Two faces of M 31: AstroSat/UVIT counterparts of XMM-Newton sources

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M 31 is a large spiral galaxy that is located in close proximity to our own Galaxy. The well known distance to it and the moderate foreground absorption in its direction makes it an ideal target for source population studies. Its X-ray source population has been intensively studied by *XMM-Newton*.

Based on a recently published catalogue of UV sources detected with *AstroSat*, we identified UV counterparts of X-ray sources in the field of M 31 observed with *XMM-Newton*.

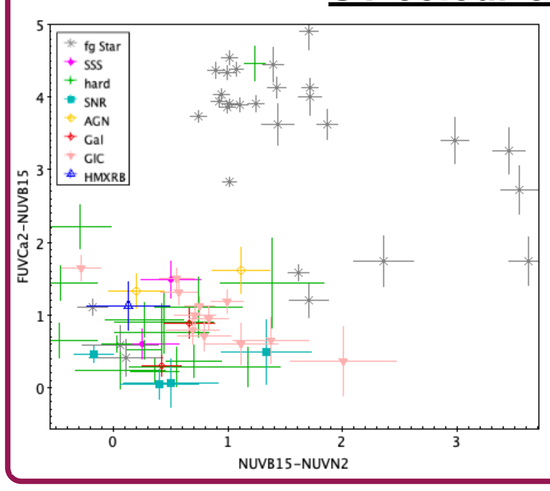
We investigated the UV colours and fitted UV spectra with simple phenomenological models. In addition, we used the X-ray spectral fits of the XMM2Athena project to study the X-ray spectra and see how they evolve with time.

We discuss our results in terms of the different source populations that can be identified in the field of M 31.

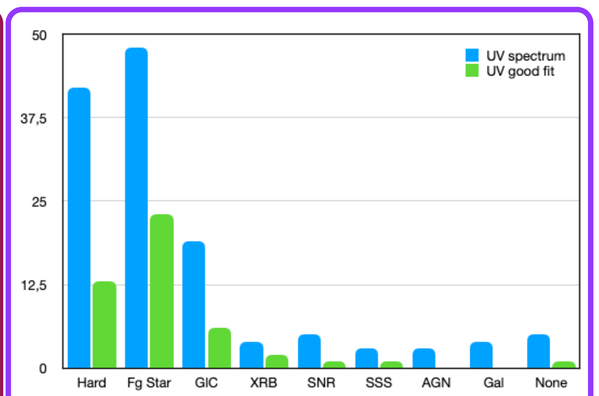
Catalogues

- **The Deep *XMM-Newton* survey of M 31**: 22 fields observed between 2000 and 2008 (some multiple times) covering the entire D_{25} ellipse down to a limiting luminosity of ~10^{35} erg s^{-1}. Energy range 0.2 –12.0 keV in five bands. (Stiele et al. 2011)
- **M 31 UVIT catalogue**: UVIT is *AstroSat*'s Ultra-Violet Imaging Telescope that consists of two 38 cm telescopes covering the far-UV (FUV; 130 – 180 nm) and near-UV (NUV; 200 – 300 nm) in six filters (some overlapping): CaF2 (123–173 nm), BaF2 (135–173 nm), Sapphire (146–175 nm), Silica (165–178 nm), NUVB15 (206–233 nm), and NUVN2 (275–284 nm). 19 different fields to cover M 31; one observation only in one filter ➜ observations spread out in time; most sources only observed in a few filters (Leahy et al. 2020)

UV colour-colour diagram



- UV colour-colour diagram for X-ray sources with UV counterparts
- Upper and right part where at least one colour is ≳ 3 is (almost) exclusively populated by foreground stars
- Behaviour also observed in study of UVIT counterparts of *Chandra* sources (Leahy & Chen 2020)
- Location in colour-colour diagram suggests that source 1502 only classified as „hard" source is most likely a foreground star



Number of sources with UV spectrum and with a formally acceptable fit for different classes

