The two Ultraluminous X-ray sources in the galaxy NGC 925

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ABSTRACT

NGC 925 ULX-1 and ULX-2 are two ultraluminous X-ray sources in the galaxy NGC 925, at a distance of 8.5 Mpc. For the first time, we analyzed high quality, simultaneous XMM-Newton and NuSTAR data of both sources. Although at a first glance ULX-1 resembles an intermediate mass black hole candidate (IMBH) because of its high X-ray luminosity ($\left(\left(2\times10^{40}\right)\text{ erg s}^{-1}\right)$) and its spectral/temporal features, a closer inspection shows that its properties are more similar to those of a typical super-Eddington accreting stellar black hole and we classify it as a ‘broadened disc’ ultraluminous X-ray source. Based on the physical interpretation of this spectral state, we suggest that ULX-1 is seen at small inclination angles, possibly through the evacuated cone of a powerful wind originating in the accretion disc. The spectral classification of ULX-2 is less certain, but we disfavour an IMBH accreting at sub-Eddington rates as none of its spectral/temporal properties can be associated to either the soft or hard state of Galactic accreting black hole binaries.

Key words: galaxies: individuals: NGC 925 – accretion, accretion discs – X-rays: binaries – X-rays: individual: NGC 925 ULX-1, NGC 925 ULX-2 – stars: black holes – stars: neutron –

1 INTRODUCTION

Ultraluminous X-ray sources (ULXs) are extragalactic, point-like objects characterized by very high X-ray luminosities in the range $10^{39} - 10^{42}$ erg s$^{-1}$ (e.g. Fabbiano 1989; Feng & Soria 2011; Kaaret et al. 2017). Observational evidences suggest that ULXs are accreting X-ray binaries (XRBs) with massive donors (e.g. Liu et al. 2013; Motch et al. 2014). The ULX luminosities can be produced from super-Eddington accretion on stellar-origin black holes (BHs) that could be similar to the Galactic ones (e.g. Gladstone et al. 2009; Sutton et al. 2013; Middleton et al. 2015) or moderately more massive (e.g. Zampieri & Roberts 2009). Alternatively, a possibility can be sub-Eddington accretion onto intermediate mass BHs (IMBHs; e.g. Colbert & Mushotzky 1999; Madau & Rees 2001; Portegies Zwart et al. 2004; Miller & Hamilton 2002). Another possibility is super-Eddington accretion onto neutron stars (NSs; e.g. Bachetti et al. 2013; Israel et al. 2017). The combination of spectral and temporal properties of ULXs should in principle allow the distinction between the nature and mass of the different accretors. In fact, IMBHs accreting sub-Eddington should present the hallmarks of the accreting states of Galactic BH binary systems (i.e. hard and soft states; McClintock & Remillard 2006), while super-Eddington accreting stellar BHs and NSs would more likely show the features of the ultraluminous state (see e.g. Roberts 2007; Gladstone et al. 2009). The latter is characterized spectrally by a curvature at energies of $2 - 5$ keV, often associated to a thermal soft excess below $\sim0.5$ keV (e.g. Gladstone et al. 2009; Bachetti et al. 2013; Caballero-Garcia et al. 2013; Rana et al. 2014; Walton et al. 2013, 2014), and temporally by random short-term variability (e.g. Heil et al. 2009; Sutton et al. 2013; Pintore et al. 2014). The high energy curvature may arise either from a cold, optically-thick corona lying above an accretion disc (e.g. Poutanen et al. 2007; Gladstone et al. 2009; Pintore & Zampieri 2012), or i) from the innermost region of an advection-dominated accretion disc (e.g. Mizuno et al. 2007), ii) from the reprocessing of hard photons by an optically-thick outflow, iii) from a combination of these effects. The soft component may instead originate from the photosphere of a radiatively-driven and clumpy wind ejected from the accretion disc (e.g. Pinto et al. 2016) when the local luminosity at the surface overcomes the Eddington limit, as expected for super-Eddington accretion rates (e.g. Poutanen et al. 2007; Ohsuga et al. 2009; Takeuchi et al. 2013). These powerful outflows may also be responsible for the unpredictable ULX short-term variability (e.g. Middleton et al. 2015).
The discovery of four pulsating ULXs (PULXs) in M82 ULX-2, NGC 5907 X-1, NGC 7793 P13 and NGC 300 ULX-1 (Bachetti et al. 2014; Israel et al. 2017a; Israel et al. 2017b; Fürst et al. 2016; Fürst et al. 2017; Carpano et al. 2018) demonstrated that ULXs can contain NSs, indicating clearly that the ULX population does not host only BHs. Furthermore, the PULXs enlarged our view of the accretion physics in ULXs and, in general, of the extreme mechanisms that can power accreting NSs. The four PULXs currently represent the most super-Eddington accreting sources. Their spectral and temporal properties are quite similar to other well studied ULXs, even though they may have a harder emission (e.g. Pintore et al. 2017; Walton et al. 2018), that could originate in a post-shock region of the accretion column above the NS surface. Magnetic fields of $\sim 10^{14}$ G or larger can produce high isotropic luminosity in the accretion column (up to 2-3 orders of magnitude higher than the ordinary Thomson Eddington limit), as shown by semi-analytical calculations and 2D radiation-hydro-simulations of accretion onto NSs with high magnetic fields (Mushtukov et al. 2015, 2017; Kawashima et al. 2016).

