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A MULTI-WAVELENGTH STUDY OF THE TRANSIENT SKY

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Abstract. The last three decades have seen the development and launch of numerous X-rays observatories, providing a long temporal baseline to use to search for long term transients and to test new transient detection methods. We present a systematic study of the cross-correlation of 5 different X-rays source catalogs (4XMM-DR10, 4XMM-DR10 Stacked, CSC2, 2SXPS and XMM Slew 2), also taking into account upper limits in the case of non-detections, to search for X-ray sources that have varied over the last 30 years. We also use complimentary multi-wavelength data to identify the sources.

This method has already allowed us to find several variable Ultra Luminous X-ray sources (ULXs), changing-look AGNs, some Hyper Luminous X-ray sources and tidal disruption event candidates. Two major interests of such a method are the wealth of different variable sources that can still be uncovered in the archival data, and the future use of this method in the XMM-Newton pipeline to alert the community in quasi real time to sources undergoing strong variability. This will allow a prompt reaction and follow-up from the community, improving our knowledge of the X-ray transient sky.

Keywords: Methods: data analysis, Catalogs, X-rays: general

1 Introduction

1.1 Variable objects

A large number of astrophysical objects are characterized by some level of variability by their intrinsic luminosity, especially in the X-rays: stars, X-ray binaries, supernovae, ... This variability can either be short-term, meaning that it can be detected within the course of a single 100ks observation, or long-term, requiring multi-epochs observations to be detected.

Among those long-term variable objects, three of them are of particular interest:

- **Tidal Disruption Events (TDEs)**: TDEs (Rees 1988) happen when a star gets so close to a black hole that the tidal forces from the compact object overcome the star's self-gravity and destroy it, resulting in a bright flare lasting about three years (Komossa 2015) and decaying as a power-law, variable over three orders of magnitude in optical. The precise emission mechanisms are still poorly understood, due to the relatively small available sample (Gezari 2021), but are linked to the self-interaction of remaining debris from the disrupted star. One of the most puzzling aspect of TDEs is the lack of simultaneous X-ray and optical counterpart; some TDEs are found in the former wavelength, other in the latter, with no clear explanation for this dichotomy (Saxton et al. 2018). TDEs can also be used to detect otherwise faint black holes, such as Intermediate Mass Black Holes for instance (Greene et al. 2020), improving our knowledge of black holes across the entire mass spectrum.
- **Ultra Luminous X-ray sources (ULXs)**: ULXs (Kaaret et al. 2017) are sources with X-ray luminosities that exceed the Eddington luminosity for a $10M_\odot$ black hole, above 10^{39}erg.s^{-1}. In order for these sources to respect the Eddington limit while being this bright, they were first thought to harbour the elusive Intermediate Mass Black Holes (Colbert & Mushotzky 1999). However, their hard X-ray spectrum (Bachetti et al. 2013) and the discovery of coherent pulsation in M82 X-2 (Bachetti et al. 2014) lead to the conclusion that at least some of the ULXs are in fact neutron stars, in a super-Eddington accretions state. Those Pulsating ULXs (PULXs) are difficult to find, with only 7 of them known (Song et al. 2020). They all appear somewhat variable, on timescales of a few months and over two orders of magnitude, leading to the use of X-ray variability as a proxy to find PULXs candidates (Webb et al. 2014; Song et al. 2020).

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- **Changing Look Active Galactic Nuclei (CLAGNs)**: CLAGNs are AGNs that undergo spectral changes between different observations. These changes are generally explained by a change in absorption due to clouds of dust traversing the line of sight; this translates into the appearance or disappearance of optical spectral lines, and changes in the soft X-ray component. Understanding these objects and their variability will help us improve our knowledge of the environment of black holes and thus their formation.

These three types of sources, while physically distinct, have some common aspects. They are rare; and as a consequence, the physical phenomena behind them are poorly understood. Thus, increasing the size of our samples might allow us to improve our knowledge of these phenomena.

1.2 Transient astronomy

To study all those events, a number of projects have been put into place in the field of time-domain astronomy: high return-rate optical campaigns with the Vera C. Rubin observatory (Ivezić et al. 2019), gravitational wave transients with the LIGO-Virgo-Kagra collaboration (Abbott et al. 2018), or multiple full-sky surveys in X-rays with eRosita (Predehl et al. 2007).

