EP Performance Verification (PV) Targets Recommendation Form

Submission Due Date: 27th October 2023

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1. TITLE

Testing FXT's capabilities in detecting mode-switching and pulsations in Transitional Millisecond Pulsars

2. ABSTRACT *(< 250 words)*

Transitional millisecond pulsars are peculiar pulsars in binary systems that have been observed to swing between an accretion-powered state and a rotation-powered state. PSR J1023+0038 (J1023) is currently the only transitional millisecond pulsar known to be in an extremely peculiar active X-ray state. During this state, the X-ray emission of J1023 switches on timescales of tens of seconds between a high-intensity mode (for 70-80% of the time) and a low-intensity mode (for 20-30%). Coherent X-ray pulsations at the 1.7-ms spin period are detected only in the high mode.

We propose a 20-ks observation of PSR J1023+0038 using the FXT in timing mode. This setup will assess the FXT's capability to detect the mode-switching phenomenon and coherent pulsations at relatively faint X-ray flux levels (1E-11 erg/s/cm^2; 0.3-10 keV). The proposed observations are essential to assess the efficiency of FXT in detecting transitional pulsars in prompt follow-up observations of sources detected by the WXT, using only time-domain analyses.

3. RECOMMENDERS' INFORMATION

Principal Recommender	
***Recommender' Name**	Francesco Coti Zelati (ICE, CSIC)
***Recommender' Email Address**	cotizelati@ice.csic.es
***Recommender' Expertise**	An expert on observational studies of X-ray binaries and in particular transitional millisecond pulsars
***Recommender' STP(s)**	STP4
Co-Recommenders	
***Recommenders' Names**	A. Marino, N. Rea
***Recommenders' Email Addresses**	marino@ice.csic.es, rea@ice.csic.es

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***Recommenders' Expertise**	Both experts on observational studies of X-ray binaries
***Recommenders' STP(s)**	STP4

4. TARGET FORM

- **TARGET 1** ***(mandatory)***

***Target Name**	PSR J1023+0038			
***Target Type**	Transitional millisecond pulsar			
***Target Coordinates**	***RA:**	10:23:47.69	***DEC:**	00:38:40.9
***Expected Flux in 0.3-10 keV**	1E-11 erg/cm^2/s			
***Primary Instrument**	FXT			
FXT Configuration ***(mandatory if the primary instrument is FXT, optional if the primary instrument is WXT)***	**FXT-A**	*timing* mode; *thin* filter	**FXT-B**	*timing* mode; *thin* filter
***Exposure Time**	20 ksec			
Suggest Joint Observation with Other X-ray Telescopes	XMM-Newton, NICER			
Other remarks	-			
*Note: * mandatory items*				

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5. SCIENTIFIC AND TECHNICAL JUSTIFICATION
(< 2 pages in total for this session, including figures, tables and references)

- **Scientific Motivations and Values**

Transitional MSPs are pulsars in binaries that have been observed to swing on timescales of days to months between two distinct emission states: a faint X-ray state ultimately powered by the rotation of the pulsar (Lx ~ 10^{31}-10^{32} erg/s) and an active X-ray state (Lx ~ 10^{33}-10^{34} erg/s) probably powered by coexisting rotation-powered and accretion-powered mechanisms. This active state is characterized by emission properties across the electromagnetic spectrum that are unique in the landscape of X-ray binaries [1].

The focus of this proposal is on PSR J1023+0038 (J1023), the only known transitional millisecond pulsar (MSP) in the active state, which has been extensively studied. In this state, the X-ray emission of J1023 switches between two well-defined, remarkably stable high and low intensity modes, occasionally interrupted by flares (**Fig. 1**). The high mode is observed 70-80% of the time, while the low mode, which usually lasts from a few tens of seconds to minutes, takes up the remaining 20-30%. The time it takes to switch between these modes ranges from approximately 10-30 seconds. Notably, coherent X-ray pulsations at the spin period of 1.7 milliseconds are seen only in the high mode (**Fig. 1**), with a background-subtracted root-mean-square amplitude of 8% ([2]; refs. therein).

The mode switching phenomenon has been observed in all three known transitional MSPs, and is exclusive to these sources. Hence, any new source exhibiting this specific variability pattern can be considered a strong candidate for being a transitional MSP. Although currently only three transitional MSPs are known, there are about 30 other MSPs in binary systems, termed 'redbacks', that are prime candidates to be transitional MSPs in the rotation-powered state and could transition to the X-ray active state at any moment [3]. Additionally, candidate transitional MSPs are known to emit gamma rays at GeV energies in both states [4]. Therefore, many candidates might be hiding among the thousands of unidentified Fermi sources and could transition to an active X-ray state.