The ULX population has continuously increased during the years reaching several hundreds known examples, although only a few of them have high-enough quality X-ray data to perform deep investigations. Here we report on two ULXs in the galaxy NGC 925 (SAB(s)d, $D \sim 8.5$ Mpc; Figure 1). These are NGC 925 ULX-1 (CXO J022727+333443, ULX-1 hereafter) and ULX-2 (CXO J022721+333500, ULX-2 hereafter), both listed in the Chandra ULX catalogue (Swartz et al. 2011). ULX-1 is located in a spiral arm, while ULX-2 is at $\sim 80''$ from ULX-1. Both sources were observed 18 times by Swift/XRT, which showed that ULX-1 presented flux variations up to a factor of 3, with a peak 0.3-10 keV luminosity of $\sim 4 \times 10^{40}$ erg s$^{-1}$ (ULX-2 was instead below the XRT threshold). Heida et al. (2016) analyzed their infrared emission and estimated that the ULX-1 donor star cannot be a supergiant star of spectral type F or later, while for ULX-2 a red supergiant star may be a possible companion.

From a preliminary analysis of the only public, short, Chandra observation of the two sources, we found that they showed hard spectra and high short-term temporal variability. Since the combination of these properties might be an indication of an accreting IMBH, in this work we investigate further the nature of both sources using new, simultaneous, high-quality XMM-Newton and NuSTAR observations.

2 DATA REDUCTION

2.1 XMM-Newton

An XMM-Newton observation of ULX-1 and ULX-2 was taken on 2017-01-18, for a total exposure time of $\sim 50$ ks. We extracted the data obtained with the EPIC-pn and the two EPIC-MOS cameras, both of them operated in full-frame mode. We reduced the data with the SAS v15.0.0 software, selecting single- and double-pixel events ($\text{PATTERN} \leq 4$), and single- and multiple-pixel events ($\text{PATTERN} \leq 12$), for pn and the MOS, respectively. We cleaned the data removing high particle background time intervals and resulting in net exposure times of $\sim 32$ ks and $\sim 42$ ks in the pn and MOS, respectively.

For the spectral and timing analysis, we extracted the background data from circular regions of 60$''$ radius, free of sources and close to the two ULXs. The ULX data were extracted from circular regions of 35$''$ and 22$''$ radii for ULX-1 and ULX-2, respectively (see Figure 1). The smaller ULX-2 radius was chosen because the source was very close to a CCD gap. We derived a total of $\sim 16920/13512$ and $\sim 1643/2420$ net counts in EPIC-pn/MOS for ULX-1 and ULX-2, respectively.
2.2 NuSTAR

We also obtained a ∼42 ks NuSTAR observation which started ∼20 minutes before the XMM-Newton one, thus broadly overlapping with it. The NuSTAR data were reduced using the standard pipeline, based on NUSTARDAS (the NuSTAR Data Analysis Software v1.3.0) in the HEASOFT ftools v6.16 and CALDB version 20180312. We obtained cleaned event files by applying standard procedures. We extracted the ULX-1 data, selecting a circular region of 50′′ radius centered on the source. The background was chosen from a nearby circular region, free of sources, of 80′′ radius. We obtained a total of ∼2300 net counts in the sum of the data from the FMPA and FMPB instruments. Although ULX-2 was very faint for NuSTAR and also close to ULX-1, a circular region of 30′′ was used to extract ULX-2 data in order to avoid strong ULX-1 contamination.

