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The ULTraS project: Understanding the X-ray variable and transient sky

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Abstract. Time variability is ubiquitous in the X-ray sky and is a unique probe of a wide diversity of astrophysical processes. The aim of the ULTraS (Understanding the X-ray variable and transient sky) project is to exploit the scientific results and products from the EU/FP7-funded project EXTraS (a systematic characterisation of time variability in all XMM-Newton sources) and from its more recent developments. In particular, we have addressed a series of science cases, from the search for rare phenomena to the characterization of the properties of source classes, on a large variety of astrophysical objects, ranging from nearby, ultracool stars to exploding supernovae in distant galaxies. Results described here prove the effectiveness and the potential for discovery of our systematic temporal characterization. A full exploitation of the temporal information in the XMM-Newton/EXTraS archive requires a different approach, based on artificial intelligence – this seems definitely the perspective we should adopt to cope with the high data volume expected from future X-ray facilities.

Key words. Time domain astronomy – Astrophysics - High Energy Astrophysical Phenomena – X-rays: general – Catalogs — Astronomical databases:miscellaneous

1. Introduction

Variability as a function of time is the rule in the soft X-ray sky (from 0.1 to ~ 10 keV). Indeed, temporal domain investigations may offer unique insight about the nature and emission physics of almost any kind of high-energy source. In this paper, and in a companion paper by Israel et al., this issue (the PULSULTraS project), we give details on the main results of a long-term project in which we use temporal variability as a tool to further our understanding of different source classes, based both on the analysis of archival soft X-ray data and on new observing programs. The paper by Israel et al. focus on the search for coherent signals, with particular emphasis on results that changed our view of Ultraluminous X-ray Sources (ULXs). In this paper, we review the results obtained within the ULTraS project on aperiodic, short term variability, mainly based on a systematic data mining approach, with results encompassing a broad diversity of astrophysical sources. This work builds upon the legacy of the FP7 EXTraS project (De Luca et al. 2021), as described in the next section.

2. The EXTraS project, its legacy and its developments

EXTraS (Exploring the X-ray Transient and variable Sky) was a collaborative project funded by the EU (2014-2016) aimed at extracting all temporal domain information in XMM-Newton EPIC archival data, characterizing it and releasing it to the community in an easy-to-use form. EXTraS studied more than 400,000 soft X-ray sources (0.1-12 keV) listed in the 3XMM serendipitous source catalog (Rosen et al. 2016). It featured a search for, and characterization of aperiodic variability, both on the "short-term" (from 1 s to several hours) and on the "long-term" (days to years) time scales; a search for coherent pulsations (period P ranging from the instrument time resolution to several hours); a search for new, faint transient sources, missed by the source detection performed within 3XMM. All XMM-Newton observing time was used in the analysis, also including time intervals usually discarded because of high particle background (about ~ 25% of the overall observing time). All results have been released in a public data archive[1], together with ~ 17 million ancillary files (e.g. light curves, cumulative distributions of rates, power spectra) and the software tools used to generate results and products. A detailed description of algorithms and products is given by De Luca et al. (2021) – see also the project web site[2]. As already stated, we will focus here on aperiodic variability study and characterization.

After the release of the public data archive, further work was performed to improve the EXTraS data analysis pipelines for the study of short-term, aperiodic variability. One of the most important changes was the implementation of a module generating light curves with uniform time binning based on the combination of data collected from all EPIC detectors (i.e. by merging simultaneous pn, MOS1 and MOS2 data whenever available). This, coupled with a number of other improvements related to the selection of source and background regions, resulted in a remarkably higher sensitivity to variability. The updated software is being run on all available EPIC data and scientific exploitation of such an extended database will be pursued in the next future.

In the following sections, we review the main results we obtained from our investigation of aperiodic variability on short time scales. Durations and luminosities of the observed phenomena are displayed in Figure 1. Results described here also serve as examples of different approaches that can be pursued to exploit the huge amount of information generated by EXTraS.

