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# The population of ULXs in the spiral galaxy NGC 2276

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We present results for X-ray point sources in the Sc galaxy NGC 2276, obtained by analyzing Chandra data. The galaxy is known to be very active in many wavelengths, possibly due to gravitational interaction with the central elliptical of the group, NGC 2300. However, previous XMM-Newton observations resulted in the detection of only one bright ULX and extended hot gas emission. We present here the X-ray population in NGC 2276 which comprises 17 sources. We found that 6 of them are new ULX sources in this spiral galaxy resolved for the first time by Chandra. We constructed the Luminosity Function that can be interpreted as mainly due of High Mass X-ray binaries, and estimate the Star Formation rate (SFR) to be SFR $\sim 5 - 10 M_{\odot}$/yr.

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## 1 Introduction

NGC 2276 is a peculiar Sc galaxy belonging to the group of NGC 2300, the first small group of galaxies in which hot diffuse intragroup gas has been observed in X-rays with ROSAT (Mulchaey et al. 1993, Davis et al. 1996). The mass estimate of the hot gas is $M_{gas} = 1.25 \pm 0.13 \times 10^{12} M_{\odot}$. The X-ray emission, of about 0.3 Mpc extent, is centered close but not exactly on the central elliptical NGC 2300. The emission is well described by a King model with a core radius $r_o = 4.28 \pm 1$ arcmin and $\beta = 0.41 \pm 0.3$ and has a luminosity of $L_X^{bol} = 1.12 \times 10^{42}$ erg/s (Davis et al. 1996).

The peculiar "bow shock" shape of NGC 2276 underlines the interaction with either the hot gas surrounding the group center or directly with the central elliptical. Condon (1983) suggests the presence of ram-pressure interaction between NGC 2276 and the IGM, while Gruendl et al. (1993) and Elmegreen et al. (1991) explore tidal interaction with the central elliptical galaxy NGC 2300. Davis et al. (1997) note that data in all observed wavelengths show enhancement of emission in the SW quadrant. They derive that the morphology of the galaxy is primarily affected by the gravitational encounter which has disturbed both the stellar and gaseous component and enhanced star formation rate along the truncated side of the galaxy. They conclude that ram pressure may enhance the star formation, but is not the dominant force shaping the galaxy.

This Sc galaxy is indeed very active. Many supernovae have been observed in the last fifty years (e.g. Barbon et al. 1989, Treffers 1993, Dimai 2005) and the Star Formation Rate (SFR) is estimated to be SFR=9.5 $M_{\odot}$/yr based on it high H$\alpha$ luminosity (Kennicutt, 1983). Values between 5 and 15 $M_{\odot}$/yr are found from different measurements, mostly H$\alpha$ and FIR (e.g. Kennicutt et al. 1994, James et al. 2004, Sanders et al. 2003). A number of HII regions is identified in the galaxy, spread all over the area (Hodge & Kennicutt 1983, Davis et al. 1997).

Using XMM-Newton data, Davis & Mushotzky (2004) identify the brightest X-ray source at the western edge of the galaxy with a ULX with luminosity of $L_X^{0.5-10keV} = 1.1 \times 10^{41}$ erg/s, making it one of the most luminous known in its class. The nuclear source instead is dimmer by at least a factor of several thousands than the ROSAT HRI source seen by Davis et al. (1997) eigth years earlier.

The finding of a single ULX is in contrast with expectations from star formation models that assume that ULXs are the heaviest and brightest tail of the High Mass X-ray binary population. For instance, using the model of Mapelli et al. (2010), with a metallicity of Z=0.22 $Z_{\odot}$ and a mean value of SFR=10 $M_{\odot}$/yr, we predict the formation of almost twenty thousand Black Holes in the galaxy and, as a consequence of their evolution, about 10 ULXs. We recall that the number of ULXs expected depends linearly on SFR and therefore it is uncertain by about a factor of 2 based on the spread of measured SFR values.

Recent Chandra data (Rasmussen et al. 2006) reveal a shock-like feature along the western edge of the galaxy and a low surface brightness tail extending to the east, similar to the morphology seen in other wavebands. Spatially resolved spectroscopy shows that the data are consistent with intragroup gas being pressurized at the leading western edge of NGC 2276 due to the galaxy moving supersonically through the IGM at a velocity of $\sim 850$ km/s.