2.3 Chandra

We analyzed an archival Chandra/ACIS-S observation (Obs.ID. = 7104) of 2005-11-23 with an exposure time of ∼2.2 ks. Chandra data were reduced with CIAO v4.9 and calibration files CALDB v4.7.6. The source events were chosen from circular regions of 3′′ radius (adequate for off-axis position of the sources; see Figure 1), while the background events were selected in a close circular region of 15′′ radius. We extracted the source spectra with the CIAO task SPECEXTRACT, which generates the appropriate response and auxiliary files for the spectral analysis.

The NuSTAR spectra were grouped with at least 100 counts per bin while the XMM-Newton and Chandra spectra were grouped with 25 counts per bin, so that minimum χ² fitting techniques could be used.

Model fitting was carried out using XSPEC v12.8.2 (Arnaud 1996). The spectra of the pn and the two MOS cameras, and (when available) of the NuSTAR detectors were fit together. A multiplicative factor was included to account for possible inter-calibration uncertainties that, as expected, we found smaller than 12% (e.g. Madsen et al. 2017). Chandra was instead analyzed singularly as it was not simultaneous with the other two datasets. For the spectral fits, we considered the 0.3–10 keV energy range for Chandra and EPIC data, and 3–70 keV energy range for NuSTAR data.

2.4 Optical data

On 2018 March 25, starting at 18:44:31.3 UTC, we took two images (300s+200s) of the field of ULX-1/ULX-2 in the Hα band with the 1.8-m Copernico Telescope at Cima Ekar (Asiago, Italy). They were reduced and analyzed using standard software and procedures (bias and flat field subtraction, astrometric calibration).

We report in this section that both ULX-1 and ULX-2 are surrounded by a diffuse emission in Hα, although the quality of the two images does not allow us to investigate the optical emission in deeper detail.
some high short-term variability. We split the 0.3–10 keV energy range in several intervals (0.3–0.5, 0.5–0.7, 0.7–1.0, 1.0–1.3, 1.3–2.0, 2.0–3.0, 3.0–4.0, 4.0–5.0, 5.0–6.0, 6.0–7.0, 7.0–8.0 and 8.0–10 keV) and for each of them we calculated the root mean square (RMS) variability. We found that the RMS fractional variability (i.e. RMS divided by the average count rate of each band, e.g. Vaughan et al. 2003) is ∼45% in each energy band.

We further investigated such findings with the use of the covariance spectra (CV; e.g. Wilkinson & Uttley 2009; Uttley et al. 2014), which have been proven as powerful tool to investigate the ULX timing properties (Middleton et al. 2015). We calculate the CV spectra in the same energy bands used for the RMS spectrum and adopting the 1.3–2.0 keV range as reference band. We choose two overlapping timescales to study short-term (300s–9600s) and long-term (1000s–16000s) correlated variability. As shown in Figure 2, both CV spectra follow the shape of the average spectrum. We fitted them with an NTHCOMP model, where we fixed all the parameters, except the normalization, to the best-fit values of the average XMM-Newton + NuSTAR spectrum, and we found acceptable fits (χ2/dof = 14.62/11 and χ2/dof = 15.93/11, null hypothesis probability > 0.14). Improvements in the best-fit statistics can be obtained by letting also the photon index and the seed photon temperature free to vary, but their uncertainties make the values still consistent with those of the average spectrum. As we do not have any evidence or hint of a second spectral component in the CV spectra, these results imply that the variability is mainly driven by a single spectral component.

We also performed an accelerated search for coherent signals in the XMM-Newton and NuSTAR data, where we corrected the arrival times of the events in a grid of about 600 P/P values in the range (±) 10−11 – 10−5 s. The search gave no statistically significant signals, and yielded a 3σ upper limit on the fractional amplitude of 15% in the period range 0.146s–100s.

