Exploring rapid transient detection with the Athena Wide Field Imager

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Abstract. X-ray transients are among the most enigmatic objects in the cosmic sky. In recent years, the unpredictability and underlying nature of their transient behavior has prompted many studies. While significant progress has been made in this field, a more complete understanding of such events is often hampered by the delay in the rapid follow-up of any transient event. An efficient way to mitigate this constraint would be to devise a way for near real-time detection of such transient phenomena. The Advanced Telescope for High-Energy Astrophysics/Wide Field Imager (Athena/WFI), with its \(400 \times 400\) field of view and large effective area, will detect a large number of x-ray variable or transient objects daily. We discuss an algorithm for the rapid onboard or ground-based detection of x-ray transients with WFI. We present a feasibility test of the algorithm using simulated Athena WFI data and show that a fairly simple algorithm can effectively detect transient and variable sources in typical Athena WFI observations. © 2020 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: 10.1117/1.JATIS.6.3.038002]

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1 Introduction

A wide variety of astronomical phenomena characterized by changes in flux and spectrum are seen at all cosmological distances and at all time scales ranging from fractions of a second to decades. In the high-energy part of the spectrum (x-rays and \(\gamma\)-rays), this variability is seen in objects ranging from nearby galactic compact objects to galactic nuclei at large redshifts. X-ray observatories in space are constantly collecting scientifically interesting information on these variable and transient sources, which is stored in data archives. With a few exceptions [such as the Burst Alert Telescope (BAT) instrument on the Swift satellite and the Monitor of All-sky X-ray Image (MAXI) instrument on the International Space Station (ISS)], long delays—often days to weeks or even months—occur before transient objects are discovered in ground analysis, by which time the transient event has often died down and cannot be investigated in detail at other wavelengths.

The launch of x-ray spacecrafts, such as Fermi,1 MAXI,2 and Swift /BAT,3 which survey large regions of the sky, has been a huge asset to facilitate near real-time reporting of such transient events. The BAT instrument, in particular, detects bright transient sources onboard and transmits key data to the ground within seconds. Once a time-critical event is acquired from these facilities, there are formal networks, such as The Astronomer’s Telegram (ATEL),4 Astrophysical Multimessenger Observatory Network (AMON),5 and the Gamma-ray Coordinates Network/Transient Astronomy Network (GCN/TAN),6 that help disseminate the information to a wider astronomical audience for their follow-up. There have also been serendipitous discoveries of these transient phenomena from x-ray spacecrafts, such as Chandra, X-ray Multi-Mirror Mission (XMM)-Newton, or Ginga, which often get lost in archival data and are often discovered weeks or months later. Examples include the discovery of a peculiar flaring source

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J1806-27 in NGC 65407 and flares from ISO-Oph 85, both discovered more than a decade after they were first observed by XMM-Newton. Such discoveries are made possible by dedicated efforts such as the EXTraS project, aimed specifically at searching the XMM-Newton archive for transient phenomenon.

In the 2030s, XMM-Newton will be succeeded by the Advanced Telescope for High-Energy Astrophysics (Athena), as European Space Agency (ESA)’s large space observatory for the exploration of the x-ray sky. Composed of a microcalorimeter [X-ray Integral Field Unit (X-IFU)] for imaging x-ray spectroscopy with high spectral resolution, and a wide field (40’ × 40’) x-ray survey instrument [Wide Field Imager (WFI)], Athena will revolutionize the field of x-ray astronomy. Especially important for the sake of x-ray transient science is the surveying capability of WFI, which we briefly mention below.

The WFI consists of two independently operated detectors, a large detector array and a separate small “fast” detector, with both detectors based on DEPFET active pixel sensor technology. The energy range of operation is 0.2 to 15 keV with a spectral resolution of <170 eV at 7 keV. The large detector array consists of four detectors of 512 × 512 pixels spanning the 40’ × 40’ field of view (FOV), while the small detector is 64 × 64 pixels and will be operated out of focus, i.e., without imaging capability, to minimize pile-up and optimize throughput performance for bright point sources. The WFI is thus designed to provide good surveying capability because of the wide FOV and large grasp for performing wide-area surveys, low pile-up for bright sources, and absolute temperature and density calibration for in-depth studies of the outskirts of nearby clusters of galaxies. It also has high count-rate capability paired with good spectral resolution, for detailed explorations of bright galactic compact objects and excellent sensitivity for low luminosity active galactic nucleus (AGNs) at high redshifts.

To maximize the science gains for transient science, we have proposed to contribute a transient analysis module (TAM), to the WFI instrument. The TAM is a software module that could perform onboard transient source detection from the real-time detector data stream. Alternatively, a similar algorithm could perform rapid transient detection in the ground data processing pipeline.

In this paper, we discuss the science enhancement achievable with the TAM and a simple baseline algorithm for onboard transient detection. The paper is organized as follows. We discuss the science benefits in Sec. 2 and outline the algorithm in Sec. 3.1 with proof of concept in Sec. 3.2, followed by a summary in Sec. 4.