The *XMM-Newton* data processing pipeline, on the other side, has not been built with the direct objective of finding transient events. Indeed, a 1-year proprietary period ensures that the data from an observation is only available to its P.I. during this time. If a transient event was serendipitously observed in this field of view and was missed by the P.I., the community would need to wait at least a year for the data to be made public, and then wait for someone to find this transient and organize a follow-up observation. This means that the second observation, whether with *XMM-Newton* or as a part of a multi-wavelength follow-up, can only take place so late that the transient will most likely be already over.

It thus appears relevant to develop a way for the *XMM-Newton* data processing pipeline to automatically detect transient events and, with the prior agreement of the PI, publish this information in quasi-real time.

2 Our method

In order to detect transient events, one needs to get as many flux measurements for each source as possible. We have implemented different methods to reach this goal.

2.1 Cross catalog correlations

The first point of our method is to perform systematic cross-correlations between several X-ray catalogs. Indeed, comparing data from different epochs obtained with different instruments can reveal long-term variation in the flux of sources. We have selected 5 different catalogs from 3 instruments, with complementary properties, depicted in Table 1: 4XMM-DR10 (Webb et al. 2020), CSC 2.0 (Evans et al. 2020a), 2SXPS (Evans et al. 2020b), XMMSL2 (Saxton et al. 2008), 4XMM-DR10s (Traulsen et al. 2019). The first three are the basic catalogs for the observatories *XMM-Newton*, *Chandra* and *Swift* respectively, while the last two catalogs correspond respectively to the sources detected during the slews between each pointing of *XMM-Newton*, and to the sources only detected when stacking all overlapping *XMM-Newton* observations.

Catalog	Number of Sources	Sensitivity	Spatial resolution	Coverage
4XMM DR10	575 k	+	+	=
CSC 2.0	300 k	++	++	–
2SXPS	200 k	=	=	+
XMMSL2	30 k	–	–	++
4XMM DR10 Stacked	90k new sources	+	+	=

Table 1. A comparison between the major available X-ray catalogs, showing their respective strengths (shown with + or ++ signs) and weaknesses (shown with – signs).

The correlations were computed at first with pairs of catalogs, using the 3σ position errors and the TopCat software (Taylor 2005). We also took into account the astrometry error between catalogs; for this purpose, we looked at the distance distribution for all the matches between two catalogs, which should look like a Rayleigh distribution with an excess at long distances due to spurious associations, and took the peak of the Rayleigh distribution as an estimate of average astrometry error. This method was used for instance to estimate ROSAT's position errors (Boller et al. 2016).

Once the 2-by-2 correlations were computed, we merged them into Master Sources, that could group up to 5 catalogs and should correspond to unique astrophysical sources. We took a conservative approach, by rejecting any ambiguous associations, in order to avoid spurious correlations that would lead in the end to erroneous high variability.

We have then correlated these Master Sources with additional catalogs to provide multi-wavelength information, such as the *XMM-Newton* Serendipitous Ultraviolet Source Survey catalogue (Page et al. 2012) that contains all the sources detected by the Optical Monitor aboard *XMM-Newton*, or the galaxy catalog GLADE (Dálya et al. 2018).

2.2 Upper limits computations

Correlations between detected sources can help us retrieve a large number of data points; but non-detections also provide valuable information. Indeed, a known source in a given catalog that was observed but not detected by another telescope means that its flux was below the sensitivity level of the second telescope; this flux upper limit can sometimes be enough to conclude on the otherall variability of the source.

To this effect, we used the *RapidXMM* framework (Ruiz et al. 2021) to systematically compute *XMM-Newton* flux upper limits on every Master Source that lies in the *XMM-Newton* footprint, whether or not it was detected by it.