3. An X-ray superflare from an L dwarf

Magnetic activity in stars at the low-mass end of the main sequence is poorly understod. Indeed, detection of white light "superflares" (with energetics exceeding 10^{33} erg) from L

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[1] `http://www.extras-fp7.eu/index.php/archive`

[2] `http://www.extras-fp7.eu/`

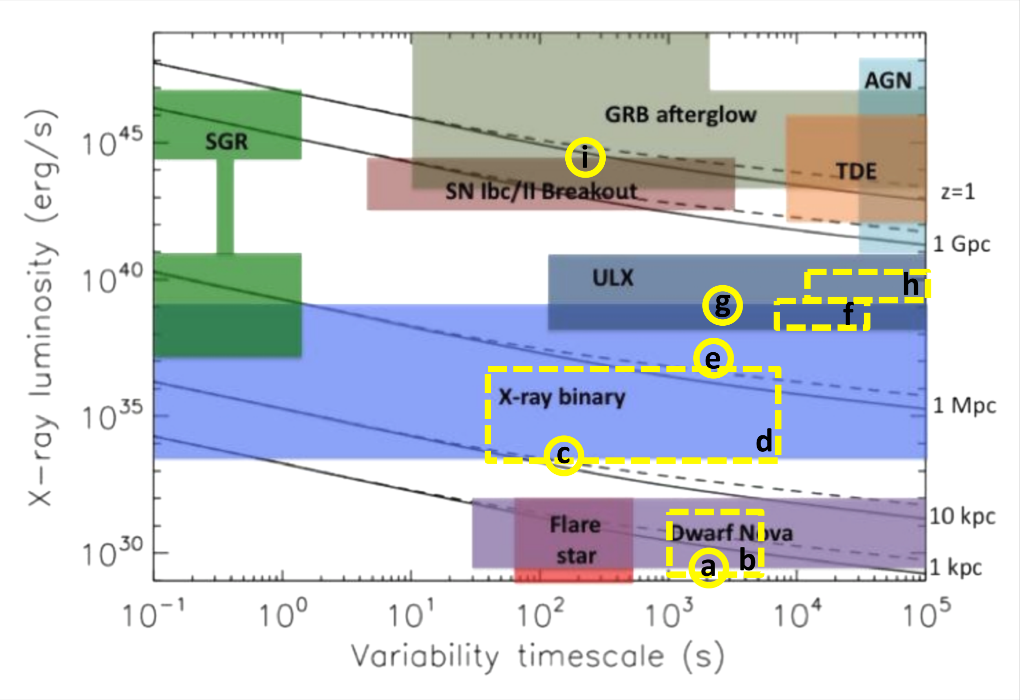

Fig. 1. X-ray luminosity vs. variability time scale for the most important classes of soft X-ray emitters, adapted from Merloni et al. (2012). Black diagonal tracks mark the approximate sensitivity of the EXTraS variability search (at 4σ confidence level, pn only. Solid lines: nominal background conditions; dashed lines: high background time intervals). Yellow boxes and circles mark results described in this paper. a): a superflare from an L dwarf (Sect. 3); b): activity from a sample of A–M class Kepler stars (Sect. 4); c): puzzling flare from the NGC6540 globular cluster (Sect. 5); d): flares from supergiant fast X-ray transients (Sect. 6); e): periodic nova in M31 (Sect. 7); f): recurrent flares from a black hole candidate in NGC4472 (Sect. 8); g): peculiar "heartbeat" oscillations in a ULX in NGC3621 (Sect. 9); h): variability of ULXs in NGC7456 (Sect. 10); i): a supernova shock breakout candidate in a distant galaxy (Sect. 11).

dwarfs came as a surprise, challenging current models, while observation of X-rays from such tiny stars remained elusive (see De Luca et al. 2020, and references therein).

To search for variable X-ray emission from very low-mass stars and brown dwarfs, we cross-correlated the recent catalog of ultracool dwarfs based on the Dark Energy Survey Year 3 Release (Carnero Rosell et al. 2019) with the EXTraS database. This allowed us to select the very interesting case of 3XMM J033158.9-273925 (hereafter J0331-27), matching the position of a candidate L dwarf – the EXTraS light curves of the source clearly display a flare.