#### 3.2 ULX-2

We found that ULX-2 showed a constant lightcurve during both Chandra and XMM-Newton/NuSTAR observations (Figure 3).

We firstly fitted its Chandra spectrum with an absorbed Powerlaw, where we fixed the column density to 0.3 × 1022 cm−2 (see below). This model gives a photon index of 1.9 ± 0.4, again
resembling a *hard* state of XRBs, and an absorbed 0.3–50 keV flux of $(7 \pm 1) \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$.

However, the *XMM-Newton* data indicate that several models can provide statistically acceptable fits (see Table 1), except for a single *DISKBB* model ($\chi^2_{\text{red}} = 282.3/101$). The *POWERLAW* model is characterized by a photon index of $\Gamma = 2.14 \pm 0.09$ and a column density of $0.3 \times 10^{22}$ cm$^{-2}$ (Figure 4). We note that the ULX-2 *NuSTAR* data are consistent with this spectral shape, although above 10 keV we found only upper limits. Instead, a fit with a *DISKBB* gives a column density of $0.23 \times 10^{22}$ cm$^{-2}$ and blackbody and multicolour blackbody disc temperatures of $kT_{\text{bb}} = 1.2$ keV and $kT_{\text{bb}} = 0.4$ keV, respectively. The corresponding 0.3–50 keV absorbed flux is $(4.0 \pm 0.1) \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$. This implies an unabsorbed 0.3–50 keV luminosity of $\sim 3.5 \times 10^{39}$ erg s$^{-1}$ (for a distance 8.5 Mpc).

We did not find any significant short-term variability or coherent pulsation in the data. Adopting an accelerated search for coherent signals, we obtained upper limits on the fractional amplitude of 29% – 45% in the period range 0.146s–100s.

### 4 DISCUSSION

We have obtained the first high quality spectral data of the two ULXs in the galaxy NGC 925, which were considered promising IMBH candidates on the basis of archival low statistics *Chandra* spectra.

#### 4.1 ULX-1

Unfortunately, we cannot draw firm conclusions on the nature of the compact object in ULX-2. In fact, its spectral properties are certainly not consistent with the thermal soft state of XRBs but, at the same time, it only marginally resembles a *hard* state (as the best-fit power-law may be too steep, $\Gamma \sim 2.1$). We found that the ULX-2 spectrum could be also equally modelled by the combination of two thermal components (a multicolour disc plus a blackbody). Assuming an inclination angle $< 60^\circ$ (because of the lack of dips or eclipses) and a distance of 8.5 Mpc, we estimate from the *DISKBB* normalization an inner disc radius of $\sim 500 – 700$ km. Instead, a rough estimate of the *BBODY* emission gives an emitting radius of 73 $\pm$ 3 km. In the scenario of super-Eddington accretion, the former may be associated to the size of the region where outflows are ejected, while the latter might be the inner disc. Should the accreting compact object be a NS, these findings would allow us to exclude that the ULX-2 spectral components in the 0.3–10 keV energy band can be associated to the surface emission of the NS. Finally, we also note, from the optical observations, that ULX-2 is surrounded by a region of diffuse emission in H$_{\alpha}$, whose origin is not clear. Hence, further and deeper X-ray and optical observations of this source are strongly needed to better constrain its nature.