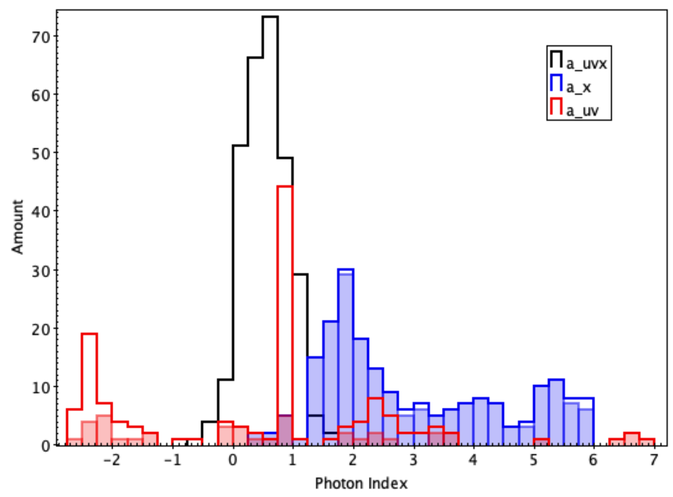
Crossmatching

- More than 99.6 per cent of *XMM-Newton* sources have uncertainties smaller than 10´´
- Position uncertainty of UVIT sources typically les than 1´´
- Correlate *XMM-Newton* catalogue with UVIT source list with maximum correlation radius of 10´´; regard sources as counterparts if positions agree within the X-ray position uncertainty + 1´´
- ➜ 291 counterparts: two sources are detected in five filters, 58 in four filters, 46 in three filters, 116 in two filters, and 117 in only one filter. There are 80 sources that are detected in the FUVCaF2, NUVB15, and NUVN2 bands

Spectral fitting

- **UV spectra** fitted with `Xspec`: two phenomenological models with absorption: power-law and blackbody model
- Only using non-overlapping bands: NUV spectra and FUV spectrum with the broadest coverage (if present): at most three spectral bins
- UV magnitudes transformed to fluxes using:
  $f_i = 10^{0.4*(8.9-ABmag_i)}/(3.34\times10^4 * \lambda_i^2) * \Delta\lambda_i$
  where f_i is the flux in erg s^{-1} cm^{-2}, λ_i the centroid wavelength and $\Delta\lambda_i$ the with of band i in Å
- Absorption in UV spectra is modelled with `redden` model
- Free parameters: for power-law: absorption + photon index & normalisation
  for blackbody: absorption + disc temperature & radius
- In case of only two UV channels: absorption is fixed at foreground absorption in the direction of M 31: 0.21
- **X-ray spectra** used fits provided by the XMM2Athena project (Webb et al. 2023)
- Absorbed power-law parameters for all spectra in the 4XMM-DR11 catalogue (Webb et al. 2020)
- Cross-correlate our source list with XMM2Athena spectral catalogue (Carrera & Stiele 2022) and select all detections
- Average of each spectral parameter for sources with more than one detection with a formally acceptable fit
- Estimation of **UV-X-ray power-law index** by deriving the inclination between the soft X-ray band (0.5 – 2 keV) and the hardest, available UV band:
  $$\alpha_{\rm uvx} = -\frac{\log(f_{\rm xs}) - \log(f_{\rm uvh})}{\log 1.25 - \log(e_{\rm uvh})}$$
  where $f_{\rm xs}$ and $f_{\rm uvh}$ are the flux in the soft X-ray and hardest UV band, respectively, and $e_{\rm uvh}$ is the mean energy of the hardest UV band
- Minus sign in front of fraction ensures that $\alpha_{\rm uvx}$ is consistent with photon index definition in `Xspec`

