Anticipated-ToO Observations of X-ray Flares from Galactic Globular Clusters

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1. Abstract

Globular clusters (GCs) are tightly bound clusters of thousands of stars. They contain various types of X-ray sources, such as X-ray binaries, cataclysmic variables, active main-sequence binaries, and millisecond pulsars. More importantly, both theoretical predictions and computational models suggest that GCs may host intermediate-mass black holes (IMBHs) capable of generating X-ray flares during the accretion process. EP/WXT may observe numerous Galactic GCs during all-sky monitoring, offering the potential to serendipitously detect X-ray flares from GCs. These events merit prompt follow-up observations using EP/FXT to verify their origins. This proposal aims to quickly follow up strong X-ray flares from a sample of Galactic GCs previously detected in X-rays with deep EP/FXT observations, in the hope of uncovering signatures of IMBHs or the outbursts from other types of X-ray sources.

2. Description of the Proposed Program

2.1 Scientific Rationale:

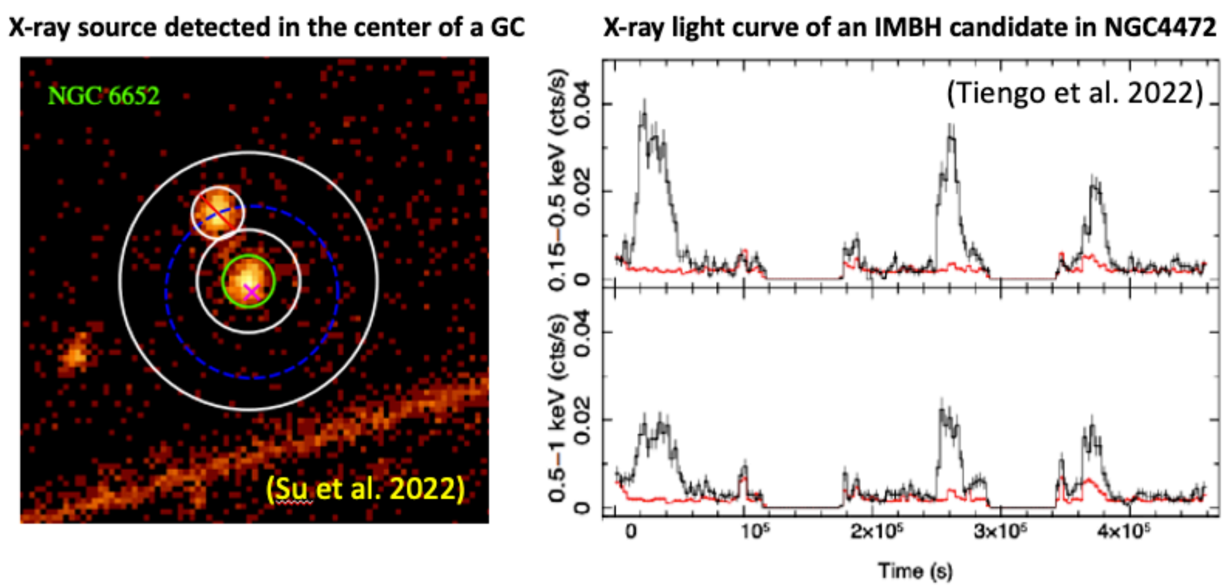

Figure 1: The left panel shows an example of X-ray source detected by *Chandra* in the center of the Galactic GC NGC 6652. The right panel shows the peculiar light curves of an IMBH candidate associated with the GC NGC 4472. Multiple flares have been observed by *XMM-Newton*, which might be the signal of a white dwarf being partially tidally disrupted by an IMBH.

Globular clusters (GCs) are tightly bound clusters of thousands of stars. They contain various types of X-ray sources, such as X-ray binaries (XRBs), cataclysmic variables, active main-sequence binaries, and millisecond pulsars. For example, in an early *ROSAT* survey of 55 GCs, about 25 sources were detected (Verbunt 2000). A more recent study of *Chandra* observations reported a comprehensive catalog of more than 1100 X-ray sources were detected in 38 Galactic GCs (Bahramian et al. 2020), and most of these sources are low-luminosity sources with an X-ray luminosity $L_{\rm X}$ of $\leq 10^{35}$ erg s^{-1}. The overabundant of XRBs in GCs compared to other locations in the Milky Way and other galaxies is believed to be linked to various dynamical XRB formation channels in GCs (Kundu et al. 2007; Kundu & Zepf 2007). These channels include interaction of a red giant star with a compact object (Sutantyo 1975), tidal capture of a companion star by the compact object (Fabian et al. 1975), or an exchange interaction, where a compact object replaces a low-mass star in a binary system (Hills 1976).

