Toward an X-ray inventory of nearby neutron stars

A. Vahdat\textsuperscript{1}\textsuperscript{*}, B. Posselt\textsuperscript{2,3}, A. Santangelo\textsuperscript{1}, and G.G. Pavlov\textsuperscript{3}

\textsuperscript{1} Institut für Astronomie und Astrophysik, Universität Tübingen, Sand 1, D-72076 Tübingen, Germany
e-mail: arminvahdat@astro.uni-tuebingen.de
\textsuperscript{2} Department of Astrophysics, University of Oxford, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, UK
\textsuperscript{3} Department of Astronomy & Astrophysics, Pennsylvania State University, 525 Davey Lab, 16802 University Park, PA, USA

Received —-, 2021; accepted —-, 2021

\textbf{ABSTRACT}

\textbf{Context.} The X-ray emission of neutron stars enables a probe of their temperatures, geometries and magnetospheric properties. The current number of X-ray emitting pulsars is insufficient to rule out observational biases that may arise from poorly known distance, age, or location of the neutron stars. One approach to overcome such biases is to create a distance-limited sample with sufficiently deep observations.

\textbf{Aims.} With the aim of better sampling of the nearby (\leq 2kpc) population of neutron stars, we started an \textit{XMM-Newton} survey of pulsars to measure their X-ray fluxes or derive respective constraining upper limits.

\textbf{Methods.} We investigated 14 nearby pulsars for potential X-ray counterparts using different energy bands and detectors. In addition to our new \textit{XMM-Newton} data, we also considered archival data and catalogs. We discuss source properties and also check for alternative counterparts to the X-ray sources.

\textbf{Results.} In our new \textit{XMM-Newton} data, we found two pulsar counterpart candidates with significance above 4\sigma and one candidate with 3.5\sigma by combining EPIC camera detection likelihoods. We also report the detection of potential X-ray counterparts to eight radio pulsars in the 4XMM-DR10 catalog which have not been reported in the literature.

\textbf{Conclusions.}

\textbf{Key words.} neutron stars – pulsars; individual: J0340+4130, J0711-6830, J0745–5353, J0942–5552, J0945–4833, J0954–5430, J0957–5432, J1000–5149, J1003–4747, J1125–5825, J1435–5954, J1535–4114, J1622–0315, J1643–1224, J1702–4310, J1725–0732, J1740–3015, J1755–0903, J1825–1446, J1831–0952, J1857+0943, J1926–1314, population study – XMM survey

1. Introduction

In solitary neutron stars (NSs), thermal X-rays are produced by the cooling of NS surfaces and from hot spots such as polar caps heated by particles accelerated in the magnetosphere. On the other hand, the accelerated particles generate non-thermal synchrotron and curvature radiation. Interaction of the pulsar wind with the interstellar medium (ISM) produces shocks that can contribute to the non-thermal X-ray emission. This can contaminate the observed pulsar spectrum considerably if the pulsar and pulsar wind nebula are not spatially resolved.

In young, energetic rotation-powered pulsars (RPPs), such as the Crab pulsar, the thermal radiation from the hot neutron star is outshined by non-thermal magnetospheric emission, and the X-ray spectra often have a power-law (PL) shape. As pulsars age, thermal emission becomes more prominent and the spectra can be described by the combination of thermal and non-thermal emission (an example is the Vela pulsar). There are also solitary pulsars that show predominantly thermal X-ray emission, such as central compact objects (CCOs) or the group of stars known as the Magnificent Seven (e.g., Haberl 2007; Gotthelf et al. 2013). Lastly, the millisecond pulsars (ms-pulsars) that are assumed to be spun up through accretion from a companion (Alpar et al. 1982) usually show both thermal and non-thermal emission components in their X-ray spectra. The small emission radii obtained by spectral fits imply the origin of thermal radiation to be one or two heated polar caps, whereas the non-thermal emission is presumed to have a magnetospheric origin (e.g., Zavlin & Pavlov 1998; Forestell et al. 2014).

X-ray emitting NSs have been identified in surveys such as the ROSAT All Sky Survey (0.1-2.4 keV energy; Voges et al. 1999), complemented by X-ray observations with \textit{XMM-Newton} and \textit{Chandra} (e.g., Becker 2009). Neutron stars that were not already known as radio or \gamma-ray pulsars were noticed in X-rays, either due to signatures of ongoing accretion or simply because they were nearby, young and powerful, or hot. Other NSs were discovered by their variability (outbursts) or activity in other wavelengths, (e.g., soft gamma-ray repeaters). Many X-ray emitting NSs were found in targeted (deeper) searches based on their radio and \gamma-ray properties. A few pulsars falling in the field of view (FOV) of pointed observations by X-ray satellites have also been discovered (e.g., Pires et al. 2009; Prinz & Becker 2015).

