Correlation between X-ray emission and stellar populations: the definitive study of nearby galaxies observed with XMM-Newton

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Introduction-Motivation

The collective emission of the X-ray binary (XRB) population dominates the hard X-ray emission of normal galaxies. Furthermore, the X-ray emission of the younger stellar populations (i.e. High-Mass X-ray binaries; HMXBs) has been found to scale with the star-formation rate (SFR) of the galaxy, while the emission of the older stellar populations (i.e. Low-Mass X-ray binaries; LMXBs) scales with its stellar mass (M_*) (e.g. Lehmer et al. 2010, Mineo et al. 2012, Lehmer at al. 2019).

However, since these scaling relations have been based on a few dozens of galaxies there are still some open questions. For example, there is poor characterization in the low-SFR end, as well as some scatter at high sSFRs, which is unclear whether it is an observational effect or it represents differences of the XRB populations (e.g. age, metallicity). Our goal is to address these issues by testing the scaling relations in the full set of star-forming galaxies observed with *XMM-Newton* so far.

Sample of galaxies

Our sample is the result of the cross-correlation between the HECATE catalogue and all public observations of *XMM-Newton*. The HECATE catalogue (Kovlakas et al. 2019 in prep.) consists of all known galaxies within D<200Mpc (163K objects). The cross-correlation yields **3041 galaxies** (2906 with >90% area coverage) observed in **2645 OBSIDs** after removing high-background observations.

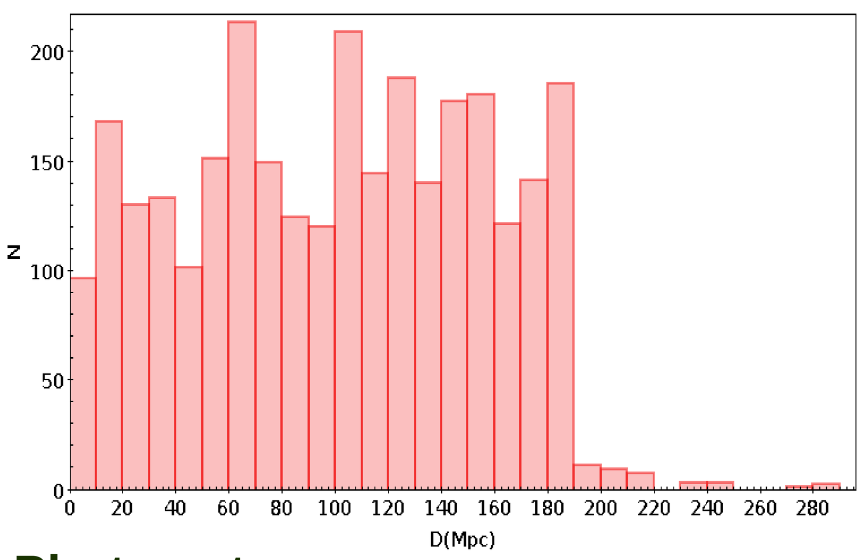

***Figure 1**: Distance distribution of the 3041 galaxies revealing a uniform coverage throughout the maximum distance of the catalogue.*

Photometry

- We ran standard analysis-pipeline (MPE-HEG) for the calibration of the *XMM-Newton* observations and produced images in the 5 standard *XMM-Newton* bands.
- Aperture photometry was performed on the images using the *dmextract* tool of CIAO and the D25 region of the galaxies folded with the PSF of the *XMM-Newton* detectors.
- A count-rate to flux conversion was computed using the *modelflux* tool of CIAO, assuming an absorbed power-law model (Γ=1.7 and line-of-sight N_H).
- The resulting luminosities where the average of all observations.

Spectroscopy

- Spectral fitting was performed for all galaxies with adequate number of counts (**1713 galaxies; 5804 spectra**).
- The vast majority (1230 objects) were well fitted with an absorbed power-law plus one or two thermal component model. 330 galaxies required more complex models, typical of AGN, and 155 cases required special attention (variable sources, high background etc.).
- The X-ray luminosity of the XRB component in each galaxy was calculated based on the power-law component of the corresponding spectral fit.

