 Introduction

Ultraluminous X-ray Sources (ULXs) are point-like, non-nuclear X-ray sources whose luminosities in the range 0.5–10 keV exceed $\sim 1 \times 10^{39}$ erg s^{-1} (up to 10^{42} erg s^{-1}, [1]), significantly above the

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isotropic Eddington luminosity for accretion onto stellar mass black holes (see [2], [3] for reviews). A likely explanation is that most ULXs with $L_x \lesssim 5 \times 10^{39}\,\mathrm{erg\,s^{-1}}$ contain stellar mass BHs in an extreme version of the very high state of galactic BHs; the 'ultra-luminous' or wind-dominated state [4–6]. Alternatively, the emission may display some anisotropy due to geometrically thick disks that funnel X-ray photons produced in the inner disk region [7]. The very highest luminosity end of the population ($L_x \gtrsim 10^{41}\,\mathrm{erg\,s^{-1}}$), termed hyper luminous X-ray source, may indeed harbor intermediate mass BHs (10^2–$10^5\,M_\odot$; IMBHs) accreting at sub-Eddington rates [e.g. 8]. The interpretation of those with $L_x \sim 10^{40}\mathrm{erg\,s^{-1}}$ is less clear. We will refer to these sources as high-luminosity ULXs, distinguishing them from the hyper luminous and "low" ones ($L < 5 \times 10^{40}\mathrm{erg\,s^{-1}}$).

Sutton et al. [6, hereafter S13] find that ULXs in this luminosity range can be classified in at least three different spectral shapes in the 0.1–10 keV band: a broadened disk state (BD), dominated by a broad multicolor disk-like component above ~1 keV; a "hard ultraluminous state" (HU), with a low-temperature < 0.5 keV disk-like component and a power law component with a photon index < 2; finally, a "soft ultraluminous state" (SU), where the photon index is > 2 and the disk-like component is still at low temperatures. Flux variability is mostly observed in the SU, seldom in the BD, but never in the HU.

In the HU and SU, the interpretation of the **disk-like component** is controversial. The temperature is low enough that if it really is produced by a disk extending to the inner most stable circular orbit (ISCO) an IMBH is implied. However the temperature-luminosity relation for this component does not seem to match the $L \propto T^4$ expected in standard accretion disks in the soft state, where the disk extends to the ISCO (e.g. [9], but see [10]). The disk-like component can alternately be interpreted as an outer region of the disk, with the inner region covered by an optically thick corona ([4]). Also, depending on how one fits the power law, this component can in some cases be modeled as an effect of absorption instead of emission [11]. Without constraint on the high-energy part of the spectrum, this disk-like component is in turn hard to constrain. A **cutoff** in the spectrum around 10 keV is observed in most ULXs [12]. The interpretation of this downturn has also been controversial (e.g. [5, 13]) due to limited spectral coverage. Whether it was a real cutoff, the effect of a broadened iron line over a poorly-modeled continuum, or even an effect of slight imperfections in the response of the instruments in their highest energy channels has been debated, but without spectral coverage above 10 keV it was difficult to solve the dispute.

The *Nuclear Spectroscopic Telescope Array NuSTAR* [14], launched in June 2012, with its focusing capabilities, large bandpass between 3 and 80 keV and effective area similar to *XMM–Newton* between 5–10 keV, represents the ideal complement to *XMM–Newton* at high energies.

Since the launch of the satellite, we have observed a sample of luminous ($L_\mathrm{x} \sim 10^{40}\,\mathrm{erg\,s^{-1}}$), close-by (d $\lesssim$ 10 Mpc) and hard (showing X-ray power law photon index $\Gamma \lesssim 2$ below 10 keV) ULXs simultaneously with *NuSTAR* and *Suzaku* or *XMM–Newton*, producing the first ULX spectra extending over the range 0.3 – 30 keV. The goal of this campaign was to use this increased spectral coverage in order to constrain both ends of the spectrum: *XMM–Newton* or *Suzaku* the low-energy part where the disk component lies and *NuSTAR* the cutoff above 10 keV. In the following section we will briefly summarize the main results.

2 Results

Our campaign of observations with *NuSTAR* plus a satellite with coverage below 10 keV (*XMM–Newton* or *Suzaku*) of the high-luminosity ULXs NGC 1313 X-1 and X-2, IC 342 X-1 and X-2, Holmberg IX X-1 and a serendipitous source in the outskirts of the Circinus Galaxy, Circinus ULX5 [15] in the 0.3–30 keV have revealed a number of interesting results, that we briefly summarize here.