## 2 Wide Field Imager Transient Science

The sensitivity limit of Athena/WFI is as low as $1 \times 10^{-17}$ erg cm$^{-2}$ s$^{-1}$, and the effective area is $\sim$30 times that of Chandra. We find that Simulation of X-ray Telescopes (SIXTE) simulations of the Chandra Deep Field South (CDFS) field yield $\geq$3000 sources per Ms pointing (Sec. 3.2) as compared to $\sim$100 to 200 with Chandra and XMM-Newton. We can estimate the number of variable sources using Swift data: the Swift/XRT Serendipitous Source catalog records $\sim$28,000 variable sources over 8 years, yielding a detection rate of $\sim$10/ day at a median sensitivity of $3 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$. Athena/WFI has $\sim$100\times the sensitivity and $\sim$3\times larger FOV compared to Swift/XRT; a simple scaling of $\log(N) - \log(S)$ and FOV suggests thousands per day in the WFI.

In this section, we elaborate on the science benefits achievable by rapid transient detection with WFI. We begin with the science enhancement of known transients science in Sec. 2.1, while the next section expands on the prospects of unknown transients in Sec. 2.2, followed by a section on discovery science in Sec. 2.3.

### 2.1 Known Transients

Among a wide variety of x-ray transients, in this section, we provide estimates of the probability of serendipitous detection of such transients in each class, taking one source as a representative for each class. We begin by assuming that a total of 100 counts in some characteristic time scale ($\delta t$) is considered a “detection,” the characteristic time scale being defined as the time during
which the transient is flaring/variable. We choose such a large detection threshold because we wish to obtain some information on the spectrum and variability of each source. Assuming a Crab spectrum, the fluence ($F$) corresponding to 100 WFI counts is $2 \times 10^{-11}$ erg cm$^{-2}$. The flux ($F$) to get 100 counts in $\delta t$ s for each source is therefore $(2 \times 10^{-11})/\delta t$ erg cm$^{-2}$ s$^{-1}$.

For each source, we first note the flux measured by present (or past) x-ray instruments, $F_0$, and the flux $F$ required for the WFI to attain 100 counts in a characteristic time. The ratio $F_0/F$ then gives us an improvement in luminosity distance, $I = \sqrt{(1+z)}$, where $z$ is the source redshift and $z_{100}$ is the redshift limit at which this source would produce 100 WFI counts in $\delta t$ s. We then calculate the enclosed volume $V$ (comoving volume at redshift $z_{100}$) corresponding to $z_{100}$.

(For our rate estimates, we take the upper limit of a Crab spectrum, the fluence ($F$) corresponding to 100 WFI counts in $\delta t$ s for each source is therefore $(2 \times 10^{-11})/\delta t$ erg cm$^{-2}$ s$^{-1}$.)

We note that the source rates throughout the paper do not account for cosmological effects, including corrections for spectral redshifts ($k$-corrections), cosmic time dilation, or source evolution over cosmic time scales. Our purpose is to make rough estimates of the probability of detecting sources of different classes, but we leave such corrections to a more detailed analysis.

We now go on to introduce each class of sources, taking one representative example of each class, and also discuss the probability of detecting the variability in each one of them. We also estimate the improvement in depth achievable with WFI. These values are tabulated in Table 1.

- Galactic compact objects: The galactic compact objects comprise white dwarfs, neutron stars, and stellar black holes, either in binary systems or in isolation. They often exhibit variability: for instance, owing to changes in accretion, thermonuclear burning causing type I/II bursts, state changes in black holes, or magnetar flashes. The time scales are varied, ranging from milliseconds to a decade. For instance, in the case of the magnetar SGR 1900 +14, Burst and Transient Source Experiment detected outbursts with a characteristic time...
The table summarizes the probability of detecting different types of x-ray transients with Athena/WFI, using known transients as exemplars. We have assumed a galaxy density ($\rho$) of $4 \times 10^{-3}$ per Mpc$^{-3}$, $H_0 = 75.0$, $\Omega_M = 0.30$, $\Omega_{\Lambda} = 0.70$, and a WFI duty cycle ($f_{\text{WFI}}$) of 40%. The first line for each source provides the source name, characteristic timescale of flares, $\delta T$, the fluence $F$, and flux $F_0$ of a typical observation, applicable parameters ($r, n_{\text{src}}, R_{\text{Dsl}}$, $\alpha$, and $N_\delta$). The second line for each source gives the limiting fluence of $2 \times 10^{-11}$ erg cm$^{-2}$ and flux detectable by WFI for 100 counts in $\delta T$; $l$ as the improvement in luminosity distance with $l = \sqrt{\frac{1+z_{100}}{1+z}}$, where $z$ is the current redshift of each source and $z_{100}$ would be achievable with WFI ($L$ indicates local universe); enclosed volume ($V$), where applicable and the rate of detection with WFI per year. The equations used for source rate calculation and the source rates are shown in the last column. See Sec. 2.1 for details.