Distribution of photon indices

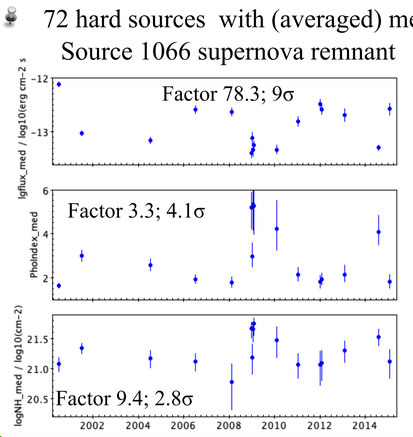


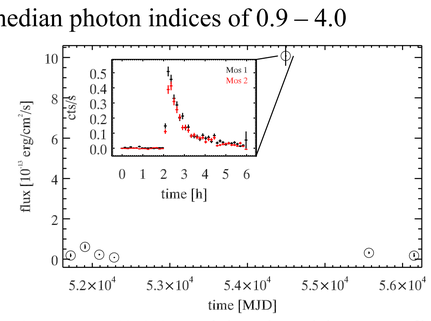
- 133 sources have counts in two or three UV filters
- Statistically acceptable fits with power-law model for 42 sources
- Even for spectra with a few broad bins presence of numerous and/or strong emission and/or absorption lines can lead to an overall spectral shape that cannot be described well with the simple models used here; this includes supernova remnants, AGN, galaxies and certain types of stars
- Photon indices between -3 and 7, where a photon index of -2 corresponds to the Rayleigh-Jeans long wavelength side of a blackbody, while high values can come from the Wien tail of a blackbody
- Non-thermal spectra have a photon index between 0 and 2
- For X-ray binaries in globular cluster UV emission comes most likely from blue horizontal branch stars in the cluster and not from the companion star of the X-ray binary, which is too faint in UV to be detected at the distance of M 31 (Leahy & Chen 2020)
- 206 sources have X-ray spectra in 4XMM-DR11 catalogue
- 199 sources have formally acceptable power-law fits in the XMM2Athena catalogue
- Photon indices lie between 0 and 6, the full range allowed in the fits
- At high values (> 3) mainly supersoft sources, supernova remnants and foreground stars are found
- Source powered by accretion onto a compact object, such as AGN and X-ray binaries, are mainly found at lower values between 1 and 3
- The UV to X-ray photon index shows values between -0.6 and 1.8, where negative values indicate a higher flux in the soft X-ray band than the hardest UV band, while positive values indicate a UV excess compared to the soft X-rays
- 23 sources UV to X-ray photon index agrees with X-ray photon index within errors
- 25 sources UV to X-ray photon index agrees with UV photon index within errors
- Two sources where all three indices agree within errors: a foreground star and a supernova remnant candidate

X-ray properties

- Seven AGN with (averaged) median photon indices of 1.7 – 2.1, except one source (745) that has a photon index of 2.7 with a variability of 3.3σ
- Nine galaxies with photon indices of 0.75 – 4.43
- Eight supernova remnants with photon indices of 2.7 – 5.5, consistent with a source dominated by thermal emission
- Three supersoft sources with photon indices of 3.9, 5.6, and 5.8; values to be expected for soft thermal spectrum
- 24 globular clusters with median photon indices of 0.5 – 2.5; three sources show variable photon index; 14 sources show variable flux
- Four X-ray binaries with photon indices of 1.6 to 2.1
- Three high-mass X-ray binaries with photon indices of 1.6 – 2.0; one with 0.32
- 65 foreground stars with (averaged) median photon indices of 0.75 – 5.96; 87.7 per cent have a photon index ≥ 3; three sources show variable photon index; 4 sources show variable flux
- 72 hard sources with (averaged) median photon indices of 0.9 – 4.0

Source 1066 supernova remnant





Source (960) with the biggest flux variability (factor: 119.7; 19.8σ). Foreground star candidate that shows a strong flare in one observation

Source 1598

- Classified as a possible very faint galaxy by Williams et al. (2018)
- Classified as high-mass X-ray binary candidate by Williams et al. (2014)
- UV spectrum with a photon index of $-2.41^{+0.04}_{-0.05}$
- X-ray photon index of $3.2^{+2.4}_{-2.0}$
- Suggest thermal emission in UV and X-ray bands supporting the galaxy classification

	Identfied	Candidate
Foreground star	32	68
Supersoft source	-	2
Supernova remnant	9	2
Globular cluster	19	6
X-ray binary	1	4
High-mass X-ray binary	-	6
Galaxy	6	6
AGN	6	2
Hard	-	112

Literature

- Leahy & Chen 2020, ApJS, 250,23
- Leahy et al. 2020, ApJS, 247, 47
- Carrera & Stiele 2022, doi:10.5281/zenodo.6599338
- Stiele et al. 2011, A&A, 534, A55
- Webb et al. 2020, A&A, 641, A136
- Webb et al. 2023, AN, arXiv:2303.10097
- Williams et al. 2014, MNRAS, 443, 2499
- Williams et al. 2018, ApJS, 239, 13