As reported in De Luca et al. (2020), J0331-27 lies within the Extended Chandra Deep Field South and a very rich, multi-wavelength dataset is available. An archival VLT/VIMOS spectrum (collected within the *VIMOS VLT deep survey*, Le Fèvre et al. 2005) confirms the spectral type to be L1. The X-ray flare, the first ever detected from an L dwarf, has an overall energetics of 2×10^{33} erg, placing it in the superflare regime. Peak luminosity, flare duration and plasma temperature are similar to the values seen in flares from M-type stars, suggesting no qualitative changes in the properties of the flares for very low-mass stars. No other flares are detected in 2.5 Ms of XMM-Newton data, which is not consistent with the canonical flare energy number distribution $dN/dE \sim E^{-2}$. This suggests that the release of magnetic energy in L dwarfs could occur predominantly through giant flares.

4. Activity and rotation of X-ray emitting Kepler stars

Rotation is one of the fundamental ingredients of magnetism in stars. The relation between rotation and magnetic activity probes the dynamo mechanism and the angular momentum evolution in stars. We investigated this relation using for the first time a homogeneous set of measurements of activity indexes and rotation periods, based on data from the XMM-Newton and Kepler missions (Pizzocaro et al. 2019).

Rotation periods were derived from the study of Kepler light curves. As activity indicators, we measured the X-ray luminosity, the number frequency of white-light flares, the amplitude of the rotational photometric modulation, and the standard deviation in the Kepler light curves. We searched for X-ray flares in the light curves provided by EXTraS, which allowed us to identify simultaneous X-ray and white-light flares.

A careful study of the X-ray sources in the Kepler field, based on multiband photometric characterisation and visual inspection of multi-band images, allowed us to select 102 X-ray emitting, main-sequence stars with spectral types from A to M. We successfully measured rotation periods for 74 stars of this sample (22 of which never measured before). In the X-ray activity/rotation relation, we see clear evidence for the already known distinction of a saturated and a correlated part, the latter with activity continuously decreasing towards slower rotators. We observe an abrupt transition, at a period of ~ 10 d, using the optical activity indicators, but this can be probed only marginally with our sample, biased towards fast rotators due to the X-ray selection. Nine XMM-Newton observations out of the 16 used in our work were carried out during the Kepler monitoring, providing strictly simultaneous optical and X-ray lightcurves. We discovered seven X-ray flares. For all of them there is evidence of a white-light counterpart in the Kepler lightcurves. We derive an X-ray flare frequency of ~ 0.15 d^{-1}, consistent with the optical flare frequency obtained from the much longer Kepler time-series.

5. A puzzling flaring source in NGC6540

A search for short-lived transient emission in EXTraS time series singled out the source 3XMM J180608.9–274553 (J1806-27 hereafter) as a very interesting case. As discussed by Mereghetti et al. (2018), it is well aligned with the Galactic globular cluster NGC6540; the light curve displays a single flare, lasting $<$ 5 minutes, with a symmetric time profile (see Fig. 2). If J1806-27 is indeed associated to NGC6540, the peak luminosity would be $\sim 5 \times 10^{33}$ erg s^{-1}, a factor ~ 40 higher than the quiescent level. The luminosity and duration of the transient defy any easy interpretation as a flare from an active star (binary) or as a burst from a low-mass X-ray binary in NGC6540. Archival Hubble Space Telescope observations also allowed us to rule out the possibility of a foreground, less luminous active star.

Discovery of such unusual transient is related to the investigation of a relatively unexplored region of the parameter space (short flares from relatively weak sources) that was made possible by the systematic temporal analysis performed by EXTraS on a very large sample of XMM-Newton sources.

