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X-RAY VARIABILITY-SELECTED SOURCES IN THE GALACTIC PLANE

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Abstract. The Galactic Center and Galactic Plane are host to large numbers of highly variable X-ray sources, many of them stellar remnants. The exact nature of the X-ray variability, and the sizes of their populations are unknown in many cases, but could give important important insight useful for our understanding of stellar evolution pathways. The STONKS pipeline identifies transient, and highly variable, X-ray sources in *XMM-Newton* observations. By applying this pipeline to the recently completed multi-year survey of the Galactic Plane conducted by *XMM* we have identified a new population of highly variable X-ray sources in the direction of the Galactic centre. These variability-selected sources, include a new magnetar candidate, several new CV candidates, new X-ray binary candidates, and a γ-Cas analogue displaying coherent pulsations.

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

1 Introduction

The X-ray sky is rich in variable phenomena, which offer opportunities to probe some of the most extreme astrophysical events. To provide the energy for X-ray emission, in a variety of sources (including stars, stellar remnants, and AGN), we require extreme physical conditions, often including strong magnetic or gravitational fields. Instabilities in these extreme environments can invoke temporal and spectral changes which then provide key information regarding these extreme environments. A survey of the Galactic plane allows us to detect a variety of variable X-ray sources, including objects at all points of stellar evolution. Examples of highly variable sources we expect to detect in the Galactic plane include:

Main sequence stars emit X-rays as the result of magnetic reconnection events in their coronae (e.g. Favata & Micela 2003) driven by their rotation. Flares from these events have timescales of the order of hours, while longer, year-long, cycles can affect the X-ray emission by orders of magnitude (Orlando et al. 2001).

Young Stellar Objects (YSOs) display significant variability from magnetic activity (Montmerle et al. 1993). This coronal activity is similar to that in main sequence stars, but there are also features in their X-ray emission which may be due to shocks from accretion or outflows, or fluorescence from an irradiated disk (Güdel & Nazé 2009). This X-ray emission can reach several orders of magnitude greater than that seen from main sequence stars (Stelzer 2017), and large variations in the X-ray luminosity can be observed between observations.

Cataclysmic variables (CVs) are powered by accretion onto white dwarfs. Many CVs will display pulsations caused by the rotation of the accreting white dwarf (e.g. Kuulkers et al. 2006; Mukai 2017), but these may be averaged out over the course of typical X-ray observations. More significant, and longer lasting, variability can be observed in CVs over several orders of magnitude due to changes in the accretion flow on to the white dwarf through the disc.

X-ray binaries are powered by accretion onto stellar mass black holes or neutron stars. Binaries fed by low-mass donors can display highly variable outbursts (e.g. Remillard & McClintock 2006) in accordance with the disk instability model. Binaries with high mass donors can vary as a result of the variable winds from the high mass companion (e.g. Fornasini et al. 2023). As outbursts can last for several weeks or months they present a prime target for detection by STONKS, allowing for prompt follow-up while still bright.

Neutron star-powered X-ray sources can also display significant shorter term variability. Type-1 X-ray bursts (Lewin et al. 1993), caused by runaway thermonuclear burning on the surfaces of neutron stars, with

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durations on the order of $\sim 10 - 100$ s. Neutron stars with very strong magnetic fields, magnetars, can display further variability as a result of those magnetic fields. Giant flares have durations of the order ~ 100 s, and luminosities up to $L_X \sim 10^{47}\,\mathrm{erg\,s^{-1}}$ (e.g. Cline et al. 1980). While these phenomena are too fast to allow for follow-up after detection, the identification of them enables them to then be monitored for further variability. Outbursts in magnetars, when they brighten by one or two orders of magnitude (Coti Zelati et al. 2018) are followed by a decay in their luminosity on the order of weeks or months, and can be followed-up if swiftly identified through STONKS.

1.1 STONKS Pipeline

Several, recent, X-ray observatories have been designed for the detection of variable X-ray sources, including the *Neil Gehrels Swift* Observatory, and the Space-based multi-band astronomical Variable Objects Monitor (SVOM). These missions use wide fields of view to maximize the likelihood of detecting transient events. Our analysis employs the Search for Transient Objects in New detections using Known Sources (STONKS) pipeline (Quintin et al. 2024). This pipeline is based upon a multi-mission catalogue of X-ray sources compiled by cross-matching catalogues of X-ray sources observed by *XMM-Newton*, *Swift*, *Chandra*, *ROSAT*, and *eROSITA*. After collation, flux estimates are obtained for all detections of each source in the range from 0.1–12 keV, assuming an absorbed power law spectrum with $\Gamma = 1.7$ and $N_H = 3 \times 10^{20}\mathrm{cm}^{-2}$. Upper limits are also obtained for non-detections in *XMM* pointed and slew observations. The variability of a new detection of a source is computed pessimistically as a ratio by taking the lower 1σ uncertainty below any high flux values, and the upper 1σ uncertainty above any low flux values. Only sources with a variability $V \geq 5$ will be used to trigger alerts. The long exposure times of pointed *XMM-Newton* observations allow for observers to identify sources which are significantly variable with fluxes several orders of magnitude below those observable to survey missions. As of the AO24 proposal cycle, STONKS is now being applied to all *XMM-Newton* observations, with alerts shared with principal investigator and, with their prior approval, with the community (`http://flix.irap.omp.eu/stonks`).