More interestingly, both theoretical predictions and computational models suggest that GCs may host intermediate-mass black holes (IMBHs). An IMBH is a class of black hole with mass in the range $10^3 \sim 10^4\ M_\odot$, significantly more than stellar black holes but much less than super-massive black holes (SMBHs). While stellar-mass black holes can be identified in XRBs (e.g. Cygnus X-1, Fabian & Miller 2002) and through gravitational-wave detections (e.g. GW150914, Abbott et al. 2016), and super-massive black holes are believed to power active galactic nuclei (AGN, Antonucci 1993), there is currently no solid evidence about the discovery of an IMBH. Therefore, searching for IMBHs within nearby GCs has become a important topic. Detecting IMBHs in GCs would validate one formation channel for seed black holes in the early universe and have strong implications for the GCs' dynamical evolution.

Indeed, SMBHs show a tight correlation between their mass and the velocity dispersion of the galaxy in which they reside (e.g. Ferrarese & Merritt 2000; Gebhardt et al. 2000). Extrapolating this relation to the lower velocity dispersions of GCs, with $\sigma \sim 10-20$ km s^{-1}, predicts IMBHs in GCs with masses of $10^3 \sim 10^4\ M_\odot$. However, directly detecting Intermediate-Mass Black Holes (IMBHs) is extremely challenging. One potential method is to detect the electromagnetic radiation generated by the accretion of the interstellar medium surrounding the IMBH, especially X-ray and radio emissions. Many efforts have been made to explore this aspect extensively. For example, Su et al. (2022) conducted a *Chandra* survey of 81 Galactic GCs, but detected only 6 X-ray sources coincident with the center of GCs (see Fig. 1 left panel). The spectral and timing properties of these sources are not distinguishable from XRBs. The *Chandra* MAVERIC survey of faint X-Ray Sources in Galactic GCs suggest that GCs host a variety of lower-luminosity X-ray sources with $L_{\rm X} < 10^{35}$ erg s^{-1}, but there is no report of any evidence of an IMBH (Bahramian et al. 2020). Therefore, these work suggest that it is indeed extremely challenging to detect accretion-induced X-ray emission from IMBHs, even if they did exist in present-day GCs. However, positive evidence also exists. Tiengo et al. (2022) reported recurrent X-ray flares of the black hole candidate XMMU J122939.7+075333 in the GC RZ 2109 in the Virgo galaxy NGC 4472. This source shows multiple X-ray flares with a tentative recurrence time of $\sim$ 34 h (see Fig. 1 right panel). Comparing this source to the peculiar X-ray transient quasi-periodic eruption (QPE, Miniutti et al. 2019), a possible explanation would be that this source is powered by the partial disruption of a white dwarf by an IMBH with a mass of $\sim\ 700\ M_\odot$. In any case, more detections of X-ray sources from the center of GCs would be extremely valuable.

EP/WXT has an instantaneous field-of-view (FoV) of 3600 deg^2. It can achieve real X-ray focusing imaging with the Lobster-eye micro-pole optics, which also increases the detection sensitivity to 3×10^{-11} erg cm^{-2} s^{-1} for a single survey pointing of 1.2 ks. Therefore, during the all-sky survey mode, EP/WXT can monitor bright X-ray flares from all the sources within its FoV, including many Galactic GCs. Assuming a GC is located in the Wilky Way at a distance of 5 kpc, the above survey sensitivity of WXT corresponds to an X-ray luminosity of $L_{\rm X}\ 9 \times 10^{34}$ erg s^{-1}. Therefore, the above WXT threshold could filter out most of stellar flares and low-luminosity X-Ray Sources in Galactic GCs, leaving most interesting bright X-ray flares probably originating from exceptional outbursts from otherwise faint XRBs, or the accretion of IMBHs. In either case, they will worth quick follow-up observations. The response time of quick Target-of-Opportunity (ToO) observation of *EP* is within tens of minutes to hours, so these bright flares can be quickly followed with EP/FXT for deep observations.

2.2 Immediate Objectives:

- **Real-time detection of bright X-ray flares from Galactic globular clusters**
  We will monitor the X-ray brightness of the proposed Galactic GCs if some of them are serendipitously covered by EP/WXT. If a new flare is detected, we will use the WXT data to check its basic properties such as the hardness ratio. A long-term light curve based on WXT observations will also be built to monitor its long-term evolution.
- **Prompt deep follow-up observation to constrain the flare's properties and origin**
  If the flare's flux exceeds the threshold, we will trigger follow-up observations with EP/FXT with a high-urgency ToO. The data will be used to characterize the detailed spectral properties of the flare, and the short-term variability patterns. If necessary, further observations of FXT may be proposed to follow the flare's evolution.