We note that the light curve of the target was selected within an educational program promoted by the EXTraS team within a workshop for high school students in Italy. Apart from demonstrating the potential of the EXTraS database (and of other public astronomical databases) for education, this story assessed the feasibility of involving non-expert (but trained) people in a complex classification task. Implementation on a larger scale of such an exercise could turn into an interesting citizen science experiment (D’Agostino et al. 2019). The discovery and the active role played

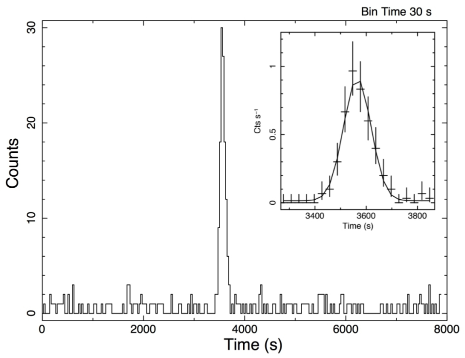

Fig. 2. XMM-Newton light curve of the transient source 3XMM J180608.9–274553 in the globular cluster NGC 6540 (adapted from Mereghetti et al. 2018)). The inset shows a zoom on the peculiar, short flare (see Sect. 5).

by students were the subject of a *News Story* of the European Space Agency[3], and were also included in the weekly *Research highlights* section by the Nature magazine[4].

6. Flares from Supergiant Fast X-ray Transients

Supergiant Fast X–ray Transients (SFXTs; Sguera et al. 2005, 2006; Negueruela et al. 2006) are a sub-class of high mass X-ray binaries where a neutron star accretes wind material outflowing from an early-type supergiant companion (Sidoli 2017). Their outbursts last a few days and are punctuated by short (a few thousand seconds) flares reaching peak luminosities of $\sim 10^{36}$–10^{37} erg s^{-1}. Their X-ray emission outside outbursts is also very variable, displaying short and weak flares with a complex morphology, down to luminosities of $\sim 10^{32}$ erg s^{-1}.

We used EXTraS products to investigate in a systematic way (Sidoli et al. 2019) the aperiodic variability shown by the SFXTs. EXTraS Bayesian blocks segmentation of light curves (De Luca et al. 2021) provided us with a powerful tool to automatically select flares, disentangling multiple and structured ones from the basal X-ray emission, measuring the following important quantities: flare durations, time intervals between consecutive flares, rise and decay times, flare luminosities and emitted energies.

We were able to pick out 144 X–ray flares from a sample of nine SFXTs, spanning peak luminosities from 10^{33} erg s^{-1} to a few 10^{36} erg s^{-1}, with emitted energies from 10^{36} erg to a few 10^{39} erg. The resulting distribution of flare durations peaked around 300–600 s, while the time intervals between flares mainly covered the range 300-5000 s; the distribution of rise and decay times peaked around 30–50 s and 50–100 s, respectively. These flare properties were compared to accretion theory, in particular the quasi-spherical settling accretion model (Shakura et al. 2012). We concluded that the development of Rayleigh-Taylor instability in a quasi-spherical shell above the neutron star magnetosphere can explain the observed properties of the SFXT flares, provided that they are slowly rotating pulsars (in many SFXTs the spin period is unknown).

7. A peculiar nova in M31

As a part of the characterisation of short-term variability in EXTraS, models describing different phenomena were fit to the light curves. We investigated sources in the direction of nearby galaxies, whose temporal behaviour turned out to be well described by eclipse and dip models. We easily selected the case of 3XMM J004401.9+412544 as one of the best eclipsing candidates. The source was detected in the follow-up observation of M31N 2013-01b, a bright optical nova in M31 (Hornoch 2013; Shafter et al. 2013), and is positionally coincident with the optical transient.

Classical Novae are close binary systems featuring a late type main sequence or red giant and an accreting white dwarf (WD) undergoing an outburst triggered by thermonuclear runaway in the hydrogen-rich accreted material

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[3] `https://sci.esa.int/web/xmm-newton/-/60533-students-digging-into-data-archive-spot-mysterious-x-ray-source`

