$\star$[1] Studying the magnetic field configuration of the Galactic Ultraluminous X-ray pulsar

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1. Abstract

Concise abstract of your proposal to be given here. It is suggested to use the same text as entered in the XMM-Newton Remote Proposal System.

2. Description of the proposed programme

A) Scientific Rationale:

Ultraluminous X-ray sources (ULXs) are exceptionally bright compact X-ray objects with X-ray luminosities surpassing the Eddington luminosity for stellar-mass black holes, with luminosities exceeding 10^{39} erg s^{-1}. They have been detected in regions off the central nucleus of the Galaxy and in neighboring galaxies. Recent observations have revealed that a number of ULXs exhibit coherent pulsations with periods ranging from approximately 1 to 10 seconds. These peculiar objects are referred to as ULX pulsars (ULXPs). It is widely accepted that these pulsations become observable when the radiation emanating from the vicinity of the neutron star (NS) undergoes periodic changes due to the NS's rotation. In such cases, the ULXP derives its energy from a super-Eddington accretion process onto the magnetized NS, given that the luminosity of the ULXP surpasses the Eddington luminosity for the NS.

One aspect of ULXPs that has long been of interest to astrophysicists is the nature of their magnetic fields. Magnetic fields play a crucial role in the evolution and dynamics of neutron stars and can influence accretion mechanisms in binary systems. Therefore, uncovering the magnetic field characteristics of ULXPs can provide invaluable insights into their nature, origins, and the underlying processes that drive their extreme luminosities.

The nature and magnitude of the magnetic field of the only galactic supercritical pulsar Swift J0243.6+6124 remains unclear. Swift J0243.6+6124, being the closest ULXP, becomes an ideal object for study, including study at the low accretion rates that are not observable in other systems.

On the one hand, the non-detection of the transition to the propeller state (when the magnetic field starts to dominate the dynamics of accretion flow, and the plasma entering the magnetosphere becomes expelled by centrifugal forces) in quiescence which strongly implies compact magnetosphere and thus rules out magnetar-like fields (Tsygankov et al. 2018, Doroshenko 2020b), Tsygankov et al. 2018 limited the magnetic field to be lower than 3×10^{12} G. This picture is confirmed by the transition of the inner regions of the accretion disc from the standard gas pressure dominated (GPD) to the radiation pressure dominated (RPD) state at luminosity 4.5×10^{38} G (Doroshenko 2020b).

On the other hand, the discovery of a cyclotron resonant scattering feature (CRSF) with energies up to 146 keV (Kong et al. 2022) indicates the presence of a magnetic field of about 1.6×10^{13} G. Kong et al. (2022) have argued that such a strong field has to be in the multipolar component, as a dipole of this magnitude would lead to contradictions with other measurements proposed for other ULXPs earlier. One possible explanation is the configuration of magnetic fields where thee presence of a very potent quadrupolar magnetic field in close proximity to the neutron star, alongside a weaker dipolar magnetic field that exerts a dominant influence on the interaction with the surrounding matter when farther away (see e.g. Israel et al. 2017a, Kong et al. 2022).

The nature of their magnetic fields of ULXPs has been of a large interest to astrophysicists in recent years. Magnetic fields play a crucial role in the evolution and dynamics of neutron stars and influence accretion mechanisms in binary systems. Therefore, uncovering the magnetic field characteristics of ULXPs can provide invaluable insights into their nature, origins, and the underlying processes that drive their extreme luminosities. The potential discovery of a quadrupole-dipole magnetic field configuration in ULXPs would shed light on accretion dynamics, pulsars' magnetic field evolution, and probing NS interiors.

didn't get logic. more details are needed (weak dipolar field (REF), strong quadrupole (REF)). line was discovered in some specific paper, not all three mentioned. more on the motivation: why do we care? large

[1] *Note: the proposal justification must be submitted in Portable Document Format (PDF). The maximum length of a justification (everything included) is 4 pages (5 pages in case of 'Large Programmes', 8 pages for 'Multi-Year Heritage Programmes', 2 pages for 'Fulfil Programmes', only)!*

picture (formation and evolution of the magnetic field etc)

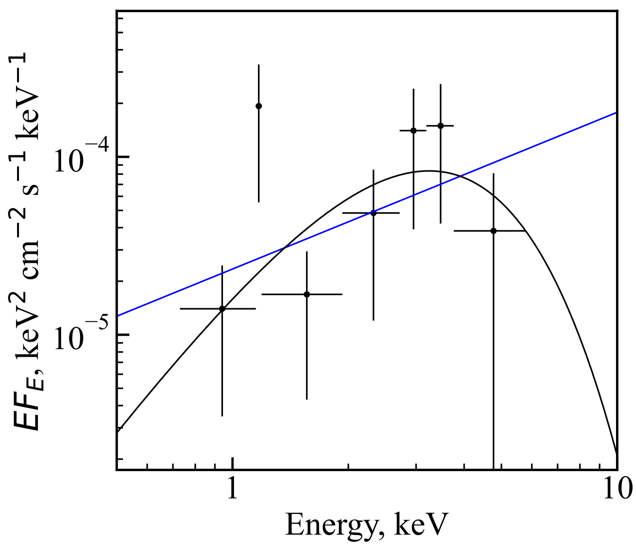

Figure 1: *Swift*/XRT spectrum of Swift J0243.6+6124 for the lowest detected 0.5-10 keV luminosity of $\approx 2 \times 10^{32}$ erg s^{-1}. Black line represents black-body model ($T = (0.8 \pm 0.2)$ keV), and a blue line is for power-law model ($\Gamma = 1.1 \pm 0.5$).