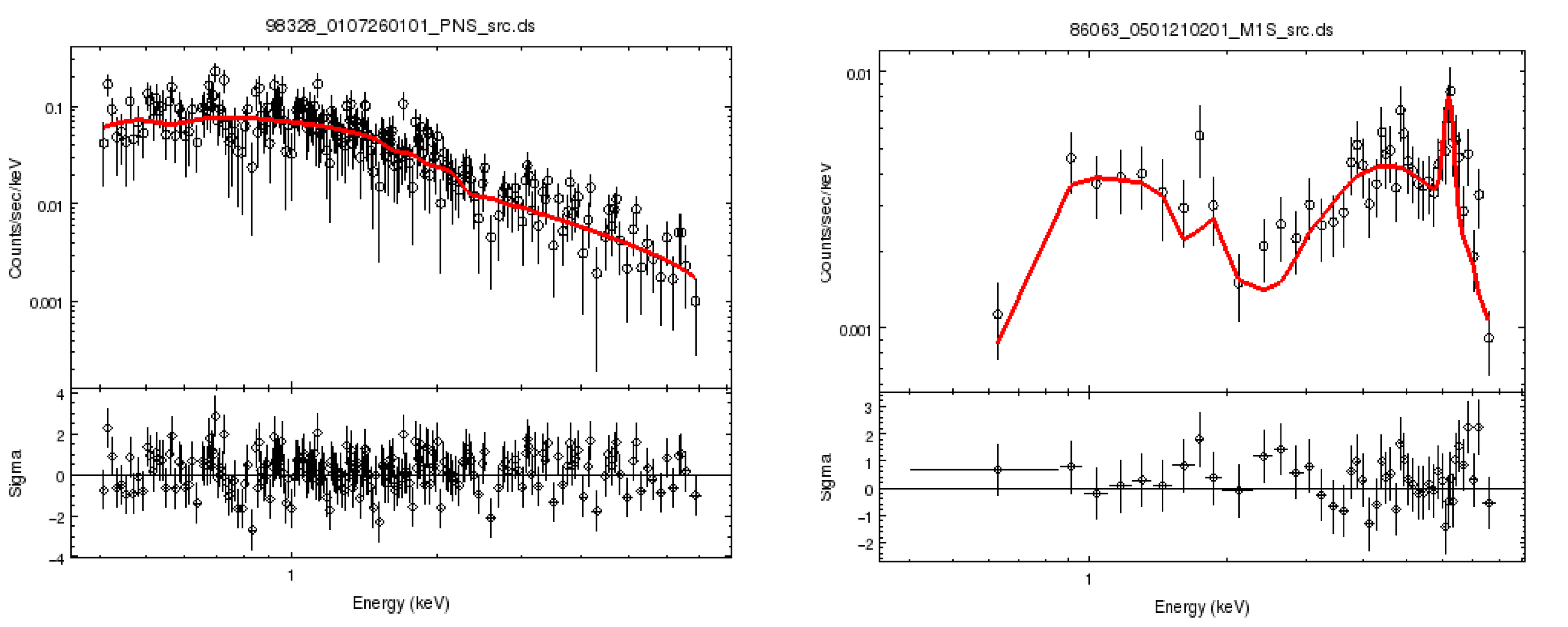

***Figure 2:** Typical examples of spectra fitted with an absorbed power-law model (left) and a more complex model (right) typical of AGN galaxies.*

Association with physical parameters and scaling laws

- Physical parameters (SFR and M_*) used in the HECATE catalogue were derived from the total infrared luminosities (IRAS and WISE data) and Ks band luminosities (2MASS) respectively.
- AGN were identified based on multi-dimensional spectral-line diagnostics (40K galaxies in SDSS-DR8; Stampoulis et al. 2019), the works of She et al. 2017, Wang et al. 2018, Ho et al. 1997, and our spectral fits (e.g. Fig. 2).

  This resulted in **650 non-AGN galaxies.**
- We fit scaling relations for the detected sources and the full sample (including non-detections).

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Maximum likelihood fit results

	logLx=α logSFR + σ			$Lx=10^{\alpha}$ SFR $+10^{\beta}$ M_* + σ		
Data	**αα**	**ββ**	**σσ**	**α**	**β**	**σ**
Detections (0.5-8 keV)	0.75 +0.08/-0.02	40.15 +/-0.03	0.52 +/-0.02	40.01 +0.08/-0.04	29.29 +0.19/-0.05	0.63 +/-0.02
Full sample (0.5-8 keV)	0.85 +0.03/-0.15	39.65 +/-0.04	0.73 +/-0.02	39.62 +0.06/-0.21	29.29 +0.05/-0.48	0.84 +/-0.02
Detections (2-10 keV)	0.67 +0.07/-0.03	39.91 +/-0.03	0.56 +/-0.02	39.85 +/-0.11	29.11 +/-0.21	0.75 +0.07/-0.02
Full sample (2-10 keV)	0.55 +0.05/-0.03	39.62 +/-0.03	0.62 +/-0.02	39.59 +0.19/-0.60	29.53 +0.12/-0.77	0.81 +/-0.02