[4] `https://www.nature.com/articles/d41586-018-05959-4`

(Bode & Evans 2008). In Marelli et al. (2018) we showed that the X-ray light curve is complex and clearly displays a periodic behaviour at $P = 1.28 \pm 0.02$ hr (5 cycles being covered by the XMM-Newton observation), with a large modulation (40% pulsed fraction). We interpreted it as the orbital modulation of the nova in the "super-soft phase" (powered by stable hydrogen burning within the accreted envelope, see e.g. Orio et al. 2001), possibly due to partial eclipses. We described in full detail the X-ray and optical/UV properties as derived from analysis of the XMM-Newton observation and of archival Chandra and Swift data. M31N 2013-01b, although not studied before, turned out to be a very interesting system, being one of the brightest and fastest novae (as for the rate of decay of the optical emission) ever detected in M31, with a very short orbital period, one of the few known below the 2–3 hr gap. Such properties support the hypothesis that M31N 2013-01b features a massive white dwarf and a very low-mass companion, consistent with the picture of a nova belonging to the disc population of the Andromeda Galaxy.

8. Recurrent flaring from BH in NGC4472

Prompted by the observation in recent years of different kinds of poorly understood, transient soft X-ray sources with peak luminosities up to $\sim 10^{42}$ erg s^{-1} associated to nearby galaxies (see, e.g. Jonker et al. 2013; Irwin et al. 2016), we selected light curves well described by a flare model for sources positionally consistent with nearby galaxies from the Gravitational Wave Galaxy Catalogue (White et al. 2011). Our search yielded the interesting case of XMMU J122939.7+075333, an ultraluminous X-ray source located in the globular cluster RZ 2109 in the Virgo galaxy NGC 4472, already known to show peculiar variability and proposed as one of the most robust black hole candidates in a globular cluster (Maccarone et al. 2007).

As reported in Tiengo et al. (2022), a careful analysis of all observations performed with XMM-Newton (including time interval previously discarded because of a high particle background) and with Chandra unveiled additional episodes of flaring variability. This suggests a possible regular pattern, the separation of the three most recent X-ray flares being consistent with a $\sim$ 34 hr recurrence time. This, coupled with the soft X-ray spectrum, makes the phenomenon very similar – although on a different range of luminosity – to the peculiar "quasi-periodic eruptions" (QPEs) recently discovered in the nuclei of active and normal galaxies (Miniutti et al. 2019; Giustini et al. 2020; Arcodia et al. 2021; Chakraborty et al. 2021) and possibly also observed in a source in the Galactic globular cluster 47 Tuc (Bahramian et al. 2017). A common property among such different sources is the crowded environment. In view of this, we proposed that the mechanism behind the common, recurrent flaring behaviour could be related to interaction with a star that might perturb a preexisting disk or provide matter through partial tidal disruption. In particular, in Tiengo et al. (2022), we investigated the possibility that XMMU J122939.7+075333 might be powered by the partial disruption of a white dwarf by an intermediate mass ($\sim$ 700 $M_\odot$) black hole.

9. Heartbeats from a ULX in NGC3621

Ultraluminous X-ray sources (ULXs) are a class of non-nuclear, accreting compact objects with X-ray luminosities above 10^{39} erg s^{-1} and up to $\sim 10^{41-42}$ erg s^{-1}. They are the most extreme accreting systems in the local universe, the matter transfer between the companion star and the compact object possibly exceeding the Eddington limit by factors of up to 500. Variability as a function of time is an important probe of accretion physics in such peculiar systems – different scenarios have been proposed, relating variability on different time scales to different phenomena in the accreting system (see e.g. Middleton et al. 2015; Tsygankov et al. 2016). In this and in the following section we will shortly summarize two different investigations of variability properties of ULXs.

We selected sources in the EXTraS short-term variability catalogue aligned with nearby galaxies and we ranked them according to the

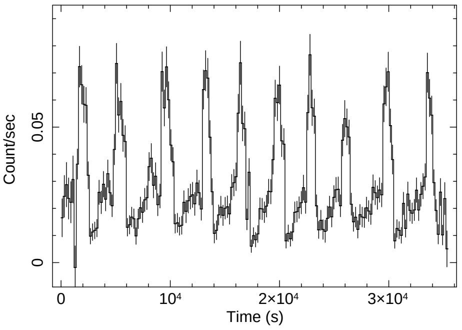

Fig. 3. XMM-Newton light curve of the Ultraluminous X-ray source 4XMM J111816.0-324910 in NGC 3621, combining data collected with all EPIC cameras (0.1-12 keV), adapted from Motta et al. (2020). The peculiar "heartbeat" oscillations are apparent (see Sect. 9).