The diffuse hot gas in NGC 2276 has an X-ray luminosity of $L_X^{(0.3-2.0keV)} = 1.86 \times 10^{40}$ erg/s and a temperature of $kT \sim 0.35$ keV, with a residual component of unresolved X-ray binaries of about 10-15% in flux (Rasmussen et al. 2006). The IGM measured by Chandra has a profile consistent with previous measures by Davis et al. (1996) and temperature of kT = 0.85 keV and Z= 0.17 $Z_{\odot}$ (Rasmussen et al.

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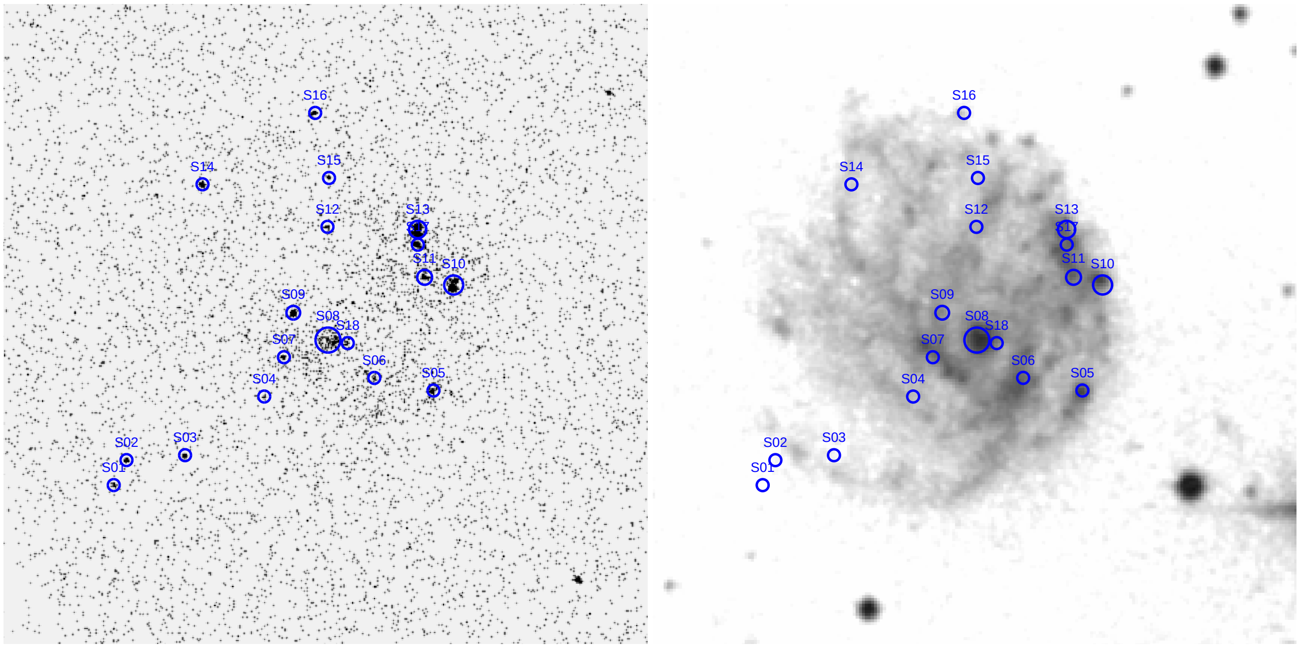


**Fig. 1** *Left:* X-ray data from Chandra in the 0.5-7 keV band. Open circles and numbers identify detected sources. *Right:* The X-ray sources' positions are overplotted on the optical image of NGC 2276 taken from the DSS.

2006). However, the superb Chandra resolution allows the detection of a number of point sources not seen or resolved before. The study of the population of point sources in the galaxy NGC 2276 and preliminary results on the ULXs are the subject of this work.

We assume here a distance of 32.8 Mpc (from NED) an rescale published values to this distance when necessary.

## 2 Chandra point sources

The Chandra observation of 45.8 ksec has been performed on June 23rd, 2004. We apply standard reduction procedures and run a sliding cell detection algorithm that finds 17 sources in the galaxy area. We illustrate the X-ray data and compare with the optical image of the galaxy in Figure 1. One of the sources (S08) corresponds to the nuclear region, which had been detected previously as variable (Davis & Mushotzky 2004), at $L_X \sim 10^{39}$ erg/s. However, a correct comparison of the flux would need a detailed modeling of the sorrounding emission, given the different resolution of the instrument that have observed NGC 2276 through the years. The spectral information is not sufficient to discriminate between a nuclear active source at very low luminosity or the natural enhancement at the center of the galaxy. We do not consider this source in the construction of the X-ray Luminosity Function (XLF).