3. Justification of Requested Observing Strategy, Exposure Time, Feasibility, and Visibility

We propose an anticipated-ToO program to follow up bright X-ray flares from a small sample of 26 Galactic GCs with previous X-ray detections. The trigger will be provided by the observation of EP/WXT. The triggering threshold is 3×10^{-11} erg cm^{-2} s^{-1}, which is roughly the sensitivity of EP/WXT in a typical survey pointing of 1.2 ks exposure. This flux threshold could efficiently filter out most of stellar flares and low-luminosity X-Ray Sources in Galactic GCs, leaving most interesting bright X-ray flares probably originating from exceptional outbursts from otherwise faint XRBs, or the accretion of IMBHs. In either case, they will worth quick follow-up observations.

The request ToO observation time is 20 ks. This is mainly driven by the requirement of constraining the spectral shape and short-term variability of the new flare, which is crucial to understand its origin. Depending on the X-ray brightness, a preliminary choice of THIN filter plus *full-frame* mode is chosen for both EP/FXT modules.

Since this is an anticipated-ToO observation, the visibility of each individual GC is not important, as long as each of them is visible for a certain period of time during the Cycle-1 period. Then during EP/WXT observations, these GCs can be serendipitously covered by the FoV of EP/WXT from time to time. Once a new X-ray flare is detected, the anticipated ToO observation will be triggered with high urgency. The typical response time will the tens of minutes to hours, which will be sufficient for an outburst of XRBs or some accretion-induced flares, whose typical timescales are much longer. The 20 ks exposure time will no double achieve a highly significant detection, provided that the flare's brightness does not drop sharply over time. This observation can provide high quality data to constrain the spectral timing properties of this new transient. Depending on the observation result, further ToOs can be planned consequently.

The proposed 26 Galactic GCs have equal priority, an X-ray flare from any of these GCs can be equally valuable to trigger follow-up observations. Such event is extremely rare, we expect to trigger no more than one flare in Cycle-1, thus only one ToO observation is requested.

4. Work Plan and Justification of the Team's Expertise

(1) Work Plan:
we will first monitor these GCs and see if any of them are covered by the FoV of WXT and if the brightness increases significantly. If a new flare is detected exceeding the threshold by WXT, we will quickly analyze the WXT data to determine the hardness ratio. Meanwhile, a quick follow-up FXT observation will be triggered. Once the data arrives, we will measure the flare's spectral shape and check its short-term variability to determine its origin. Depending on the results, further multi-wavelength observations may be proposed to follow the long-term evolution of the new flare.
(2) Team's Expertise:

The proposal team contains several experts in studying X-ray spectral timing properties of XRBs, AGNs and TDEs. The team members are all core members of the *EP* mission, and so they have the best knowledges about *EP*'s performance and scientific operation. If a new transient is discovered, the team can guarantee the success of follow-up observation and analysis of the X-ray and multi-wavelength data.

5. Most Relevant Proposer's Publications and References

(1) Jin, C. et al., 2022, MNRAS, 512, 5642, *Multiwavelength campaign on the Super-Eddington NLS1 RX J0134.2-4258 - I. Peculiar X-ray spectra and variability*

(2) Yang, H. et al., 2022, ApJ, 936, 36, Exploring the Link between the X-Ray Power Spectra and Energy Spectra of Active Galactic Nuclei

(3) Zhang, W., 2022, MNRAS, 511, 19, XMM-Newton detection of soft time lags in the TDE candidate AT 2018fyk

(4) Li D. et al., 2022, MNRAS, 512, 3858, Populations of highly variable X-ray sources in the XMM-Newton slew survey

(5) Hu, J. et al., 2022, ApJ, 936, 105, A Systematic Study of the Short-term X-Ray Variability of Seyfert Galaxies. I. Diversity of the X-Ray rms Spectra

(6) Jin C. et al., 2020, MNRAS, 495, 3538, *Reobserving the NLS1 galaxy RE J1034+396 - I. The long-term, recurrent X-ray QPO with a high significance*

(7) Jin C., et al., 2016, MNRAS, 455, 691, *Strong constraints on a super-Eddington accretion flow: XMM-Newton observations of an intermediate-mass black hole*