Massive Young Star Clusters Near and Far: From the Milky Way to Reionization
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# Ultraluminous X-ray Sources in Extremely Metal Deficient Galaxies

E. Ripamonti[1], and M. Gomitoni[2]

**Abstract** Theoretical considerations suggest that Ultra-Luminous X-ray sources (ULXs) preferentially form in star-forming, metal-poor galaxies. The correlation between the number of ULXs ($N_{ULX}$) and the Star Formation Rate (SFR) of a galaxy is indeed very robust; instead, the evidence about metallicity is weaker. Here we look at a sample of 22 newly observed extremely metal-deficient galaxies (with metallicity $\leq$ 1/20 of the solar value), and find that both the ratios $N_{ULX}$/SFR and $L_X$/SFR (where $L_X$ is the total X-ray luminosity of sources in the sample) are higher than what is found in samples of galaxies of higher metallicity.

## 1 Introduction

Ultra-Luminous X-ray sources (ULXs) are non-nuclear X-ray sources with a luminosity $L_X \geq 10^{39}\,\mathrm{erg\,s^{-1}}$, i.e. larger than the Eddington limit for a $\sim 10\mathrm{M}_\odot$ Black Hole (BH). Only a few of these objects might be related to intermediate-mass black holes (e.g. Colbert & Mushotzky 1999; Mapelli et al. 2008; Farrell et al. 2009) and most of them are likely associated with stellar X-ray binaries. In fact, the number of ULXs in a galaxy scales linearly with its Star Formation Rate (SFR) (e.g. Mapelli et al. 2010), and the relation is very similar to what is found for High-mass X-ray binaries (Grimm, Gilfanov & Sunyaev 2003; Ranalli, Comastri & Setti 2003; Mineo, Gilfanov & Sunyaev 2012); furthermore, ULXs are usually found in the vicinity of young stellar clusters and associations.

It has been suggested by several authors (e.g. Zampieri & Roberts 2009; Mapelli, Colpi & Zampieri 2009) that ULXs are more frequent in low-metallicity environments. In fact, metal-dependent stellar evolution and supernova models (e.g. Belczynski et al. 2010) suggest that in moderately low-metallicity environments ($Z \leq 0.3\,Z_\odot$) it is possible to form "massive stellar black holes" (with $M_{\mathrm{BH}} \geq 25\,\mathrm{M}_\odot$), which are at least twice more massive than what is commonly found ($M_{\mathrm{BH}} \leq 10\,\mathrm{M}_\odot$) in Galactic X-ray binaries (e.g. Mapelli et al. 2010; Belczynski et al. 2010; Mapelli et al. 2013); furthermore, because of somewhat smaller stellar radii, the orbits of metal-poor stars can have smaller semi-major axis, and therefore the system can more easily achieve very high mass transfer rates through Roche-lobe overflow (Linden et al. 2010).

These theoretical expectations are partially confirmed by observations: Mapelli et al. (2010) found that there is an inverse correlation between metallicity and the number $N_{\mathrm{ULX}}$ of ULXs in a galaxy normalized to its SFR; and Kaaret, Schmitt & Gorski (2011) found that the ratio of total X-ray luminosity $L_{\mathrm{X,gal}}$ of a galaxy to SFR is higher in metal-poor galaxies.

[1]Università di Padova, Dipartimento di Fisica e Astronomia "G. Galilei", Vicolo dell'Osservatorio 3, I-35122, Padova, Italy, e-mail: ripamonti.e@gmail.com
[2]Università di Milano-Bicocca, Dipartimento di Fisica "G.Occhialini", Piazza della Scienza 3, I-20126 Milano, Italy

However, none of these results has high significance, mainly because of low-number statistics.

In this proceedings, we report about a further observational test of whether ULXs form preferentially in low-metallicity environments, i.e. we look at whether the observed trends about the ratios $N_{\rm ULX}/SFR$ and $L_{\rm X,gal}/SFR$ are confirmed when we look at a sample of 22 eXtremely Metal-Deficient Galaxies (XMDGs) recently observed with *Chandra* (see Prestwich et al. 2013).

## 2 Extremely metal deficient galaxies: X-ray data

XMDGs are galaxies with $12+\log{\rm O/H} \leq 7.65$, corresponding to a metallicity $Z \leq 0.05 Z_{\odot}$ - are the most metal-poor galaxies known (see e.g. Papaderos et al. 2008). These objects are typically small, but often exhibit a large specific star formation rate.