| SRC            | $\delta T$ (s) | Reference | $F$ (erg cm$^{-2}$) | Flux (erg cm$^{-2}$ s$^{-1}$) | $l$ | Reference | $z_{100}$ | $R_{\text{WFI}}$ (yr$^{-1}$) | $V$ (Gpc$^3$) | Using Eq. (1) |
|----------------|----------------|-----------|---------------------|-------------------------------|-----|-----------|-----------|-----------------|----------------|----------------|
| Magnetar       | 0.040          | 19        | $4 \times 10^{-8}$ | $1 \times 10^{-6}$            |     |           |           | 2$^y$r$^{-1}$   | 20             | 40             |
| SGR 1900+14    | $2 \times 10^{-11}$ | 5 $\times 10^{-10}$ | 45                  |                               |     |           |           |                               | $L$             | $<1$           |
| SFXT           | 200            | 21        | $2 \times 10^{-5}$ | $1 \times 10^{-7}$            | $2^y$r$^{-1}$   | 20        | 40                 |                               |                               |                |
| IGR J17544-2619| $2 \times 10^{-11}$ | $1 \times 10^{-13}$ | 1000                |                               | 11             | $<1$      |                               |                               |                |
|ULX M82         | 100,000        | 22        | $1 \times 10^{-6}$ | $1 \times 10^{-11}$          | 23, 24          |           |                               |                               |                |
|                |                |           | $2 \times 10^{-11}$ | $2 \times 10^{-16}$          | 224            |           |                               |                               |                |
| Jetted TDE     | 100,000        | 25        | $2 \times 10^{-5}$ | $2 \times 10^{-10}$          | 26             |           |                               |                               |                |
| SW J1644+573   | $2 \times 10^{-11}$ | $2 \times 10^{-16}$ | 1000                |                               | 3048          | 11        | $<1$              |                               |                |
| "Faint" TDE   | 100,000        | 27        | $3 \times 10^{-8}$ | $3 \times 10^{-13}$          | 26             |           |                               |                               |                |
| NGC 3599       | $2 \times 10^{-11}$ | $2 \times 10^{-16}$ | 40                  |                               | 11             | $<1$      |                               |                               |                |
| "Bright" TDE  | 100,000        | 28        | $1 \times 10^{-7}$ | $1 \times 10^{-12}$          | 26             |           |                               |                               |                |
| SDSS J120136.02+300305.5 | 2 $\times 10^{-11}$ | $2 \times 10^{-16}$ | 71                   |                               | 1700          | 5         | 75                |                               |                |
### Table 1 (Continued).

| SRC          | $\delta T$ (s) | Reference | $F$ (erg cm$^{-2}$) | Flux (erg cm$^{-2}$ s$^{-1}$) | $I$          | Reference | $z_{100}$ | $R_{\text{DWE1}}$ (yr$^{-1}$) |
|--------------|----------------|-----------|---------------------|------------------------------|--------------|-----------|-----------|-------------------------------|
| Supernova    | 200            | 29        | $14 \times 10^{-8}$ | $7 \times 10^{-10}$           | $10^{-4}$ Mpc$^{-3}$ yr$^{-1}$ | 30        |           |                               |
| 2008d        | 2 $\times 10^{-11}$ | 1 $\times 10^{-13}$ | 85                  |                              |              |           | 23        | 0.5              | 10                          |
| GRB 060124   | 100            | 31        | $7 \times 10^{-6}$  | $7 \times 10^{-8}$           | $100$ to $1800$ Gpc$^{-3}$ yr$^{-1}$ | 32        |           |                               |
|              | $2 \times 10^{-11}$ | $2 \times 10^{-13}$ | 590                  |                              |              |           | 3048      | 11              | 1 to 24                      |
| FSRQ         | 100,000        | 33        | $12 \times 10^{-7}$ | $12 \times 10^{-12}$         | $4 \times 10^{-7}$ Mpc$^{-3}$ yr$^{-1}$ | 34        |           |                               |
| 3C 279       | $2 \times 10^{-11}$ | $2 \times 10^{-16}$ | 245                  |                              |              |           | 3048      | 11              | 5                           |
| BL Lacertae  | 40,000         | 35        | $1.5 \times 10^{-5}$ | $3.7 \times 10^{-10}$        | $2 \times 10^{-7}$ Mpc$^{-3}$ yr$^{-1}$ | 34        |           |                               |
| Mrk 421      | $2 \times 10^{-11}$ | $5 \times 10^{-16}$ | 860                  |                              |              |           | 3048      | 11              | 3                           |
| FRB 121102   | 3.2$^b$        | 36        | $1 \times 10^{-9}$  | $3 \times 10^{-10}$          | $10^9$ Gpc$^{-3}$ day$^{-1}$ | 37 and 38 |           |                               |
|              | $2 \times 10^{-11}$ | $6 \times 10^{-12}$ | 7                    |                              |              |           | 123       | 1               | >1000                       |
| CDF-S XT2    | 100            | 39        | $6 \times 10^{-11}$ | $6 \times 10^{-13}$          | $1.8 \times 10^3$ Gpc$^{-3}$ yr$^{-1}$ | 39        |           |                               |
| (or NS-NS merger) |           |           |                      |                              |              |           | 214       | 1.3             | 2                           |

