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# *XMM-Newton* observations of the $\gamma$ -ray pulsar J0633 + 0632

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#### Abstract.

We briefly report the results of XMM-Newton X-ray observations of the  $\gamma$ -ray pulsar J0633+0632. We detected, for the first time, X-ray pulsations from J0633+0632 with the pulsar period. The pulse profile is typical for spin-modulated thermal emission from the surface of a neutron star. The pulsed fraction in the 0.3–2 keV band is  $23 \pm 6\%$ . We confirmed previous results that the X-ray spectrum of J0633+0632 contains a non-thermal power law and a thermal (described either by the blackbody or the neutron star atmosphere models) components. However, XMM-Newton observations do not confirm the absorption line in the pulsar spectrum at  $\approx 0.8$  keV found in the *Chandra* data (Danilenko *et al* 2015 *PASA* 32 e038). Using the interstellar absorption-distance relations, we constrained the distance to the pulsar in the range of 0.7–2.2 kpc.

#### 1. Introduction

The radio-quiet *Fermi* pulsar J0633+0632 (hereafter J0633) has a period P = 297 ms, a characteristic age  $\tau = 59$  kyr, a spin-down luminosity  $\dot{E} = 1.2 \times 10^{35}$  erg s<sup>-1</sup>, and a magnetic field  $B = 4.9 \times 10^{12}$  G [1]. *Chandra* observations revealed the pulsar and its wind nebula (PWN) [2] (see figure 1, left). The J0633 X-ray spectrum contains a non-thermal power-law (PL) and a thermal component. Reanalysing Chandra observations, Danilenko et al [3] found an absorption feature in the J0633 spectrum at  $\approx 0.8$  keV with equivalent width of  $\approx 60$  eV. The interstellar absorption-distance relation suggests that the distance to J0633 is 1-4 kpc [3]. The PWN morphology and extent indicate a likely high pulsar proper motion of 80 mas  $yr^{-1} = 380D_{1kpc}$ km s<sup>-1</sup>, where  $D_{1\text{kpc}}$  is the distance in units of 1 kpc [3].

Besides J0633, only one rotation-powered pulsar, J1740+1000, has absorption lines in its spectrum [4]. Short Chandra observations of J0633 did not allow to constrain the shape and nature of the spectral line (e.g., cyclotron resonance scattering, atomic transitions in the interstellar medium (ISM) or the neutron star (NS) atmosphere, an observational artefact). Here we briefly report the results of our longer (93 ks) XMM-Newton observations of J0633 which were carried out on 2016 March 31 (ObsID 0764020101, PI Danilenko).

#### 2. XMM-Newton images

XMM-Newton data were filtered from the periods of high background that resulted in exposures of 51.8, 63.6 and 33.0 ks for EPIC-MOS1, -MOS2 and -pn detectors, respectively. The image IOP Conf. Series: Journal of Physics: Conf. Series 932 (2017) 012010



Figure 1. Left: 0.3–10 keV Chandra/ACIS image of the J0633 field. J0633, its tail-like PWN and unrelated source 'A' projected onto the PWN are marked. Right: Field of view of the XMM-Newton EPIC-pn camera in the 0.3–10 keV band. J0633 and source 'A' positions obtained from Chandra data are marked by the '+' and 'x' symbols, respectively. The solid and dashed boxes show regions used for extraction of the PWN and background spectra, respectively.



Figure 2. Combined XMM-Newton MOS1+MOS2 exposure-corrected image of the J0633 field in 0.4–7 keV. J0633 and source 'A' positions are marked by the '+' and 'x' symbols, respectively.

obtained with the pn detector, operated in Small Window mode, is presented in figure 1, right. J0633 and unrelated source 'A' positions derived from *Chandra* data are marked. We also constructed the combined image from MOS detectors operated in the Full Frame mode following the recipe from XMM-Newton Extended Source Analysis Software Cookbook [5]. The resulting image in 0.4–7.0 keV energy range is shown in figure 2. Besides the bright PWN seen in *Chandra* and XMM-Newton/pn images, this image also revealed a fainter large-scale emission south, west and north-west to J0633. Detailed analysis of this emission is beyond the scope of this Paper.





**Figure 3.** Left: J0633 pulse profiles in different energy bands indicated in the panels. Right: Observed phase-averaged J0633 spectrum, best-fit BB+PL model and fit residuals. The data from different instruments are shown by different colours, as indicated in the panel.