Contamination from background sources is estimated according to the logN-logS of Hasinger et al. (1993). At the detection limit of $f_X^{(0.5-2keV)} = 7 \times 10^{-16}$ erg cm$^{-2}$ s$^{-1}$ (which corresponds to $L_X = 10^{38}$ erg/s at the distance of NGC 2276) we expect 1.4 sources by chance in the total area covered by the galaxy. To account for this we randomly exclude one of the sources in the fainter flux range to construct the XLF.

The XLF is matched to the Universal Luminosity function of High Mass X-ray binaries (HMXB) proposed by Grimm et al. (2003). The scale parameter is the SFR, that we can derive from comparison with the data. If the model holds, than we see from Figure 2 that values between 5 and 10 $M_\odot$/yr are consistent with the derived luminosity function. Also comparing the total X-ray luminosity or the number of ULX with the results of Grimm et al. (2003) we derive similar results of SFR = 5 and 5.5 $M_\odot$/yr respectively. These values are in the same range of star formation rates derived in other wavebands (see Section 1). This makes the XLF of NGC 2276 very close to those of the Antennae (Zezas et al. 2002) and the Cartwheel (Wolter & Trinchieri 2004) which are fitted respectively with SFR=7.1 $M_\odot$/yr and SFR$\sim$ 20 $M_\odot$/yr.

## 3 The ULXs

The number of sources with $L_X \geq 10^{39}$ erg/s, which is the assumed definition for ULXs, are 7, many more than the only ULX detected earlier in XMM-Newton data (Davis et al. 1994), and consistent with the prediction of the model by Mapelli et al. (2010) for a SFR = 5-10 $M_\odot$/yr. A comparison of XMM-Newton and Chandra data in the region of the XMM-Newton ULX is shown in Fig.3. The XMM-Newton source is resolved in 6 individual sources, of luminosities ranging from a few $10^{38}$ erg/s to almost $10^{40}$ erg/s. Lower background per detection cell in Chandra also contributes to the finding of a large number of point sources in the whole galaxy.

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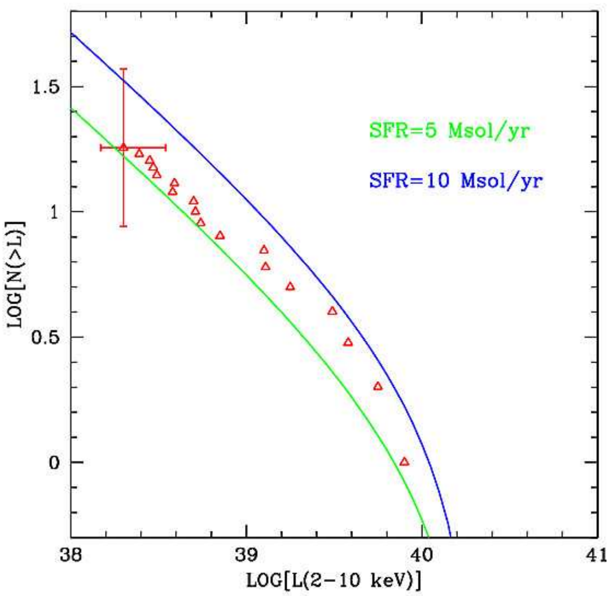


**Fig. 2** The X-ray Luminosity Function computed in the 2-10 keV band by using the 15 sources detected in the galaxy area: the nucleus has been removed, as well as one of the faint sources to account for background contamination. The solid lines describes the Grimm et al. 2003 luminosity function for the HMXB, normalized respectively to 5 and 10 $M_\odot$/yr. No formal fit has been performed. The errorbar on the faintest point are indicative of the uncertainty in flux and density.

The brightest sources have enough counts (100-400) to allow a spectral fit: a single absorbed power law is a good description of these spectra, with $N_H \sim 2 \times 10^{21}$ cm$^{-2}$ and slopes between $\Gamma = 1.4$ and 2.2, consistent with mean results for the sample of ULXs studied by Swartz et al. (2004).