| $S$ | $\alpha$ | $N_0$ | Using Eq. (3) |
|-----|---------|-------|--------------|
| XRT110103 | 10 | $8.7 \times 10^{-10}$ | $8.7 \times 10^{-11}$ | $3/2$ | 40 | $4 \times 10^{-10}$ yr$^{-1}$ | 2 |
|      |       | $2 \times 10^{-11}$ | $2 \times 10^{-12}$ | 7   |     |                           | 578 |

$^a$Typical values.

$^b$Chandra readout time during the observation.
scale ($\delta t$) of 40 ms.\textsuperscript{19} The probability of serendipitously detecting magnetars such as SGR 1900+14 yielding 100 counts in this 40 ms is inevitably very low. However, the important consideration is the improvement in detection depth of 45 times with WFI compared to its actual distance, since WFI can detect a flux that is only 0.05% of its actual flux, allowing us to probe deeper for magnetars than any other x-ray spacecraft so far. Similarly for the case of the supergiant fast x-ray transient (SFXT) INTEGRAL (IGR) J17544-2619 (known for quiescent emission most of the time interrupted by sudden flares), WFI could detect this object 1000 times farther away, delving into a new discovery space.

- Ultraluminous x-ray sources (ULXs): These x-ray sources have Eddington luminosities larger than that of stellar-mass objects, ranging around $10^{39}$ erg s$^{-1}$. These are thought to result from beamed emission from x-ray binary systems containing a heavy neutron star or an intermediate black hole. The variability in ULXs is often attributed to changes in the accretion rate and lasts from a few ks to years.\textsuperscript{41,42} Taking ULX M82\textsuperscript{22} as a typical example, we would be able to detect 100 counts in 100 ks at a distance of $\sim$224$\times$ farther than ULX M82 in the local universe.

A significant fraction of ULXs exhibit transient pulsations that are often detected during their “high” state, possibly because of low counts captured during normal flux states. The excellent sensitivity of Athena will enable pulsation searches and investigation of propeller effects in ULXs, even in their normal flux states.\textsuperscript{43}

- Tidal disruption events (TDEs): TDEs\textsuperscript{44} occur when the tidal forces exerted on a star upon close approach to a massive black hole overcome its self gravity and pull it apart. If we consider 100 counts being detected in 100 ks in a jetted TDE such as Swift J1644+573,\textsuperscript{25} we will detect these events across the whole observable universe. “Normal” nonjetted TDEs, such as NGC 3599 and SDSS J120136.02+300305.5, will be detected to significant cosmological distances, up to redshifts of 5 for the latter. If we take SDSS J120136.02+300305.5 as being representative, we estimate that WFI would detect $\sim$75 per year.

- Core collapse supernovae (CCSNe): CCSNe are spectacular explosions that mark the violent deaths of massive stars. These events are the most energetic explosions in the cosmos, releasing energy of order $10^{51}$ ergs. The supernova shock breakout lasts for hundreds of seconds. For CCSNe such as SN2008D with $\delta t$ of $\sim$200 s,\textsuperscript{29} we will detect $\sim$10 per year and up to 85$\times$ farther than SN2008D.

- Gamma-ray bursts (GRBs): GRBs\textsuperscript{45} are extremely energetic explosions that can last from ten milliseconds to several hours. If the event is less (more) than 2s, it is termed a short (long) GRB. After the initial flash in $\gamma$-rays, a longer-lived afterglow—lasting typically from hundreds of seconds to days or weeks—is emitted at longer wavelengths.\textsuperscript{46} In the case of the long GRB 060124, where the Swift BAT triggered on a precursor and the Swift XRT, therefore, measured the entire x-ray light curve of the prompt emission, the brightest part of the x-ray emission lasted for $\sim$100 s.\textsuperscript{31} Considering the improvement in the luminosity distance, WFI could detect this burst even at the farthest redshift of $z_{100} = 11$. We expect to serendipitously detect $\sim$1 to 24 GRBs per year with the WFI.