#### 4.2 ULX-1

The high statistics obtained for ULX-1 allowed us some clearer insights on its nature. Assuming that the sub-Eddington accretion onto an IMBH shows the same states of the Galactic BH binaries, our results indicate that the IMBH scenario can be excluded and a super-Eddington accretion onto a stellar compact object appears more likely. In fact, its *XMM-Newton* spectra revealed that the source has a very hard spectral shape but with a significant high energy cut-off. These spectral properties can be associated to a single optically thick Comptonization component, with electron temperature of $\sim 3.5$ keV and seed photon temperature of 0.15 keV. Such a spectral shape allows us to classify ULX-1 as a *broadened disc* ULXs (Sutton et al. 2013). Its measured X-ray luminosity during the *XMM-Newton* and *NuSTAR* observations was $\sim 2.5 \times 10^{30}$ erg s$^{-1}$. However, analyzing the archival *Swift/XRT* observations$^1$ and assuming no significant spectral changes, we found that ULX-1 reached a peak luminosity up to $\sim 4 \times 10^{30}$ erg s$^{-1}$, making ULX-1 one of the brightest known ULXs. We note that other sources with luminosities exceeding $10^{30}$ erg s$^{-1}$ present similar properties (e.g. NGC 470 ULX-1, Circinus ULX5, NGC 5907 X-1, NGC 5643 X-1 Sutton et al. 2012; Walton et al. 2013; Sutton et al. 2013; Pintore et al. 2016). Following Pintore et al. (2017), we compared the position of ULX-1 with those of other well studied ULXs on a X-ray color-color diagram (softness = $(2 - 4 \text{ keV})/(4 - 6 \text{ keV})$, hardness = $(6 - 30 \text{ keV})/(4 - 6 \text{ keV})$). We found that the position of ULX-1 on this hardness-vs-softness diagram (Figure 5) is close to that of the PULXs. If we assume that hard ULX spectra may be associated to the PULXs, from this point of view alone we might consider ULX-1 as a possible candidate to host a NS. Recently, Walton et al. (2018) analyzed the spectra of a sample of bright ULXs adopting a model based on super-Eddington accretion onto magnetized NSs. They showed that all spectra led to

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1 we used the online tool, http://www.swift.ac.uk/user_objects/; Evans et al. (2009)
an excess above 10 keV well described by a cut-off powerlaw, the origin of which may be associated to the accretion column. This would suggest that all the ULXs of the sample can host NSs. In our analysis, we adopted a similar spectral model (DISKBB+BBODY) and we also observed an excess at high energy, which can be modelled with a cut-off powerlaw (although not statistically requested by the data). Therefore, according to this spectral model, ULX-1 can be described as another NS accreting above Eddington, where its pulsed emission would not be detected because of the strong dilution by the high disc+wind emission. According to the work of Koliopanos et al. (2017), who analyzed a similar ULX sample with a similar spectral model, it would be also possible to estimate the magnetic field of the NS in ULX-1: for a high blackbody temperature of $\sim 2$ keV and considering a 0.3–10 keV unabsorbed luminosity of $\sim 2 \times 10^{39}$ erg cm$^{-2}$ s$^{-1}$, the magnetic field should be $\sim 5 \times 10^{12}$ G.

ULX-1 showed also high short-term variability which rules out the scenario of a stable advection dominated disc (unless it was patchy; Miller et al. 2014). The RMS and covariance spectra showed that the strong variability is independent of the energy, supporting the hypothesis that it originates in a single component. Combining the ULX-1 spectral and temporal properties, we suggest that the source is seen at small inclination angles and, if the accretion rate is highly super-Eddington, strong (clumpy) outflows are ejected. MHD simulations (e.g. Kawashima et al. 2012) indicate that such outflows create a funnel around the central compact object. We probably see the hard X-ray emission produced in the regions very close to the compact object through such a funnel (see e.g. Middleton et al. 2015). In addition, the high level of short-term variability may be produced by the clumps of the outflow that occasionally cross our line of sight towards the central regions. The existence of powerful winds around ULX-1 is supported by the properties of its infrared counterpart: Heida et al. (2016) found that the IR emission is characterized by several emission features (where the Fe II is the dominant one), likely having their origin in an extended nebula around ULX-1 which is possibly fed by the ULX outflows. This interpretation is supported by our optical observations that show clear diffuse H$\alpha$ emission around the source.

Deeper observations in the optical band are definitely needed to constrain the origin of such a diffuse emission.

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Figure 5. Color-color diagram obtained from the ratios of the fluxes in the energy ranges 2–4 keV, 4–6 keV and 6–30 keV and calculated from the best-fits with an absorbed HIGHECUT+POWERLAW. The grey points are the sources shown in Pintore et al. (2017), while the blue points are the two PULXs NGC 5907 X-1 and NGC 7793 P13. The green triangle and the red square indicate ULX-1 and ULX-2, respectively.
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