# EP Performance Verification (PV) Targets Recommendation Form

**Submission Due Date: 15th October 2023**

*NOTE: Please do not change or delete the words marked in blue.*

## 1. TITLE

Using X-ray pulsar PSR J0538+2817 and its vicinity to verify the spectral resolution, timing capability, and sensitivity of FXT

## 2. ABSTRACT *(< 250 words)*

The X-ray pulsar PSR J0538+2817 has an unusual spin-velocity alignment. Very recently, it is found to have a straight, narrow radio filament 6' ahead of it along its proper motion direction. Archival X-ray and optical observations claim no detection of the strange filament, thus leaving its origin unclear. Still, the pulsar itself has been monitored through X-rays by *Chandra* and *XMM-Newton* in detail, so we apply here for deeper imagining and timing observation toward PSR J0538+2817 and its vicinity with EP FXT-A in full-frame and FXT-B in timing mode. The resulting data can verify FXT's spectral resolution and timing capability when compared with archival data. Moreover, the deep image of the radio filament region may give new physical insights to the nature of the filament, and verify the sensitivity of the FXT.

## 3. RECOMMENDERS' INFORMATION

| **Principal Recommender** | |
|---|---|
| ***Recommender' Name** | Yongfeng HUANG |
| ***Recommender' Email Address** | hyf@nju.edu.cn |
| ***Recommender' Expertise** | Yongfeng HUANG is an expert in the study of neutron stars and gamma-ray bursts, and has led a theoretical study on the proposed target. |
| ***Recommender' STP(s)** | STP2, 4 |
| **Co-Recommenders** | |
| ***Recommenders' Names** | Ze-Cheng Zou, Jinjun Geng, Lang Cui |
| ***Recommenders' Email Addresses** | zou.ze-cheng@smail.nju.edu.cn, jjgeng@pmo.ac.cn, cuilang@xao.ac.cn |
| ***Recommenders' Expertise** | Ze-Cheng Zou is an expert in the study of pulsars and had been involved in the RACS survey, which leads to a recent paper on |

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| | |
|---|---|
| | the proposed target. Jinjun Geng is an expert in the study of high-energy astrophysics and MHD simulations, and has contributed to a theoretical study on the proposed target. Lang Cui is an expert of the observational study of compact stars. |
| ***Recommenders' STP(s)** | STP3, STP2 |

## 4. TARGET FORM

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

| | | | | |
|---|---|---|---|---|
| ***Target Name** | PSR J0538+2817 | | | |
| ***Target Type** | Pulsar | | | |
| ***Target Coordinates** | ***RA:** | 84:36:15.93 | ***DEC:** | 28:17:09.1 |
| ***Expected Flux in 0.3-10 keV** | 7.24e-13 erg $cm^2$ $s^{-1}$ | | | |
| ***Primary Instrument** | FXT | | | |
| **FXT Configuration** ***(mandatory if the primary instrument is FXT, optional if the primary instrument is WXT)*** | **FXT-A** | full-frame mode<br>thin filter | **FXT-B** | timing mode<br>thin filter |
| ***Exposure Time** | 36 ksec | | | |
| **Suggest Joint Observation with Other X-ray Telescopes** | | | | |
| **Other remarks** | | | | |
| *Note: * mandatory items* | | | | |

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- **TARGET 2 and more…**
  *(optional, if there are more than one target in this recommendation, copy the entire target form above to the empty space below; note that this is only for the case that one observing proposal includes multiple targets; for targets of a different proposal with distinct technical and scientific goals, please submit them in separate proposals.)*

## 5. SCIENTIFIC AND TECHNICAL JUSTIFICATION

***(< 2 pages in total for this session, including figures, tables and references)***

- **Scientific Motivations and Values**

PSR J0538+2817 (also known as J0538+2813) is an X-ray pulsar with a flux of ~7.24e-13 erg $cm^{-2}$ $s^{-1}$ (0.5-8 keV). It is observed to have a spin-velocity alignment by FAST recently (Yao et al. 2021). We propose that this alignment can be produced by the electromagnetic rocket mechanism, accompanied by a gamma-ray burst (Xu et al. 2022). More recently, a one-sided, straight, and narrow radio filament 6' ahead of the pulsar along its proper motion is discovered in RACS survey by ASKAP at 887.5 MHz and 1367.5 MHz, confirmed by archival data of CGPS and NVSS surveys at 1.4 GHz (Khabibullin et al. 2023, Figure 1). As a result, a spin-velocity-filament alignment presents in PSR J0538+2817. This unique feature makes PSR J0538+2817 a very interesting target to observe.

This pulsar has been observed by both *XMM-Newton* and *Chandra*. Detailed and consistent spectra are obtained in 0.2-3 keV by MOS1 onboard *XMM-Newton* (McGowan et al. 2003) and in 0.5-8 keV by ACIS-I array onboard *Chandra* (Ng et al. 2007). Therefore, a direct comparison between these two spectra and FXT observation is possible and can help verify the spectral performance of EP FXT. Moreover, *XMM-Newton* obtains a ~143 ms period for the pulsed X-ray emission, consistent with the radio measurement (McGowan et al. 2003). As a result, monitoring PSR J0538+2817 can further test the timing capability of FXT.