- AGN: An AGN\textsuperscript{47} is a compact region at the center of a galaxy that is very luminous, emitting $10^{40}$--$47$ erg s$^{-1}$. The radiation from an AGN is believed to result from the accretion of matter by a supermassive black hole at the center of its host “active” galaxy.\textsuperscript{48} Three important classes of AGN are (i) the Seyfert galaxies, which have modest luminosities but are best studied since they are relatively close; (ii) the quasars, which are more luminous than the host galaxy and are particularly numerous at a redshift of $\sim$2; and (iii) the blazars, including BL Lacs as well as flat spectrum radio quasars (FSRQs) and optically violent variables, seen when our line of sight lies close to the direction of a jet. The x-ray variability in AGNs, caused either by accretion rate or environment change or jets, lasts from minutes to months. In the case of blazars, if 100 counts are to be detected in a typical 100 ks observation, we will detect $\sim$5 such flares from blazars similar to the FSRQ 3C 279 or $\sim$3 from Mrk 421-like BL Lacs, anywhere in the observable universe. Of course, different thresholds of detection and different variability timescale probes would produce different rates of blazar flare detection. Although there have been extensive studies of AGN...
variability, new discoveries continue to intrigue the astrophysics community. For instance, x-ray variability characterized by short, high-amplitude, quasiperiodic x-ray bursts over a rather stable baseline flux, termed quasiperiodic eruptions (QPEs), was recently observed for the first time in GSN 069. Such variability, possibly caused by instabilities of the accretion flow, is reminiscent of “heartbeat” oscillations seen in BH binaries, such as GRS 1915+105 and can be explored by Athena to much lower flux levels than current observatories.

The TAM algorithm will detect variability on time scales of few kiloseconds or less. To illustrate the utility of this capability for studying AGN, we investigate the variability on timescales of ks in the long-term Swift BAT observations of Mrk 421. The Swift light curve [Fig. 1(a)] was divided into segments spanning 4 h. We then calculated the percentage of variability change in the weighted average in one observation to the next. A histogram of the percentage of variability is shown in Fig. 1(b). The figure shows that there are hundreds of such cases where the percentage change over 4 h is significant.

In addition to the compact region x-ray variability discussed so far, noncompact region variability from nearby luminous galaxies subtending at least tens of arcseconds can also be detected. However, the 5-arc sec point spread function (PSF) of the Athena mirrors will not be sufficient to explore x-ray lensing of quasars and galaxies, which require subarcsecond spatial resolution.

- Fast radio bursts (FRBs): FRBs are transient pulses discovered in the radio band, characterized by large dispersion measure and timescales of milliseconds. Their origins are unclear; possible explanations include giant SGR flares or coalescing compact objects (for example, see Ref. 52). While most FRBs are transient in nature, at least two (FRB 121102 and FRB 180814.J0422+73) have repeated outbursts. For typical event rates of FRBs as $10^4$ sky$^{-1}$ day$^{-1}$ and FRB distribution of $10^4$ Gpc$^{-3}$ and assuming that the typical x-ray flux is equal to the upper limit found for FRB 121102 during its Chandra observation, we could detect more than 1000 such FRBs per year with WFI. However, we caution that since no FRBs have yet been detected in x-rays, this number is highly uncertain. (If x-ray bursts from SGR 1935+2154 is associated with an FRB, its source detection rate and improvement in distance, using x-ray flux and δT from Neutron star Interior Composition Explorer, are of similar order for the magnetar SGR 1900+14 derived here.)

![Fig. 1](image-url) (a) Long-term Swift/BAT light curve of Mrk 421 with 4-h integration times per data point. The inset shows two random time segments between which variability is calculated. (b) Histogram of the percentage change in count rate for the Swift/BAT light curve of Mrk 421 between successive data points.
2.2 Unknown Transients

A new type of fast x-ray transients has been found in Chandra data. These exhibit x-ray and multiwavelength properties unfamiliar to known x-ray transients discussed in Sec. 2.1. The first detection, named XRT 000519 [Fig. 2 (a)], showed a double-peaked light curve.\textsuperscript{56} This transient was found close to M86 in the Virgo cluster and the flux increased from being undetected to a peak Chandra count rate of 20 counts s\(^{-1}\) in 10 s, decayed gradually in 20 s to \(\sim\) 1 count s\(^{-1}\), and rose again to count rate of 24 counts s\(^{-1}\). The second peak had a flat top lasting around 20 s before gradually decreasing on a timescale of about 100 s, followed by a power-law decay with index of \(-0.3\) for 20 ks until the observation ended.\textsuperscript{56} Possible mechanisms include the disruption of a compact white dwarf star by an intermediate black hole, but alternative scenarios such as a foreground neutron star accreting an asteroid or an off-axis (short) \(\gamma\)-ray burst are also possible. Similar light curve behavior was also found for XRT 110103, although it did not exhibit a precursor nor a twin peak in the main flare and was a factor of a few fainter compared to XRT 000519.\textsuperscript{40} With an all sky distribution of \(1.4 \times 10^5\) yr\(^{-1}\) sky\(^{-1}\) with flux \(S > 2 \times 10^{-10}\) erg cm\(^{-2}\) s\(^{-1}\),\textsuperscript{40} and assuming a log \(N\)-log \(S\) distribution, \(N(S) = N_0 S^{-\alpha}\), with slope \(\alpha = 3/2\), we would detect \(\sim 2\) XRT 110103 like events per year with WFI.