number of blocks in the Bayesian Block representation of the light curve – a proxy for a complex variability pattern. The source 4XMM J111816.0-324910 (J1118 hereafter) stood up as a very interesting case. J1118 is a transient ULX in the NGC3621 galaxy. As we show in Motta et al. (2020), its light curve in the bright state ($L_X \sim 3\times10^{39}$ erg s^{-1}) displays a dramatic quasi-periodic time modulation at ~ 1 hour, with a factor > 5 variation in luminosity, and a complex, recurrent pattern of variability in flux and spectral shape across the cycle (see Fig. 3, closely resembling the "heartbeat" ρ mode oscillations discovered in the galactic BH binary GRS 1915+105 (see Belloni et al. 2000). This is a rare phenomenon, observed in only 2 Galactic binaries (IGR J17091-3624 and the Rapid Burster, the latter featuring a neutron star, see Altamirano et al. 2011; Bagnoli & in't Zand 2015, respectively) and in QPE sources, such as the peculiar AGN GSN 069 (Miniutti et al. 2019). In the emerging picture, heartbeats are possibly related to radiation pressure limit-cycle instability in the accretion disk. Interestingly, the luminosity and the cycle time scale of the heartbeat in J1118 are intermediate between the ones of the mentioned accreting binaries and those of the supermassive black hole in GSN 069, pointing to an intermediate-mass BH ($\sim 75 - 450\ M_\odot$) hosted in the J1118 system. This interpretation is not in agreement with the spectral analysis, that points to a neutron star accreting well above the Eddington limit, challenging all the theoretical models built to explain the "heartbeat" systems. See Motta et al. (2020) for further details.

10. Properties of the ULXs in NGC7456

Within the context of an XMM-Newton Large Programme devoted to the search for ULX pulsars (more details in the companion paper by Israel et al.), we obtained a deep observation of the NGC7456 galaxy. We performed a complete characterization of the spectral and temporal properties of all ULX detected in the field (Pintore et al. 2020) – variability was assessed by running the EXTraS pipelines. A shorter XMM-Newton observation performed 13 yr before was used to assess the source behaviour on longer time scales.

The main findings reported by Pintore et al. (2020) can be summarized as follows. Two objects turned out to be persistent sources with a luminosity of $5 \times 10^{39} - 10^{40}$ erg s^{-1}. One of them displays a 50% fractional variability on time scales ranging from few minutes to one hour, driven by the high-energy portion of the spectrum. This is one of the largest short-term variabilities ever observed in a ULX. We interpreted the phenomenon as due to an optically thick turbulent outflow, producing variable covering of the inner regions surrounding the compact object (whose nature cannot be constrained), where the high energy emission is produced. Two other sources display a factor ~ 10 flux changes. They can be considered candidate transient ULXs – a property observed in all ULX pulsars (see e.g. Earnshaw et al. 2018). A fifth object is seen in the deepest XMM-Newton observation, with a luminosity of $\sim 10^{39}$ erg s^{-1} and a hard power law spectral shape. Its nature, nor its actual association to NGC7456, remained undetermined.

11. A supernova shock breakout candidate in a distant galaxy

High-energy transients are usually discovered by dedicated instruments, monitoring large portions of the sky. However, in the soft X-rays, telescopes with focusing optics have a much larger sensitivity than large field-of-view instruments and, after accumulating many years of exposure time, serendipitous discovery of rare transient events becomes possible. This was the main driver of the EXTraS search for faint, transient sources, which unveiled 136 objects (De Luca et al. 2021) missed by the standard source detection used to produce the XMM-Newton serendipitous source catalogue.