However, the radio filament along the proper motion direction in the pulsar's vicinity is not detected in 0.5-3 keV or 3-7 keV images obtained by MOS1 onboard *XMM-Newton*. No convincing optical emission from the filament is detected either, making the origin of the filament unclear. Khabibullin et al. (2023) speculate that the filament is produced by leptons escaping from the pulsar wind nebula and injected into the surrounding supernova remnant S147. However, this scenario is usually applied to X-ray bright filaments, like the ones in Lighthouse and Guitar nebulae. On the other hand, if PSR J0538+2817 has already broken out of S147, as allowed by the measured large line-of-sight velocity, a bow shock emitting X-rays may present ahead of the pulsar. Therefore, deeper observations by FXT may help reveal the underlying nature of the radio filament, thus helping solve the mystery of the spin-velocity-filament trio.

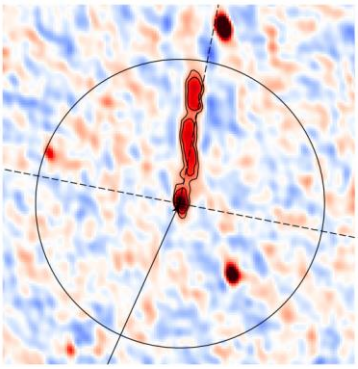

Figure 1: RACS's view of the vicinity of PSR J0538+2817 at 887.5 MHz (Khabibullin et al. 2023). Contours show the 3 and 5 RMS levels of the radio map. The large circle is centered on PSR J0538+2817 with a radius of 6'. The arrow ends in the pulsar's position and points to the proper motion direction. The dashed line shows the orientation of the *Chandra*-observed extended X-ray emission region and its perpendicular direction.

- **EP Capabilities to be Verified**

This target can demonstrate FXT's spectral resolution, timing capability, and sensitivity.

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- **Immediate Objectives**

**Clarifying the nature of the unusual radio filament.** We propose here to obtain a deeper image of the vicinity of PSR J0538+2817. This may reveal the faint X-rays emitted by the filament, or set a tighter limit for its X-ray flux. Assuming the radio-emitting electrons in the filament form the same population together with the high-energy ones, the high-energy tail can emit X-rays by inverse Compton scattering cosmic microwave background. As a result, deeper X-ray observations can probe the magnetic field inside the filament (Khabibullin et al. 2023), thus clarifying the filament's environment, e.g., whether it is inside the supernova remnant or inside the interstellar medium. The morphology, if observed, can also aid in understanding the mechanisms driving the production of the straight, narrow, and aligned filament.

**Providing better information for PSR J0538+2817.** Existing spectral analyses state that the pulsar's X-ray emission can be well-fitted by both the blackbody and the atmospheric model (McGowan et al. 2003; Ng et al. 2007). However, these two models give quite different stellar properties: the blackbody model predicts higher temperature and a much smaller emission region, favoring polar cap geometry. With the observation we proposed, the stellar model can be tested by using more abundant data. On the other hand, the timing results by FXT, combined with the much earlier result by *XMM-Newton*, can help determine the spin-down behavior between these two observation epochs.

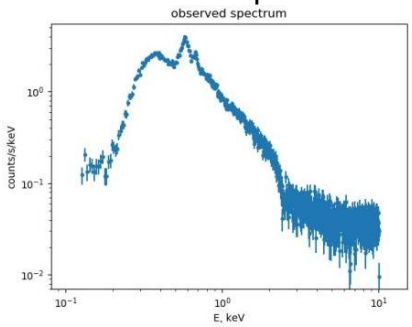


Figure 2: Simulated on-source spectrum produced by the online FXT observation simulator. Parameters are set as Flux=7.24e-13, nH=0.247, Emin=0.5, Emax=8, Spectrum=BB, Temperature=0.1818, filter=thin, Mode=FF, Exposure=36000 (all in the unit of the online simulator).

- **Technical Justification**

According to the long-term visibility prediction tool, PSR J0538+2817 is visible from Feb. 22 to Mar. 14 in 2024, being able to be observed if EP is launched not too late. Applying the stellar properties inferred from *Chandra* observation fitted by the blackbody model with temperature of 2.11e6 Kelvin (0.1818 keV), i.e., $N_H$ = 2.47e21 cm$^{-2}$, $f_{0.5\text{-}8keV}$= 7.24e-13 erg cm$^{-2}$ s$^{-1}$ (Ng et al. 2007), an on-source exposure for 36 ksec (10 cycles, 2/3 day) results in a SNR of 74.74 for the pulsar in FF mode with thin filter. The simulated SED is ideal (Figure 2). Assuming that the X-ray flux of the radio filament is the same as the noise level in the non-detection by *XMM-Newton*, i.e., ~2e-14 erg cm$^{-2}$ s$^{-1}$ arcmin$^{-2}$ (Khabibullin et al. 2023), the X-ray emitting region is 2' in diameter (the size of the northern knot of the radio filament), and its spectrum is a power law with photon index 1.5, our proposed observation results in an SNR of 4.91, being probable to claim a detection. In timing mode, the time resolution of 94 μs is capable of capturing the >100 ms period of this pulsar.

- **References**

Khabibullin et al. 2023, arXiv:2309.13670, submitted to MNRAS ● McGowan et al. 2003, ApJ, 591:380 ● Ng et al. 2007, ApJ, 654:487 ● Xu, Geng, Wang, Li, Huang, 2022, MNRAS, 509:4916 ● Yao et al. 2021, Nature Astronomy, 5:788.

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