Another fast transient is XRT 120830 [Fig. 2(b)]. The count rate increased by 3 orders of magnitude from the background level reaching a peak and rapidly decayed by more than an order of magnitude. This rise and decay occurred in \(\sim 10\) s. The transient continued to decay further with some marginally significant flaring events \(\sim 7\) and 14 ks after the main burst. The flare from XRT 120830 could be an x-ray flare from a late \(M\) or early \(L\) dwarf star with possible minor flares \(\sim 7\) and 14 ks after main flaring related to the rotation period of the star.\textsuperscript{40}

The x-ray event named CDF-S XT1 [Fig. 2(c)] produced \(\sim 115\) net counts in Chandra, with a light curve characterized by a \(\sim 100\) s rise time and a power-law decay time slope of \(\sim -1.53\).\textsuperscript{57} There have been speculations of the origin of its transient behavior as an orphan x-ray afterglow from an off-axis short-duration GRB, a dimmer and farther GRB, or a beamed and less variable TDE wherein an intermediate black hole is engulfing a white dwarf. However, none of the above scenarios can completely explain all observed properties of this x-ray flare.\textsuperscript{57}

Another peculiar x-ray flaring source was found near the galaxy NGC 4697, where two brief, ultraluminous flares (separated by 4 years) were seen. These flares were characterized by a flux increase of a factor of 90 in about 1 min.\textsuperscript{58} Since only two such examples were detected among several thousand x-ray point sources within 70 Chandra observations of nearby galaxies, it is plausible that the Milky Way has no analogs to these sources. Given the small number (\(\sim 40\)) of x-ray sources in the Milky Way brighter than \(10^{37}\) erg s\(^{-1}\), lack of x-ray binaries more luminous than \(10^{38}\) erg s\(^{-1}\) in galactic globular clusters, and rarity of burst sources in the extragalactic sample, a detection of only two seem right. The nature of these sources remains largely uncertain, and rapid multiwavelength follow-up of such detections is probably the only way to probe the nature of such erratic transients. That requires rapid identification of these sources either on the spacecraft or in rapid ground processing.

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**Fig. 2** Light curves for different Chandra transients. (a) XRT 000519,\textsuperscript{56} (b) XRT 120830,\textsuperscript{40} and (c) CDF-S XT1.\textsuperscript{57} The variability behavior of such transients are currently unexplained by any known transient behavior. See text for details.
We also note that, although the transients discussed already are widely categorized as fast x-ray transients, each type of transient is unique in its variability behavior. The latest discovery is named CDF-S XT2 and is speculated to be an aftermath of an NS–NS merger. The probable rate of detecting CDF-S XT2 type events (and potentially similar NS–NS mergers that have similar event rates) with WFI is nearly 2 year$^{-1}$.

Overall, the CDF-S transients are speculated to be either a part of an unexplored regime for known transient class or a new variable phenomenon whose nature is unknown. The potential for discovery science from these onboard triggers is therefore significant. Athena will be in a much better position to characterize the light curves in detail and probe fainter (and perhaps more abundant) versions of these transients, and will strongly benefit from rapid multiwavelength follow-up to help constrain their physical nature.

2.3 Discovery Space and Synergy with Other Facilities

As discussed earlier, WFI will have the capability to probe into parameter space not explored by any x-ray observatory to date. This will undoubtedly open new avenues for discovery science, allowing us to delve into an unexplored regime of the x-ray universe. Many excellent AGN targets for Athena will be within the Large Synoptic Survey Telescope (LSST) sample and spectroscopy of the first quasars from Euclid, Wide Field Infrared Space Telescope, and LSST.

While our main focus of this paper is to demonstrate the usefulness of an onboard or ground-based rapid transient detection system in Athena/WFI, it is worthwhile to consider some of the multiwavelength studies obtainable by the synergy between Athena and other observatories in the 2030s (e.g., Athena Multimessenger and High Energy Astrophysics Synergy, by Piro et al.). Athena will be operating in an era of deep multiwavelength extragalactic surveys such as the LSST. Given its wide FOV, the LSST is capable of imaging its field of regard in 3 to 4 nights; LSST will, therefore, observe millions of AGNs during its operation.

Athena observations will likely be complementary to LSST, since optical surveys detect very luminous AGNs while Athena will be useful to uncover the x-ray emission of “fainter” AGNs at high redshifts to constrain the seeds/processes that led to the early growth of SMBHs. Athena and the Square Kilometer Array (SKA) will also have excellent synergy for studying objects in very different energy regimes. While the survey strategy for SKA and WFI may have room for a planned overlap for observing similar regions in sky, one needs to keep in mind that the SKA will typically have better (subarcsecond) angular resolution than Athena. Targets will therefore have to be carefully selected taking this into account. There have already been combined efforts to investigate the science enabled by the SKA and Athena surveys. These include a large range of astrophysical topics, from the very first stars and galaxies to transients at all timescales.

Important multimessenger synergies also exist between Laser Interferometer Space Antenna (LISA) and Athena. LISA will localize gravitational wave emission from any point on the sky; Athena will be able to observe locations provided by LISA and observe x-rays from the surrounding gas of the newly born black hole. Recent studies have shown that $\sim 10$ BH binaries in the mass range of $10^5$ to $10^9M_\odot$ discovered by LISA at $z < 3.5$ can be detected by Athena in 100 ks, for a prompt x-ray emission of $\sim 1\%$ to $10\%$ of the Eddington luminosity.