#### 3. Timing

To search for pulsations from J0633 we used the pn data with the temporal resolution of  $\approx 6$  ms and  $Z_1^2$ -test [6]. Event times extracted from the 15"-radius aperture were corrected to the solar system barycentre using J0633 *Chandra* coordinates (R.A. = 06:33:44.142, Dec = +06:32:30.40; [2]). We ran  $Z_1^2$ -test in the 3.35–3.37 Hz frequency range. It yielded a peak  $Z_{1,\max}^2 = 38.7$  at the frequency 3.3623316(14) Hz in the 0.3–2 keV band<sup>1</sup>. This corresponds to a pulsation detection at  $\approx 4.5\sigma$ . The pulsation frequency is consistent with the pulsar rotation frequency extrapolated from the epoch of the *Fermi* timing solution<sup>2</sup> [8]. Thus, we used the *Fermi* ephemeris to assign a pulse phase to X-ray photons. In  $\gamma$ -rays, the J0633 pulse profile shows two distinct peaks representing the magnetospheric emission while in X-rays the profile is broad, as typical for the spin-modulated thermal emission from a NS surface (see figure 3, left). The X-ray pulsed fraction PF =  $(I_{\max} - I_{\min})/(I_{\max} + I_{\min})$ , where  $I_{\max}$  and  $I_{\min}$  are maximum and minimum intensities of the pulse profile, corrected for the background is  $23 \pm 6\%$  in the 0.3–2 keV band.

#### 4. Phase-averaged spectral analysis

For the spectral analysis we used MOS and pn data. J0633 and PWN spectra were extracted from the 15"-radius aperture and the solid box shown in the right panel of figure 1, respectively (J0633 and source 'A' were excluded from the PWN region). The background spectrum was extracted from the dashed box (figure 1, right panel). J0633 and PWN spectra were fitted simultaneously with a common absorbing column density in the 0.3–10 keV band using *C*-statistic [9] and the model for a Poisson background, where each bin in the background spectrum is described by its own parameter. For the J0633 spectrum, we used models consisting of a non-thermal (PL) component, describing the pulsar magnetosphere emission, and a thermal component, representing NS surface emission. For the latter, we applied the blackbody (BB) model and the NS atmosphere model NSMAX [10]. The PWN spectrum was fitted with a PL model. The best-fit parameters are presented in table 1 while the pulsar spectrum and the best-fit BB+PL model are shown in figure 3, left. No absorption line at 0.8 keV is seen in the phase-averaged spectra. The derived spectral parameters within uncertainties are in agreement with values from [3].

<sup>&</sup>lt;sup>1</sup> We used the formula from [7] to calculate  $1\sigma$  frequency uncertainty

<sup>&</sup>lt;sup>2</sup> http://www.slac.stanford.edu/~kerrm/fermi\_pulsar\_timing/

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**Table 1.** Best-fit spectral parameters for J0633 and its PWN. All uncertainties correspond to 90% confidence.  $N_{\rm H}[10^{21} {\rm ~cm^{-2}}]$  is the absorption column density,  $\Gamma$  are photon indices,  $K[10^{-5} {\rm ~ph~s^{-1}~cm^{-2}~keV^{-1}}]$  are normalizations of PL components. For the NSMAX model, the redshift parameter  $1 + z_g = 1.21$  and magnetic field  $B = 4 \times 10^{12}$  G. Temperatures  $T[{\rm eV}]$  and emitting area radii  $R[{\rm km}]$  at the distance of 1 kpc are given as measured by a distant observer. d.o.f. = degrees of freedom.

Model	$N_{\rm H}$	$\Gamma_{\rm psr}$	$K_{\rm psr}$	Т	R	$\Gamma_{\rm pwn}$	$K_{\rm pwn}$	C/d.o.f.
BB+PL NSMAX+PL	$1.5^{+0.4}_{-0.3}\\1.9^{+0.4}_{-0.4}$	${\begin{array}{c}{1.85}\substack{+0.29\\-0.30}\\{1.36}\substack{+0.30\\-0.33\end{array}}$	$\begin{array}{c} 1.0^{+0.3}_{-0.3} \\ 0.5^{+0.3}_{-0.2} \end{array}$	$\begin{array}{c} 120^{+9}_{-8} \\ 54^{+6}_{-5} \end{array}$	$\begin{array}{c} 1.1\substack{+0.5\\-0.3}\\ 9.2\substack{+5.3\\-3.6} \end{array}$	$\begin{array}{c} 1.58\substack{+0.13\\-0.12}\\ 1.67\substack{+0.13\\-0.13}\end{array}$	$2.4_{-0.3}^{+0.3} \\ 2.7_{-0.4}^{+0.3}$	769/765 772/765

#### 5. Distance to J0633

We estimated the distance to J0633 using the column densities  $N_{\rm H}$  obtained from the X-ray fits (table 1) and different correlations between the distance and the reddening E(B - V) [11, 12, 13]. The E(B - V) values were obtained using an empirical correlation  $N_{\rm H} = (0.7 \pm 0.1) \times E(B - V) \times 10^{22} \text{ cm}^{-2}$  [14]. This results in the distance range of 0.7–2.2 kpc.

#### 6. Summary

We detected, for the first time, the X-ray pulsations from J0633 with the pulsar period. The pulse profile is broad as expected for spin-modulated thermal emission. The pulsed fraction in the 0.3-2 keV band is  $23 \pm 6\%$ . The X-ray phase-averaged spectrum of J0633 can be well described either by the BB+PL or NSMAX+PL model. Resulting parameters are in agreement with [3] though XMM-Newton observations do not confirm the absorption line at 0.8 keV in the pulsar spectrum detected in *Chandra* data. The distance to J0633 estimated using interstellar extinction-distance relations is 0.7-2.2 kpc.

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