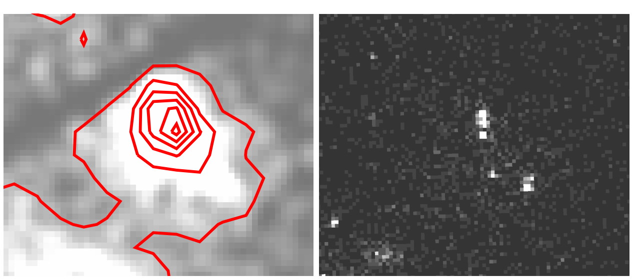

**Fig. 3** *Left:* A zoomed in region of the XMM-Newton data representing the ULX region. *Right:* Chandra data for the same region of the galaxy: a number of point sources is evident.

To investigate possible variability of the ULX source previously detected by XMM, we estimate the Chandra luminosity of the corresponding source as the sum of all the resolved point sources. We rescale the energy range given by Davis & Mushotzky (2004) from the 0.5-10 keV to the 2-10 keV band and also correct to the adopted distance of 32.8 Mpc. This results in a Chandra luminosity of $L_X^{(2-10keV)} = 2 \times 10^{40}$ erg/s to be compared to the total luminosity measured by XMM of $L_X^{(2-10keV)} = 3.8 \times 10^{40}$ erg/s. The XMM-Newton value might be affected also by a contribution of diffuse gas which falls in the detection cell. However the fraction of hot gas emission amounts to only about 30% in the Chandra data. Therefore it is possible that at least the brightest ULXs have partially dimmed in the two years between the two observations. We know that variablity is a common property of ULXs (see e.g. Crivellari et al. 2009 and Zezas et al. 2006). New Chandra observations are needed in order to study the variability pattern in detail.

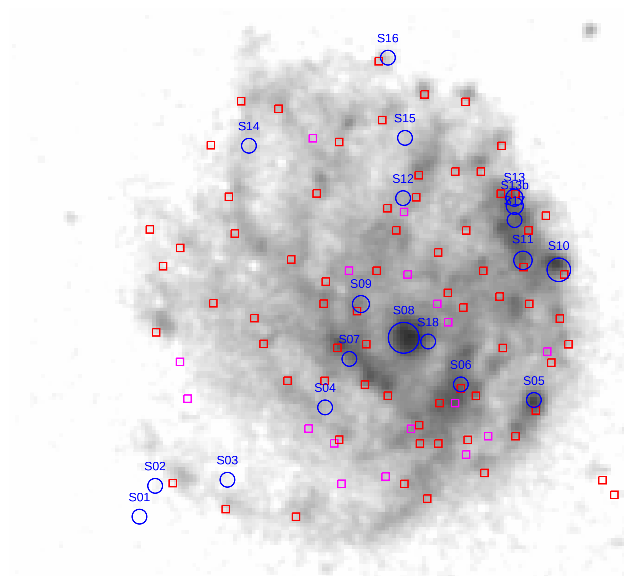


**Fig. 4** The DSS image of the galaxy: overplotted in blue are the position of the detected Chandra X-ray sources presented in this work, in red and in magenta are the locations of HII regions listed in Hodge & Kennicutt, (1983) Davis et al. (1997) respectively. The ULXs reported in this paper are S09, S10, S11, S13, S13b, S14, S17.

Hodge et al. (1983) list 72 HII regions detected in the galaxy, and Davis et al. (1997) find a few more. The positions of the HII region are plotted in Fig. 4, together with the position of X-ray sources. Davis et al. (1997) notice that many of the HII regions are also associated with strong non-thermal radio sources, which is a fact not well explained, and propose an association with a supernova remnant (SNR) in dense environment to explain the emission. Although the spatial resolution at the distance of NGC 2276 is not enough to warrant a physical association, we find that six of the HII region are positionally coincident ($1'' - 2''$) also with bright X-ray sources, four of which are ULXs. It is tempting therefore to associate the HII regions to the ULXs. The main interpretation of ULXs is in term of accretion, however, at least 25% of all known ULXs have a spatial coincidence


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with a Supernova (SN), and also one of the brightest known ULXs, N10 in the Cartwheel galaxy, might be explained as a very bright and peculiar SN, as well as an almost ordinary HMXB (see Pizzolato et al. 2010). Therefore a deeper study of the association with HII regions and radio emission could give more insight in the explanation of ULXs as a class.

## 4 Conclusions

We have analyzed a Chandra observation of NGC 2276, a spiral galaxy in the group of the elliptical NGC 2300. We have paid particular attention to the point sources detected in the area of the galaxy. We find that a large number of ULXs are present, which makes NGC 2276 one of the richest enviroment of this still enigmatic bright sources. Further observations are needed in order to study in detail spectral and variability properties of this class.

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