2 Methods and Data

This analysis concerns all of the Multi-Year Heritage Programme observations of the Galactic Plane conducted by *XMM-Newton* between 13th March 2021 and 10th October 2024. A total of 230 observations were recorded and the pipeline performed source detection on 212 of these.

2.1 Classification

The X-ray sources which trigger alerts were classified to determine the nature of the variability. Sources were classified by examination of features in X-ray data, from new and archival detections, and using multi-wavelength information. In the Galactic plane we expect the majority of alert sources to fall into a small number of categories, associated with Galactic X-ray sources: Star, Young Stellar Object (YSO), Cataclysmic Variable (CV), X-ray binary (XRB).

X-ray lightcurves and spectra were examined using either the pre-created *XMM-Newton* processing pipeline products, or by reprocessing the raw event data. We visually inspected the lightcurves on a range of scales, and where appropriate, we also attempted to identify periodicities in source event lists using the `stingray` (Huppenkothen et al. 2019) module for `python`.

Multi-wavelength information was obtained from the SIMBAD Astronomical Database and X-ray source locations were also queried through VizieR to obtain optical counterparts in the *Gaia* DR3 catalogue (Gaia Collaboration et al. 2016), near IR counterparts in the *2MASS* All-Sky Catalog of Point Sources (Cutri et al. 2003), and mid-IR counterparts in the *AllWISE* data release (Cutri et al. 2021).

Finally, we also considered previous classifications of X-ray sources in the *XMM-Newton* and *Chandra* archives using machine learning. We searched for previously detected sources in the 4XMM-DR12 catalogue (Webb et al. 2020) as classified by CLAXBOI (Tranin et al. 2022), and those sources with previous *Chandra* detections in the *Chandra* Source Catalog Release 2.0 (Evans et al. 2024) as classified by MUWCLASS (Yang et al. 2022).

3 Results

From the 212 observations with detected sources there were 142 alerts; they were screened and 64 were rejected as observational artefacts. The 78 true alerts were classed as: 25 - First Detection; 29 - High Flux State; 15 - Low Flux State; 9 - Past Variability. These 78 alerts were associated with 70 sources, with six sources being observed in multiple fields. The alert sources were well distributed across the survey area, as shown in Fig. 1.

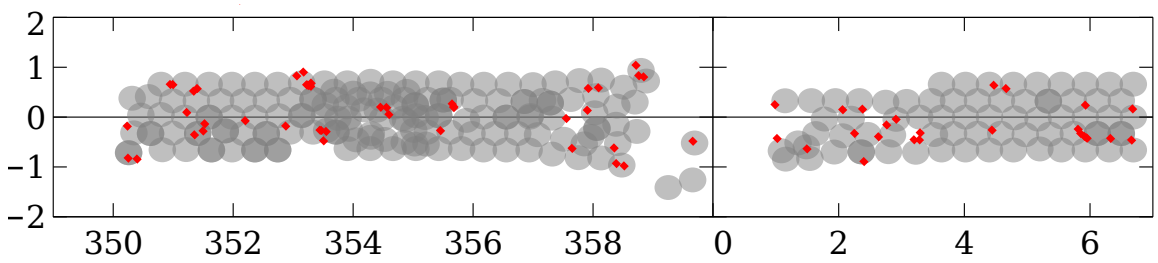

Fig. 1. Locations of alerts within Galactic Plane observations in galactic coordinates. Alert sources are indicated by red diamonds overlaid on observations presented as grey circles.

The 70 Alert Sources were referenced and cross-matched with multi-wavelength catalogues. Of these, 25 had SIMBAD associations with STONKS variable sources: 11 - Star; 5 - YSO; 2 - X-ray source; 2 - X-ray binary; 2 - IR source; 2 - Radio source; 1 - Cataclysmic variable. A significant minority (44%) of these SIMBAD associations are for stars, with a small number of others in expected Galactic transient classes. We identified counterparts with *Gaia*, *2MASS* or *AllWISE* to 49 of the 70 alert sources, with 35 of those having a counterpart in at least two bands.