For relatively nearby candidates, we expect a state transition from the rotation-powered state to the active X-ray state to manifest as an X-ray alert for the WXT. Therefore, with the upcoming launch of the Einstein Probe, it becomes vital to quickly test the ability of the FXT to detect the mode switching phenomenon and coherent pulsations in prompt follow-up observations of WXT-discovered transients. A quick identification of new transitional MSPs would also be crucial for coordinating dedicated observational campaigns to characterize their emission properties across the electromagnetic spectrum.

Observing J1023 as a PV target will be key to fine-tune the pipeline we are currently developing to characterise aperiodic variability of EP transients. This will maximize our chances of promptly identifying transitional MSPs right from the beginning of the mission.

- **EP Capabilities to be Verified**

This target can demonstrate the capabilities of the FXT in the timing mode to spot the X-ray mode switching phenomenon in transitional MSPs, and at the same time detect and characterize X-ray pulsations at millisecond periods.

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- **Immediate Objectives**

We aim to characterize the short-term variability properties of the X-ray emission from J1023, particularly the mode switching phenomenon. For this, we will extract background-subtracted time series using different time bins in the range between 10 and 100 s. We will then extract the count-rate distribution and employ Gaussian Mixture models to assess the presence of bimodality in the X-ray emission. Furthermore, we will select and stack high-mode episodes by applying intensity filters on the time series, and search for pulsations at the known spin period of 1.7 ms.

- **Technical Justification**

All previous X-ray observations of J1023 during its active X-ray state show that its X-ray spectrum can be accurately described by an absorbed power-law model with an absorption column density of nH=5x10^{20} cm^{-2} and a photon index of Gamma=1.6. The observed flux in the high mode is 1E-11 erg/s/cm^2 over the 0.3-10 keV energy range [5]. This converts to a FXT net count rate of 0.11 cts/s according to the Observation Simulator.

We request the FXT to be set in the timing mode to achieve the time resolution needed to detect the pulsations at the pulsar spin period. To narrow down the parameter space for the search, we will request quasi-simultaneous observations with NICER for a duration of 20 ks. Past observations of this duration have proven sufficient to detect the pulsations.

We propose 20 ks with FXT to cover a sufficient number of mode switches ensure adequate count statistics in the high mode for pulsation detection. Based on past observations, we expect to detect between 2 and 10 low mode episodes per hour.

In March 2024, the anticipated month for the Einstein Probe PV observations, J1023 will be visible throughout the month except between March 19 and March 25.

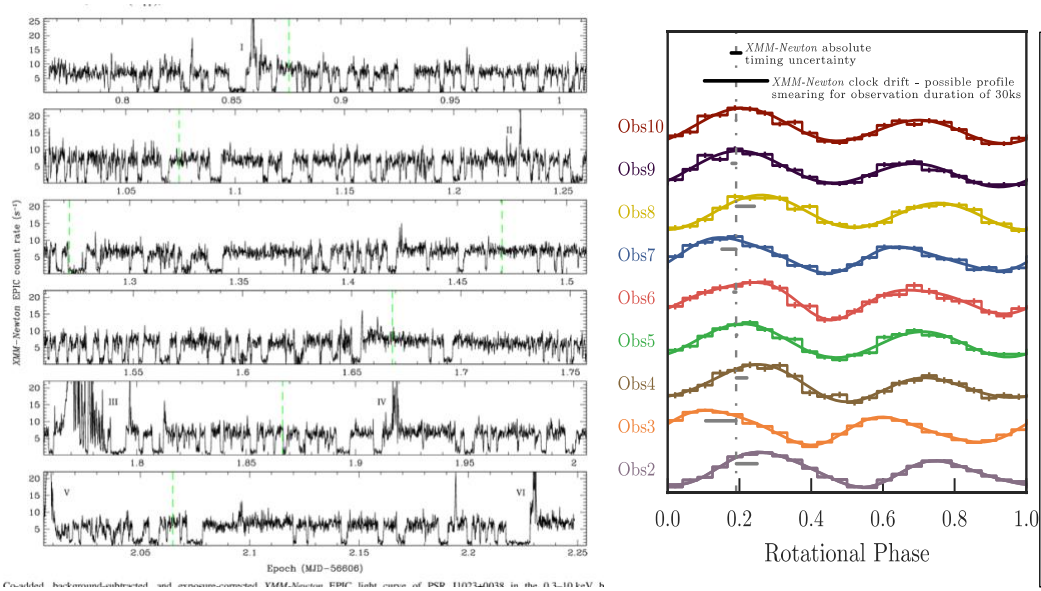

Fig. 1. Left: the X-ray mode switching phenomenon of J1023 [6]. Right: pulse profiles extracted from 10 XMM-Newton observations [7].

- **References**

[1] Papitto & de Martino 2022, ASSL, 465; [2] Baglio, Coti Zelati et al. 2023, A&A, 677; [3] Koljonen & Linares 2023, MNRAS, 525; [4] Torres et al. 2017, ApJ, 836; [5] Campana et al. 2016, A&A, 594; [6] Bogdanov et al. 2015, ApJ, 806; [7] Jaodand et al. 2016, ApJ, 830.

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