B) Immediate Objective:

From an observational perspective, one method to uncover the potential dipole component of the magnetic field is to assess the anticipated decrease in rotational speed during a period of low luminosity (10^{33} erg s^{-1}), when accretion rate is very low. During this phase, accretion may be hindered as a result of the neutron star's rapid rotation. In such circumstances, the primary force causing the neutron star to slow down is the dipole component of the magnetic field interacting with the remaining accretion disk (Parfrey et al. 2016), while the quadrupole component of the magnetic field, dominant at the NS surface, practically does not interact with matter. why? why do we think that there is any dipole component?

On the other hand, the question of the transition of pulsars to the regimes of absence or low accretion at luminosity of 10^{33} erg s^{-1} remains open, which is expected to dramatically affect temporal and spectral properties of the source. Studying these will thus allow us to answer the following questions for the first time:

1. *What does the magnetic field configuration of Ultraluminous X-ray pulsars look like?* It has previously been suggested that the magnetic field of ULXPs consists of a quadrupole and a weaker dipole component. The proposed observations will allow us to establish the presence/absence of a weaker dipole component.

2. *What physical processes do ULXP experience when the luminosity drops to the level $\sim 10^{33}$ erg s^{-1}?* Physical processes in X-ray pulsars at ultra-low accretion rates ($\sim 10^{33}$ erg s^{-}1) remain very poorly understood. To date, the spectral and temporal properties of no ULXP have been studied at such luminosities, which leaves large blind spots in our understanding of the interaction of the NS magnetosphere with plasma.

3. *How the pulsar initial magnetic field configuration looks like?* The presence of a combined dipolar-quadrupolar magnetic field configuration might provide clues about the initial conditions at the birth of the neutron star. The magnetic field configuration during a neutron star's formation is likely influenced by the progenitor star's properties, rotation rate, mass, and the specifics of the supernova explosion.

To achieve the above scientific goals, we request four XMM observations during the state of low or no accretion rates at luminosities of $\sim 10^{33}$ erg s^{-1}, i.e. long after the outburst. These luminosities were previously studied using data from the Swift observatory, but, unfortunately, short exposures with low timing resolution of the XRT telescope, as well as its low sensitivity, did not allow one to reach the immediate objectives of the proposal (see Fig. 1).

If pulsations are detected, the period of the pulsar as well as its derivative will be obtained, using phase connection technique. Using the model for pulsar spin-down via interaction with remnant accretion disk (seem e.g. equation 18 of Parfrey et al. 2016), , we will calculate the value of the magnetic field braking the pulsar and draw a conclusion about the configuration of its magnetic field. We also plan to study the stability of the light curve and pulse profile of the pulsar in a low accretion state. The detection of instability may indicate possible magnetospheric accretion.

If pulsations are not detected, then we also plan to study its power spectrum. Accreting systems are characterized by the presence of low-frequency red noise associated with the stochastic variability of the mass accretion rate in the accretion disk (Lyubarskii 1997). The clear absence of such noise will be one of the signs of the absence of accretion.

Spectral observations will complement the overall picture. Accreting pulsars, even at low rates, are characterized by a power-law shape of the spectrum, while cooling NSs in the absence of accretion have a black-body spectrum. To differentiate between these spectral forms, we will use the Akaike criterion (Akaike 1974).

3. Justification of requested observing time, feasibility and visibility

We propose to carry out 3 observations of 30 ks with an interval of 2 days between them in full frame (XMM-PN) and large window (XMM-MOS) modes. Using the WebPIMMS service, we estimated that for luminosities $\sim 10^{33}$ erg s^{-1} (flux $\sim 10^{-12}$ erg s^{-1} cm^{-2} assuming a distance of 5.2 kpc) we can expect a count rate of 0.3 (0.1) counts s^{-1} for XMM-PN (XMM-MOS), assuming a black-body $T = 0.8$ keV. A window of 2 days is sufficient to detect the spin-down of the pulsar, while at the same time not "losing" the phase, applying the phase-connection technique. Using the XMM-Newton visibility checker, we found that the average available window for observations is always at least 30 ks every 2 days. This makes it possible to carry out the observations we propose. As the trigger criteria, we will monitor the low state using the Swift observatory. If flux of a source in an observation is detected at a level of 10^{-12} erg s^{-1} cm^{-2}, then a trigger for the XMM-Newton observation will be sent. We expect to detect rotational spin-down of $\sim 10^{-11}$ Hz s^{-1} (see e.g. Chakrabarty et al. 1997), and our simulations show that our proposed observations result in detect this (assuming the count rate equal to 0.3 counts s^{-1}). Our spectral simulations show that 3 observations with a combined exposure of 90 ks will produce statistics good enough to reliably distinguish between blackbody and power law models in the range 0.4-10 keV using the Akaike criterion, expecting one of the models to be several hundred times larger more likely than the other (see, e.g., Tsygankov et al. 2017).

4. Report on the last use of XMM-Newton data

I have not received data in previous AOs, it is my first AO proposal.

5. Most relevant proposer's publications

(linked to the subject of this proposal, and especially publications resulting from accepted XMM-Newton proposals during the past two years)

Name1 A., Name2 B., 2015, ApJ, 599, 111: Title of article1

Name3 A., Name4 B., 2016, A&A, 403, 17: Title of article2

Name5 A. et al., 2017, AJ, 130, 1567: Title of article3