By comparing X-ray and multi-wavelength information for the 70 highly-variable sources we were able to identify 38 with confident classifications, as: 21 - Stars (inc. 1 RS CVn star); 7 X-ray binaries, including 1 HMXB, 4 CVs, 4 YSOs, 1 γ-Cas analogue, 1 Magnetar candidate. Of these, 13 stars, 5 X-ray binaries, 3 cataclysmic variables, 1 young stellar object, and the magnetar candidate were not previously identified as such.

3.1 New Magnetar candidate - 4XMM J175136.8-275858

Among the 70 highly-variable sources one was classified as a new magnetar candidate, 4XMM J175136.8-275858 (4XJ1751-2759). It was identified as being in a high flux state, and an examination of the lightcurve identified a fast, significant, increase in brightness within the last 5 ks of the observation, with the increase in countrate coming at photon energies above 2 keV. We show this in Figure 2.

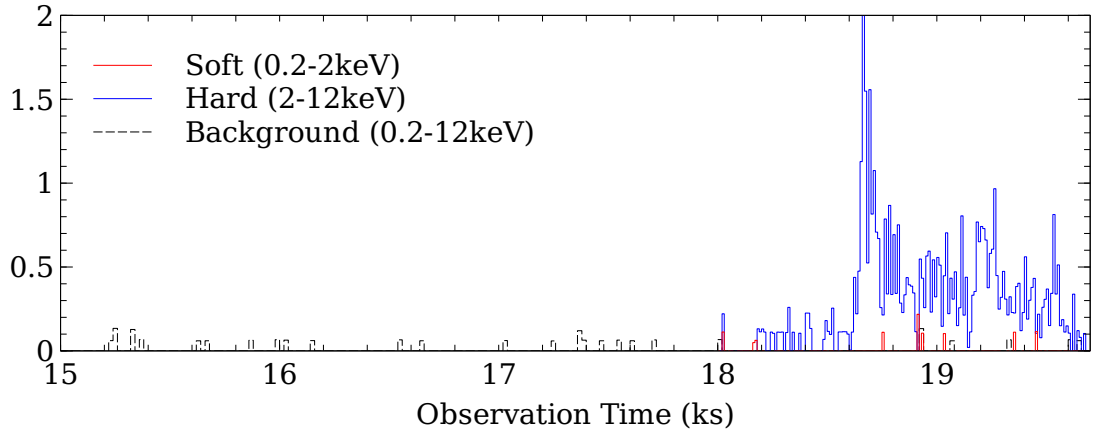

Fig. 2. Energy dependent behaviour of the magnetar candidate 4XJ1751-2759 during the outburst detected. The red and blue lines show the soft (0.2-2keV) and hard (2-12keV) band emission respectively against the background (black dashed line).

There were two further *XMM-Newton* and three *Chandra* observations with 4XJ1751-2759 in the field of view of during the twelve months around the outburst. During one of the *Chandra* observations it was not detected with a constraining upper limit. During the outburst the flux of 4XJ1751-2759 increased by nearly two orders of magnitude within a period of a few hours, and was still higher by a factor of ∼2 than the initial level nearly six months later. The spectrum of 4XJ1751-2759 was well described by a combination of blackbody components, but with a blackbody temperature, albeit unconstrained, of 200 keV during the outburst. Fitting to spectra of the other observations revealed blackbody temperatures between ∼1–4 keV, consistent with those seen in the known magnetar XTE J1810-197 at a similar time after an observed outburst (Borghese et al. 2021).

A search for pulsations in the X-ray observations did not return a significant result, but this does not preclude a magnetar classification as they simply may not be detectable in the current observational data. The full details of the temporal, spectral, and multi-wavelength analysis of this source can be found in Webbe et al. (2025).

4 Conclusions

We have presented an application of the STONKS pipeline for the detection of highly variable X-ray sources to an *XMM-Newton* survey of the Galactic plane. The pipeline processed the source lists from 218 observations and produced 142 alerts for variable sources. Screening for observational artefacts resulted in the identification of 78 true alerts for variability associated with 70 sources. The high number of spurious alerts is due to the crowded nature of the Galactic Plane, with many bright sources. These sources were classified through considering a combination of: X-ray variability within observations; X-ray spectral fitting; previous X-ray source detections; optical, and near- and mid-IR detections. This approach allowed for the detection with firm classification of 38 of the 70 sources, including a new magnetar candidate, and several new XRB and CV candidates. The population of CV candidates identified are located at greater distances than those routinely selected in optical surveys.

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