2.3 Quasi real-time transient alert system

Cross-catalog correlations and flux upper limits allow to enhance our knowledge of long-term evolution of X-ray sources. This can be used to dig into the 20 years of existing data, as will be shown in 3; it also allows to develop a real-time alert system, by comparing the existing Master Sources to the new detections and updating the variability of any matching Master Source. To assess the effectiveness of this method, we took two random months of *XMM-Newton* observations and sent alerts for any source with an overall 3σ variability of over a factor 3. We then identified by hand every alert, to estimate the rate of false positive alerts.

3 Results

3.1 Master sources catalog

The main outcome of our method is a catalog comprised of all Master Sources, that encompasses all 5 X-ray catalogs. This gives a total of 1 million Master Sources, 10% of them having sources in at least 2 different catalogs. An additional 325 000 *XMM-Newton* upper limits were computed using *RapidXMM*.

This method has generally allowed us to increase the long-term variability of the Master Sources, compared to those of their constitutive catalog sources, which is a confirmation of the effectiveness of our method. This large catalog, encompassing multi-wavelength and multi-epoch information, needs to be exploited in a systematic fashion. This work is still ongoing, and will be the object of a future publication; but several highly variable objects have already been uncovered, including a new highly transient ULX candidate.

3.2 NGC 7793 ULX-4

Using our method, we have discovered a new candidate pulsating ULX, NGC 7793 ULX-4 (Quintin et al. 2021). This source was only detected once by *XMM-Newton*, despite having been observed more than a dozen times. Its transient nature was revealed once the *Swift* detections, as well as both *Chandra* and *XMM-Newton* flux upper limits, were taken into account (see Figure 1). As explained in Section 1.1, variability is a hint at the presence of a neutron star and therefore possible pulsations, and we did manage to find a candidate pulsation in the X-ray signal at 3.4σ significance, making this ULX a candidate for the 8^{th} PULX.

3.3 Alert system early results

Our alert system was tested on the course of 2 random months of *XMM-Newton* data and revealed about one transient a day, with most of them being stellar flares or variable AGNs. Out of those alerts, about 75% of them are serendipitous detections, which confirms the usefulness of our method.

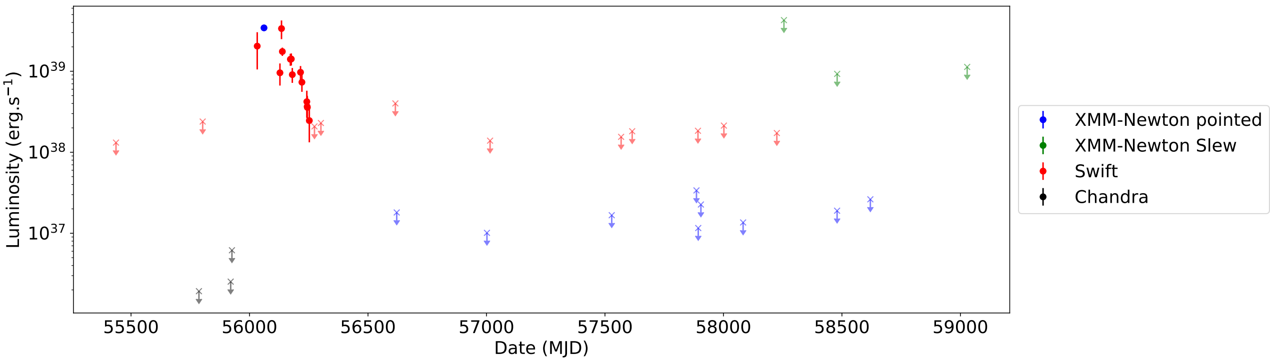

Fig. 1. Long-term multi-instrument lightcurve of NGC 7793 ULX-4, with detections depicted with dots and upper limits with downwards arrows. This reveals the transient nature of the object. Figure from Quintin et al. (2021).

4 Conclusions

Our work has been focused on improving the synergy between 5 existing X-ray catalogs by cross-correlating them and taking non-detections into account. This allows for a quasi-real time transient alert system, intended for the *XMM-Newton* data processing pipeline. The tests on two random months of data have confirmed the efficiency of this method, with a low number of false positives and a majority of serendipitous transients.

In the future, we intend to implement this code within the *XMM-Newton* pipeline, and anticipate the creation of synergy with both *LSST* and *Athena* data for a multi-wavelength study of transient events.

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