Two very notable (though somewhat larger than average) XMDGs are IZw 18 and SBS0335-052: both of them have metallicity $Z \sim 0.02 Z_{\odot}$ (that is, they are among the most-metal poor galaxies known), while their SFRs are $0.06\,{\rm M_{\odot}\,yr^{-1}}$ and $0.86\,{\rm M_{\odot}\,yr^{-1}}$ (both from H$\alpha$ photometry), respectively. Before the observations reported by Prestwich et al. (2013), these two galaxies were the only XMDGs for which *Chandra* data were available (Thuan et al. 2004): the fact that 1 ULX was observed in IZw 18, and 2 ULXs were detected in SBS0335-052 was quite suggestive of a metallicity effect (Mapelli et al. 2011); also note that IZw 18 is in the sample used by Kaaret, Schmitt & Gorski (2011) and is somewhat driving their results).

According to Prestwich et al. (2013) there are $N_{\rm ULX,22} = 2$ ULXs (plus one source with $L_{\rm X} \simeq 0.7\times10^{39}\,{\rm erg\,s^{-1}}$) in the 22 galaxies of their sample; this is to be compared with an expected total number of background sources (i.e. unrelated to the target galaxies) $N_{\rm bkg,22} =$ 1.2. Instead, in the full XMDG sample (including IZw 18 and SBS0335-052), $N_{\rm ULX,XMDG} = 5$, and $N_{\rm bkg,XMDG} = 1.3$. The total luminosity of X-ray sources detected in the sample of 22 galaxies is $L_{\rm X,22} = 4.9\times10^{39}\,{\rm erg\,s^{-1}}$, whereas in the full XMDG sample $L_{\rm X,XMDG} = 19.2\times10^{39}\,{\rm erg\,s^{-1}}$. More details can be found in Table 1, where we take the X-ray data ($\rm N_{ULX}$, $\rm N_{bkg}$, and $\rm L_X$) from Prestwich et al. (2013).

## 3 Optical observations: H$\alpha$ photometry

We performed narrow-band H$\alpha$ photometry of 13 of the 22 XMDGs observed by Prestwich et al. (2013), in order to estimate their SFRs. These observations were carried out with the 3.5m Telescopio Nazionale Galileo at the ORM, La Palma, and their results are reported in Table 1. Table 1 also includes SFR data from the literature for the remaining 9 galaxies: in 7 cases, we were able to retrieve H$\alpha$ data, whereas in the remaining two cases we had to revert to UV (Galex) data reported by Prestwich et al. (2013). Table 1 also includes the data for IZw 18 and SBS0335-052, and the totals for both the sample of 22 newly observed galaxies, and for the full (24 galaxies) sample.

The total SFR of the 22 galaxies in the sample is ${\rm SFR_{22}} = 0.48\,{\rm M_{\odot}\,yr^{-1}}$; whereas in the sample of all XMDGs the total is ${\rm SFR_{XMDG}} = 1.4\,{\rm M_{\odot}\,yr^{-1}}$.