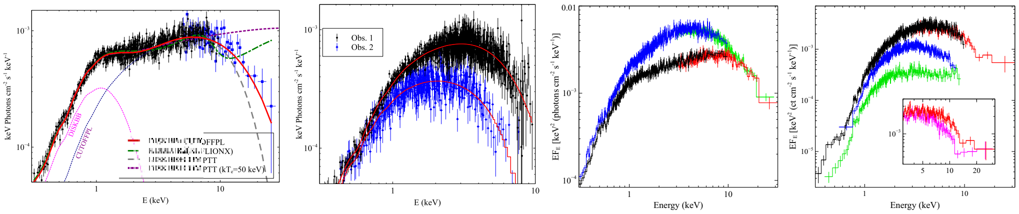

Figure 1: (*Left*) *XMM–Newton +NuSTAR* observation of NGC 1313 X-1 showing how *NuSTAR* data disentangle between the predictions of four models fitted in the *XMM–Newton* band; (*center-left*) the two observations of NGC 1313 X-2 in our sample (*XMM–Newton* only); (*center-right*) spectral variability shown by Holmberg IX X-1 in 2 weeks during our campaign and by (*right*) Circinus ULX5 in all available archival observations plus the *NuSTAR +XMM–Newton* pointings.

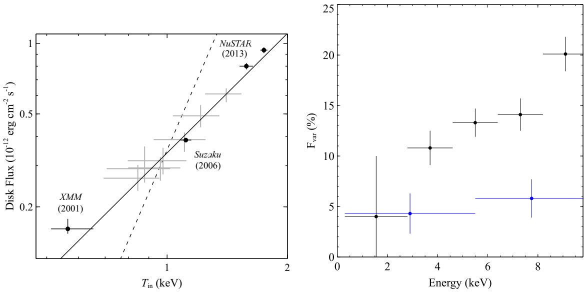

Figure 2: (*Left*) Luminosity-temperature relation for Cir ULX5: the dashed line indicates the theoretical $L \sim T^4$ relation, while the solid line indicates the best-fit relation; (*Right*) variability of NGC 1313 X-2 in the two observations in Fig. 1.

All sources have a clear cutoff of the spectrum above 10 keV [15–17, see Fig. 1]; largely solving the long-lasting dispute between competing models, and favoring an interpretation of these ULXs as stellar-mass black holes (StMBHs) accreting close to, or moderately above, the Eddington limit. The disk component at low energies is still required in the fits of the brightest ULXs after constraining the cutoff.

Cir ULX5 and NGC 1313 X-1 show an excess component at high energies, with respect to a simple Comptonization model. This excess was impossible to spot in the pre-*NuSTAR* era.

NGC 1313 X-1 and Cir ULX5 are probably heavy StMBHs: fitting the spectrum of NGC 1313 X-1 with the `optxagnf` model [18] in order to account for the hard excess, we estimate its mass to be above $\sim 70 M_\odot$. See below for Cir ULX5. NGC 1313 X-2, instead, is well fitted by a slim disk model [19] that, using multi-epoch fitting, permits to estimate the mass as $\lesssim 30 M_\odot$.

Some ULX in our sample can be very variable, from a spectral point of view, in quite short timescales (~1 week) in the *XMM–Newton* band ([15, 16, 20]); in the *NuSTAR* band (> 10keV) they are less variable, suggesting that the disk component is driving the spectral variation [20].

We observed Cir ULX5 in a very high flux state: looking at archival observations it is clear that this source exhibits a very strong variability: a low state, that the authors associate with a very high state reminiscent of that observed in Galactic BHs at Eddington fractions $\sim$ 0.3, and two thermal states reminiscent of the BD. The authors interpret this behavior as a transition taking place around the Eddington limit.

In Cir ULX5, the temperature of the disk-like component is related to the luminosity as $L \sim T^2$ rather than the $L \sim T^4$ expected by a standard thin disk, (à la [21]) but reminiscent of that found in some Galactic BH binaries accreting close to Eddington (e.g. [22]). This permits to estimate its mass around $\sim 90 M_\odot$.

Table 1: Summary of the observations in our program. **Notes.** “Soft exposure” refers a *XMM–Newton* or *Suzaku* observation, simultaneous to *NuSTAR*. * not detected significantly. Exposure times are in ks, and multiple numbers indicate multiple exposures. HU: hard ultraluminous; SU: soft ultraluminous; BD: broadened disk

Target	Soft exposure	*NuSTAR* exposure	Spectral shape	Variability
NGC 1313 X-1	94/80	100/130	HU	no
NGC 1313 X-2	94/80	*	SU/BD	13%/<5%
IC 342 X-1	36/32	100/127	HU	no
IC 342 X-2	36/32	100/127	SU	yes
Holmberg IX	320	60	HU/SU (/BD?)	yes
Cir ULX5	40	36/40	BD?	no

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