With its unparalleled capabilities, Athena in the 2030s will therefore be a transformational observatory, operating in tandem with other observatories spanning wide electromagnetic spectrum with SKA, Atacama Large Millimeter/submillimeter Array, Extremely Large Telescope, James Webb Space Telescope, and Cherenkov Telescope Array and large efforts to plan for this science are already under way.

3 Methodology

The primary aim of the TAM is to generate alerts about transient activity, either for detection of new transients or for variable behavior for known sources. In this section, we will discuss in stepwise the algorithm we developed for the case of onboard detection, followed by the proof-of-concept of this algorithm. While it currently appears that this module will not be included in the WFI instrument, a similar capability is under consideration for the WFI ground
processing pipeline. As we show below, this onboard processing is feasible with modern flight computers, and this capability could be considered for other x-ray telescopes in the future.

3.1 Outline of the Algorithm for Onboard Transient Detection

The stepwise implementation of the algorithm is demonstrated by the flow chart shown in Fig. 3. We emphasize that this proof-of-concept algorithm was developed to show that onboard transient detection is feasible within the computing constraints of the WFI instrument and was tailored to demonstrate compliance with a set of requirements from the WFI team.

The algorithm begins with the detection of transients with the WFI onboard Athena (s1 in Fig. 3). We then check in step two (s2) whether the count rate for this detection is above a specified threshold chosen to be 30 counts here. (We also successfully demonstrated the algorithm efficacy by assuming a threshold of 50 counts as chosen by the WFI team for these tests.) This is important since we would only want to send onboard alerts for the most interesting/bright objects for their follow-up. Depending on whether the source matches with any source position in the onboard catalog or not (s3), the subsequent steps either proceed in the downward vertical direction as branch 1 (b1) or in the horizontal direction as branch 2 (b2). If the position of the detected transient matches with the onboard catalog, it is a known source; if it is brighter than the catalog flux (b1-1), or if it is variable during the observation (b1-2), we have detected variability.
in a known source, and we flag this source (b1-3) and generate science products, such as light
curves in several energy bands, hardness ratios, and a periodogram (b1-4). Branch 2 starts if the
detected transient does not match with the onboard catalog (i.e., s3). We then check whether the
flux for this detected transient is above the catalog limit (b2-1). If it is, the source is bright and
qualifies as a variable/transient (b1-3), which subsequently leads to production of science prod-
ucts in step b1-4. In any case, if the source does not match with any known source, we flag it as
new (b2-2) and update the onboard catalog with the information from this new detected source
(b2-3). The onboard catalog is also updated when the flux of a known source is dimmer than its
catalog value (b1-1 to b2-3). We note that the algorithm shown is designed to detect transients
that grow more luminous than their normal state. However, the algorithm can easily be modified
to also detect source “dimming.”

The utility of onboard alerts is, however, inevitably dependent on the frequency of the sat-
ellite’s contact with the ground station. The current mission strategy for Athena is a single
ground pass of 4 h per day (Arne Rau, private communication at WFI consortium meetings).
While the daily ground pass produces a latency of up to 20 h for distribution of onboard alerts to
the community, the 4-h window permits real-time alerts with <1-ks latency about 16% of time.
These prompt transient alerts will facilitate multiwavelength observations, thereby allowing us a
unique opportunity to investigate these enigmatic objects in many wavelengths simultaneously,
as discussed in Sec. 2.

3.2 Testing of Algorithm: Proof-of-Concept

To provide a demonstration of the algorithm outlined above, we created simulated WFI data sets of
1 ks duration using SIXTE.66 We used the Lehmer et al.66 catalog of sources from the extended
CDFS to simulate a typical field of x-ray background sources, and included the effects of spacecraft
dither with the attitude file “CDFS_lissajous_80ksec.att” (available on the SIXTE website). To this
simulated data set, we added six transient sources of varying intensities with their light curves and
spectra taken from XMM-Newton observations, either in the flaring phase or quiescent emission.

In the first step of the algorithm, s1 (Fig. 3), the algorithm does a blind source detection,
using “wavdetect” with a false-positive probability threshold (sigthresh) of $10^{-10}$, background
significance threshold of $10^{-6}$, and wavelet scales of (2.0 and 4.0). We provided a PSF file giving
the Athena WFI PSF size for each image pixel. For step 2 (s2), we set the threshold for detection
to 30 counts. Step s3 then compares the position of the detected sources with the ones in the
Lehmer catalog. If the angular difference between a detected source and a catalog source is less
than a conservative value of 7 arc sec, we consider it a match, and the algorithm proceeds to the
step (b1-1) where we compare the count rates between the source and the catalog. If the source
rate exceeds the catalog rate, a transient has been detected and we proceed to step b1-4 where
the science products (light curve, hardness ratio, and periodogram) are extracted. The sources
detected by this exercise are shown in Fig. 4(a).