Lx-SFR scaling relation

Plotting the XRB luminosity versus the SFR, we see (Fig. 4) that our results for the full sample of galaxies agree well with previous works. However the fit shows sub-linear behavior, which is driven by a few very bright galaxies in the low SFRs.
This could be the result of observational bias (low-luminosity sources are less likely to be observed / detected) and/or physical effect:
a) A galaxy will appear to be more X-ray luminous if a single bright source (i.e. a ULX) or an AGN is dominating its emission,
b) It could also be a result of significant LMXB contribution, particularly in the low-SFRs.
We argue that most likely this is not the result of significant LMXB contribution, since the fit results remain unchanged when we exclude the LMXB dominated galaxies, and that this result is mostly driven by bright ULXs dominating the X-ray luminosity of these galaxies.

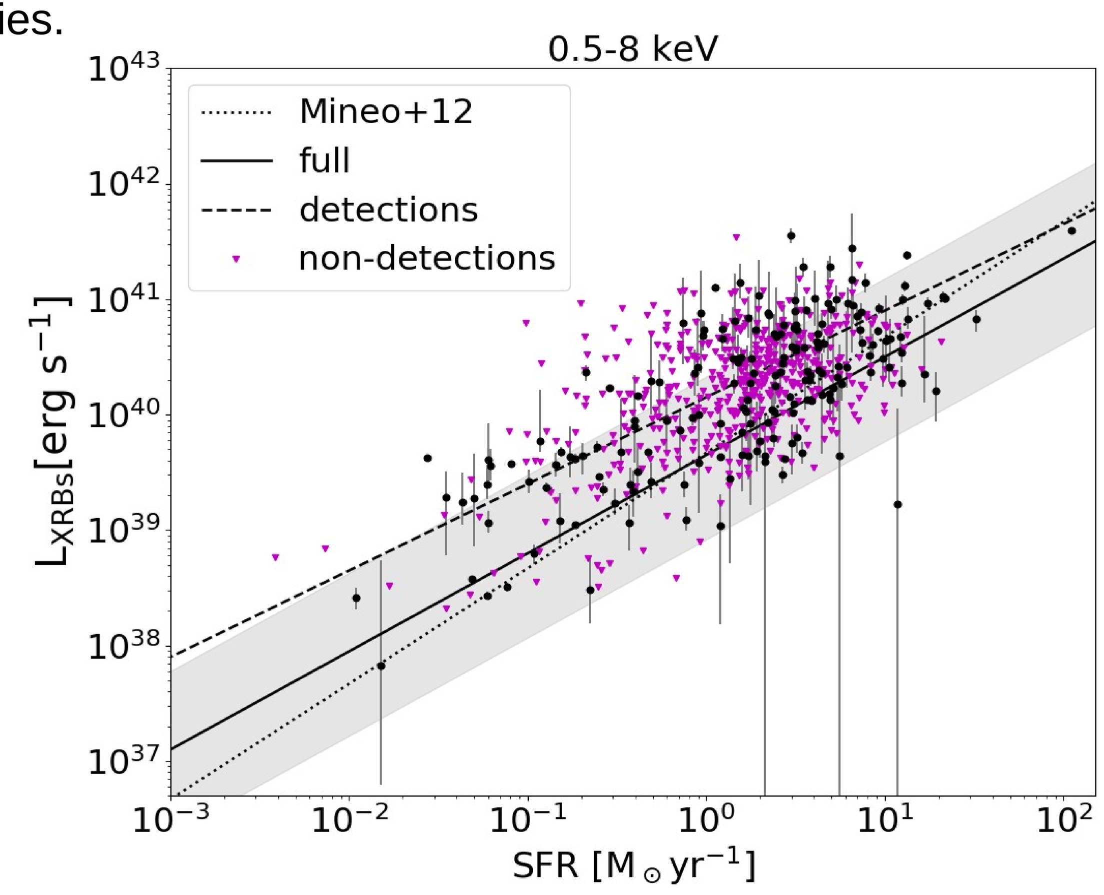

***Figure 4:** Luminosity of XRBs (0.5-8 keV) versus SFR scaling relation. The black line and shaded area indicate our best-fit result for the full sample and its scatter. We also show for comparison the best fit (dashed) line for only the detected galaxies, and the relation (dotted line) of Mineo et al. 2012.*

Lx/SFR-sSFR scaling relation

Plotting the SFR-normalized XRB luminosity against the sSFR, we see that our results for the full sample, as well as for the non-detections, are in close agreement with the reference scaling relation of Lehmer et al. 2016. There are still some galaxies showing an excess which could be the result of very bright sources dominating the X-ray output of the galaxy.