Table 1: List of galaxy properties

| Galaxy | $N_{ULX}$ | $N_{bkg}$ | $L_X^a$ | $L_{H\alpha}^a$ | SFR$^b$ | Ref.$^e$ |
|---|---|---|---|---|---|---|
| UGC 772 | 0 | 0.014 | 0 | 1.0 | 7.9 | (f) |
| SDSS J210455.31003522.2 | 0 | 0.039 | 0 | 0.94 | 7.4 | (f) |
| SBS 1129+576 | 0 | 0.034 | 0.72 | 2.35 | 18.5 | (f) |
| HS 0822+3542 | 0 | 0.004 | 0 | 0.7 | 5.6 | (g) |
| SDSS J120122.32+021108.5 | 0 | 0.010 | 0 | 1.3 | 10 | (f) |
| RC2 A1116+51 | 1 | 0.012 | 2.93 | 7.5 | 60 | (f) |
| SBS 0940+544 | 1 | 0.776 | 1.26 | 3.5 | 28 | (h) |
| KUG 1013+381 | 0 | 0.026 | 0 | 13.6 | 110 | (f) |
| SBS 1415+437 | 0 | 0.010 | 0 | 6.2 | 49 | (h) |
| 6dF J0405204364859 | 0 | 0.017 | 0 | - | 10 | (i) |
| SDSS J141454.13020822.9 | 0 | 0.034 | 0 | 0.83 | 6.6 | (f) |
| SDSS J223036.79000636.9 | 0 | 0.012 | 0 | 2.85 | 22.5 | (f) |
| UGCA 292 | 0 | 0.041 | 0 | 0.2 | 1.6 | (g) |
| HS 1442+4250 | 0 | 0.028 | 0 | 1.8 | 14 | (h) |
| KUG 0201103 | 0 | 0.031 | 0 | - | 13 | (i) |
| SDSS J081239.52+483645.3 | 0 | 0.008 | 0 | 0.15 | 1.2 | (f) |
| SDSS J085946.92+392305.6 | 0 | 0.011 | 0 | 0.09 | 0.7 | (f) |
| KUG 0743+513 | 0 | 0.014 | 0 | 5 | 40 | (g) |
| KUG 0937+298 | 0 | 0.015 | 0 | 1.8 | 14.5 | (f) |
| KUG 0942+551 | 0 | 0.027 | 0 | 0.7 | 5.5 | (f) |
| SBS 1102+606 | 0 | 0.048 | 0 | 1.79 | 14.5 | (f) |
| RC2 A1228+12 | 0 | 0.014 | 0 | 5 | 40 | (j) |
| Total of 22 "new" XMDGs | 2 | 1.225 | 4.91 | 57.3$^c$ | 480.5 | - |
| IZw 18 | 1 | 0.013 | 4.92 | 7.8 | 62 | (k) |
| SBS0335-052$^d$ | 2 | 0.090 | 9.39 | 110 | 860 | (l) |
| Total of the XMDG sample | 5 | 1.328 | 19.22 | 175.1$^c$ | 1402 | - |

$^a$ In units of $10^{39}$ erg s$^{-1}$; errors are dominated by the uncertainty in the distance, and are usually of the order of 20–40 per cent; we adopted the same distances used by Prestwich et al. (2013). $^b$ In units of $10^{-3}$ M$_\odot$ yr$^{-1}$; H$\alpha$ luminosity was transformed into a SFR using the conversion factor given by Kennicutt (1998). $^c$ Not including 6dF J0405204364859 and KUG 0201103. $^d$ For simplicity, we decided to consider SBS0335-052 as a single object, even if it is often split into an East and a West component. $^e$ Origin of the H$\alpha$ data: (f) this work; (g) Kennicutt et al. (2008); (h) Gil de Paz, Madore & Pevunova (2003); (i) Prestwich et al. (2013); (j) Gavazzi et al. (2003); (k) Kong (2004); and (l) Pustilnik, Pramskij & Kniazev (2004).

## 4 Discussion and conclusion

It is straightforward to estimate the occurrence rate of ULXs per unit star formation rate ($N_{\rm ULX} - N_{\rm bkg}$/SFR) both for the 22-galaxy sample, and for the full sample of XMDGs: the former is 1.6 ULX/(M$_\odot$yr$^{-1}$), and the latter is 2.6 ULX/(M$_\odot$yr$^{-1}$). Both values are slightly lower than what was previously obtained for IZw 18 and SBS0335-052 [3.1 ULX/(M$_\odot$yr$^{-1}$)], and also than of the ratio of 4.5 ULX/(M$_\odot$yr$^{-1}$) found by Prestwich et al. (2013), using different indicators for star formation. However, both values are higher than 1.2 ULX/(M$_\odot$yr$^{-1}$), which was found in Mapelli et al. (2010) by fitting the $N_{\rm ULX}$–SFR relation for a sample of 63 galaxies with metallicities in the 0.1Z$_\odot$–0.5Z$_\odot$ range.

The same test can be performed for the ratio $L_X$/SFR, for which we obtain (neglecting the presence of background sources) values of $10.2\times10^{39}\,{\rm erg/s/(M_\odot\,yr^{-1})}$ for the 22-galaxy sample, and of $13.6\times10^{39}\,{\rm erg/s/(M_\odot\,yr^{-1})}$ for the full XMDG sample. Samples of higher metallicity galaxies lead to quite lower estimate: for example, Mineo, Gilfanov & Sunyaev (2012) recently found a value of $2.6 \times 10^{39}\,\mathrm{erg/s/(M_\odot\,yr^{-1})}$.

The fact that both ratios are significantly higher than what is found in galaxies with "normal" metallicities clearly supports the view that ULXs are more frequent in low-metallicity galaxies. However, this conclusion is still somewhat tentative because of the low number of ULXs, and of the low total SFR of the sample.

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