To test the algorithm performance for sources in the direction of a bright background source
such as a galaxy cluster or supernova remnant, we also checked how many sources are detected
while including a large x-ray background of 400 counts/ks/source region (each source region
being the average of background region obtained from wavdetect during source detection,
$\sim$250 pixels). We have intentionally chosen a high background rate to ensure that the observa-
tions were background dominated, to bound the problem in two cases: without/with background.
The histogram for source detection with the background is shown in Fig. 4(b). Even with such a
large background, the brighter sources are still detectable by WFI.

Next, to ensure that we are indeed measuring the variability in detected sources, we inserted
15 more artificial test sources with light curves shaped as Gaussians, square waves, pulses, step
functions, or sine waves, with each light curve shape having one source each with $\sim$30, 50, or
100 counts in total. The spectral shape for all these light curves was assumed to be Crab-like.
We also inserted one source with the XMM-Newton light curve and spectrum of the pulsar Large
Magellanic Cloud (LMC) X-4. All 22 sources that were injected in the WFI CDFS image are
shown in Fig. 5.

The execution of the algorithm showed that we were able to retrieve all the transients already
in the catalog and the inserted ones. Irrespective of whether the source was brighter than the
We looked for variability in segments of 100 s. We define variability as a $5\sigma$ deviation of the count rate in each 100 s from the median count rate over the whole 1 ks. For the purposes of this test, we only generated light curves as science products for these 100 s segments. We recovered all such segments where the criteria are satisfied and verified them against the inserted light curves. Two such variable sources are shown in Fig. 6(a). The upper light curve is from a CDFS transient while the lower one is from an injected transient with a step function light curve.

We were also able to detect the periodicity for brighter sources with large significance. One such periodogram for an inserted transient (LMC X-4) is shown in Fig. 6. We caution that an artificial periodicity at the readout time of 5 ms in the normal mode and 80 $\mu$s in the fast detector mode will be seen in the periodogram so any periodic detection around those values (and their
harmonics) will have to be carefully examined. It is worthy to note that, to generate light curves, we have used the SIXTE command “makelc.” The hardness ratio was calculated as a ratio of count rates in the bands 0.5 to 2.0 keV and 2.0 to 15 keV. Periodicities in the light curves were determined using the FTOOLS command “powspec” on the 1-s binned light curves.

To mimic the uncertainties arising from star tracker errors, we executed the algorithm 100 times with random positional errors of ±3 arc sec on each axis. We were able to detect 99% of sources with astrometry errors <7 arc sec, thereby demonstrating the robustness of the onboard detection to spacecraft attitude errors.

Timing tests of the algorithm were executed to verify that the target space-qualified CPU could execute the required processing in real time. The version of the proof-of-concept algorithm used in this test included a combination of shell scripts, SIXTE analysis tools, CIAO code, FTOOLS, and Python code. Tests were run under Linux on a Dell Inspiron 15-3000 series laptop with an Intel Core i5-5200U CPU running at 2.20 GHz. We used Dhrystone and Coremark benchmark tests to estimate the execution time ratio between this machine and the flight target dual-core Leon-3FT processor. Our tests showed that the flight CPU could fully process the simulated data, including production of exposure maps, images, source detection, and variability tests, and output source positions, light curves in two energy bands, harness ratios, and periodograms, in 50% of real time. We expect that optimization of the code could significantly improve this performance.

The discussions throughout the paper assume the execution of the onboard algorithm during normal operating modes of WFI. It also demonstrated the implementation of this algorithm on simulated slew survey data, similar to the highly successful XMM slew survey. If this is implemented, a rough estimate indicates that with WFI, the possible number of highly variable sources with flux changes of a factor of 10 and more detectable in the slews will be ~7 per year.

To summarize, we have verified that our algorithm detects all types of variable sources, including the inserted sources that were not included in the catalog and were therefore classified as transients.

4 Summary

With sensitivity better than current existing spacecraft such as Chandra and XMM-Newton, Athena/WFI will enrich our understanding of the known transients and will contribute to the discovery and study of new x-ray transients. This increase in sensitivity coupled with faster readout times will also aid in probing faint x-ray transients, which has so far been hindered...
by current instruments that have typical readout of seconds. In this paper, we have presented an algorithm for rapid onboard or ground-based detection of x-ray transients with the WFI onboard Athena. In addition to this improvement in the understanding of transients with TAM, such alerts will also facilitate multiwavelength follow-ups with other observatories.

Tests using simulated data with artificial and real x-ray variable and transient sources show that this simple algorithm can successfully detect both transient and variable sources on time scales of <1 k s with the available computational resources, and the results could be relayed to the ground with very low latency for the 16% of the time that Athena is in contact with the ground station. This is expected to produce significant numbers of prompt alerts for interesting transient x-ray sources. Discussions with NASA and the WFI team are continuing to determine whether this onboard transient detection capability will be included on Athena.

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