As we described in Novara et al. (2020), investigation of the basic properties of such transients allowed us to select the case of EXMM 023135.0–603743, the one with the shortest duration (315 s), positionally consistent with a faint, blue galaxy in the SDSS survey. Based on dedicated follow-up observations, we measured the redshift to be $z = 0.092$ and assessed the galaxy to have a low stellar mass ($\sim 2 - 3 \times 10^8$ $M_\odot$) and a high specific star formation rate ($\sim 1 - 2$ $M_\odot$ yr^{-1}). The transient has a temporal evolution consistent with a fast rise, exponential decay profile and a power-law spectrum. The peak luminosity is $\sim 10^{44}$ erg s^{-1} and the overall energetics is $\sim 3 \times 10^{46}$ erg.

The properties of EXMM 023135.0–603743 are very similar to the ones of the X-ray transient associated to SN 2008D in the supernova-rich galaxy NGC 2770 (Soderberg et al. 2008). We interpret the transient as a supernova shock break-out or an early cocoon. Serendipitous discovery of this transient in a field galaxy allows us to derive an unbiased estimate of the rate of such events. Based on extensive simulations, we measure the rate to be broadly consistent with the core-collapse supernova rate by Cappellaro et al. (2015) in the $z < 0.2$ range sampled by our investigation. See Novara et al. (2020) for further details.

12. Classifying EXTraS sources with Artificial Intelligence

Our systematic temporal analysis of XMM-Newton sources resulted in a very large database, with a very high potential for discoveries. Indeed, its size and complexity defy traditional analysis methods. A full exploitation requires an automated data-mining approach for the classification of sources.

As described by Kovacevic et al. (2022), we investigated the full set of characterized sources with an unsupervised classification method. We adopted the Self Organizing Maps algorithm (SOM; Kohonen 1982, 2001), a kind of artificial neural networks which performs both dimensionality reduction and clustering at the same time. This technique identifies groups of sources with similar properties, mapping them out onto a plane.

We applied our SOM on 128,000 detections from the EXTraS short-term variability catalog. Temporal-only parameters were used for the training. The 2500 most variable sources are divided in clusters in the resulting map, based on temporal properties – each group includes sources that appear similar by eye. Different regions of the SOM map turned out to be associated with flares, eclipses, dips, linear light curves, and other kind of temporal features, despite the fact that the method is agnostic with respect to the underlying physics. We easily selected a handful of interesting sources for further study.

Our work proved that the condensed view of the dataset provided by SOMs allows one to identify groups of similar sources, speeding up visual inspection and manual characterization by orders of magnitude. It also proved to be more effective in selecting specific temporal behaviours than standard model fitting to light curves. Statistical approaches like the SOM will be crucial for fully exploiting the high data volume expected from upcoming X-ray surveys, and possibly as an aid in interpreting supervised classification models. See Kovacevic et al. (2022) for further details.

13. Conclusions

The systematic temporal investigation on XMM-Newton sources carried out within the EXTraS project and its recent extensions proved to be very effective, producing the largest sample of X-ray emitters characterized in the time domain (also recovering a large fraction of XMM-Newton observing time usually discarded because of high background). We plan to continue our work by updating our pipelines (e.g. to produce Bayesian block representation of light curves after combining data from all EPIC cameras) and by applying them to more recent data. The astrophysical information disclosed by the analysis is huge and has a potential impact for the study of almost all classes of sources. Different ways of exploitation can be easily attempted, as witnessed by results described in this paper. One can study the temporal properties of a predefined sample of sources; or, search for rare events or peculiar objects using different markers for variability and/or for specific temporal properties. Exploration of such a database is only at its beginning. A full exploitation would require a different, statistical approach based on artificial intelligence algorithms. Different machine learning algorithms could be used to explore and classify sources based on the temporal properties derived from the EXTraS pipelines – this could be completed by other spectral and multiwavelength information provided by other large efforts such as, e.g., the XMM-Newton serendipitous source catalogue (Webb et al. 2020) and the XMM-Newton spectral-fit database (XMMFITCAT[5]). We expect such techniques to become the most powerful approach in the near future, to cope with the growth in size and complexity of datasets that will be collected by forecoming X-ray experiments.

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