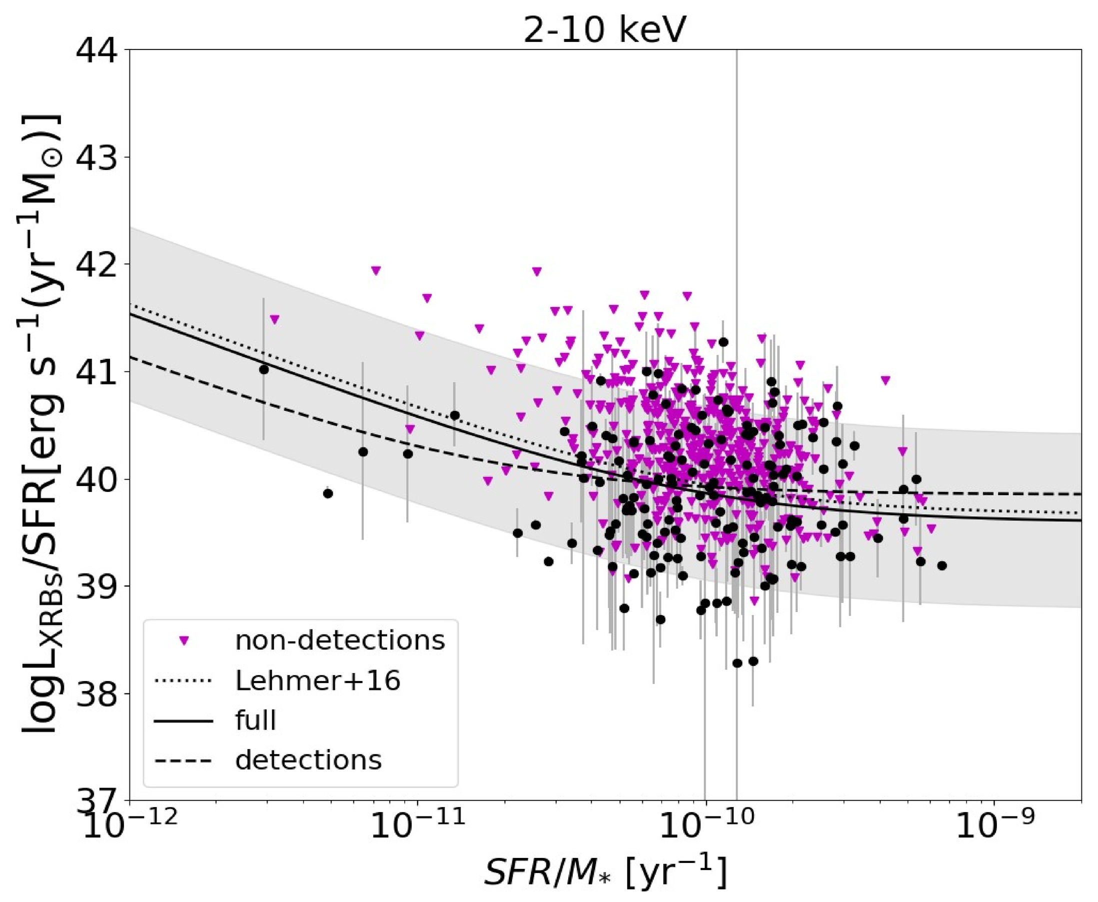

***Figure 5:** Luminosity of XRBs (2-10 keV) per SFR versus sSFR scaling relation. The black line and shaded area indicate our best-fit result for the full sample and its scatter. We also show for comparison the best-fit (dashed) line for only the detected galaxies, and the relation (dotted line) of Lehmer et al. 2016.*

Conclusions

- **We present the most extensive X-ray survey of galaxies in the local Universe.**
- **We measure the correlation of the XRB luminosity with the SFR and stellar mass of the host galaxies for the star forming galaxies.**
- **We find in general good agreement with previous works, but about 2-3 times larger scatter arising possibly from variations of the stellar populations (e.g. metallicity, age), or stochastic sampling of the XRB luminosity functions combined with variability of the luminous sources.**