However, many NSs were not covered by sufficiently deep X-ray exposures. A selection effect cannot be excluded and may lead to a biased view of the known X-ray emitting NS population, which could result in a biased interpretation of their general X-ray properties such as temperature, spectral index of non-thermal emission, and X-ray efficiency. To date, roughly 5-7\% of the known pulsar population has been detected in X-rays.
Pulsars lacking X-ray detection may simply be too faint for the previous surveys, for example because they are too far away or too absorbed, or they may indeed be “X-ray quiet.” X-ray monitoring with all-sky surveys such as the ongoing eROSITA will provide an important contribution to obtain a flux-limited population of X-ray emitting NSs in the Galaxy. A complementary approach that aims for an unbiased coverage of the NS population is to restrict the analyzed sample to a certain distance and increase the number of observed sources in that distance range. In this study, we present the first results of an XMM-Newton survey aimed at a better sampling of the nearby (≤ 2 kpc) NS population.

Although thermal and non-thermal emission can coexist during the lifespan of a NS, the dominant type of emission depends on its physical properties such as age and overall energy budget. One key question at the origin of X-ray emission from pulsars is to figure out how much of the available energy budget is converted into X-rays, and how this changes over the NS lifespan.

There is a general correlation between the X-ray luminosity ($L_X$) from non-thermal and thermal emission (from polar caps) and spin-down luminosity ($E$) of NSs, but the X-ray efficiency ($\eta_X = L_X/E$) shows a large variation ($\eta_X \sim 10^{-6} - 10^{-2}$). The reported spread of $\eta_X$ can be related to the choice of energy range, spectral model, and consideration of extended emission (Becker & Truemper 1997; Possenti et al. 2002; Li et al. 2008; Kargaltsev et al. 2012). For example, the fluxes in the soft X-ray range are more sensitive to the uncertainties due to the interstellar absorption which may cause a biased view toward the population of thermally dominated NSs.

Furthermore, it has been pointed out by several authors that the X-ray emission becomes more efficient at $E \leq 10^{34} - 10^{35}$ erg s$^{-1}$. This could support polar cap and pair cascade model predictions indicating an increase in electron-positron pair heating luminosity (Harding & Muslimov 2011; Harding & Muslimov 2001) or it could reflect the presence of the dominant non-dipole magnetic field (Kisaka & Tanaka 2017). However, there are too few pulsars with $E \leq 10^{44}$ ergs s$^{-1}$ to constrain theoretical models. Different sample selections may lead to different X-ray efficiencies. For instance, in middle-aged pulsars the X-ray efficiencies, $\eta_X \sim 10^{-3} - 10^{-2}$, seem to be higher than in younger ones, $\eta_X \sim 10^{-5} - 10^{-3}$ (Kargaltsev et al. 2012; Posselt et al. 2012).

The number of X-ray detected nearby pulsars is currently insufficient to exclude selection biases towards their observational properties. We approach this problem by conducting a survey of the nearby (≤ 2 kpc) NS population. In §2 we describe our source selection strategy and data analysis steps for our survey, including the consideration of nearby multiwavelength sources as alternative X-ray counterparts. In §3 we present the initial results of the survey, where we provide the significance and upper limits for the observed sources. §4 covers the details of our additional serendipitous archival candidate studies. Finally, §5 discusses the X-ray efficiency of sources, the effect of different distance estimates, and the implications.

2. Observations and analyses

2.1. Source selection and observations

We used the ATNF catalog (Manchester et al. 2005, V1.57) to select all known nearby (≤ 2 kpc) NSs that had no X-ray coverage in the field of view of archived XMM-Newton pointing (search radius 13’ around pulsar position) and Chandra pointing (search radius 10’) observations. We chose 2 kpc as a cutoff threshold for the distance of the pulsars. Above this value, the absorption effects become much more problematic for thermal emission, making it harder to detect NS where this type of emission dominates (e.g., the Magnificent Seven, Haberl et al. 2004).

We used distance estimates from the ATNF, which are typically based on the dispersion measure (DM) from radio timing observations, and the electron density model by Yao et al. (2017) (YMWF+17). Some of these estimates may differ up by to an order of magnitude from the results based on the electron density model by Cordes & Lazio (2002) (NE2001). We also list these distances for completeness in Table 1 and discuss distance differences of these estimates in §5.1. Using the pulsar’s spin-down luminosity ($\dot{E}$), distance ($D$), and average expected hydrogen column density ($N_H$) calculated from the DM, we assumed a preliminary X-ray efficiency of $10^{-4}$ to estimate expected absorbed X-ray fluxes. We started our survey with those pulsars for which a detection seemed most likely in a short exposure time. Fourteen pulsars were observed with the XMM-Newton EPIC instrument in 2018, with 5-20 ks exposures (Program ID: 082303) with the Thin and Medium filters. Here we present the results of the first year of the survey. The survey sources observed to date, their exposure times, and their selected observational properties are presented in Table 1.

2.2. Source detection optimization

To optimize the choice of our energy bands for source detection, we analyzed the detection likelihoods of known X-ray-detected pulsars in 4XMM-DR10. We found that the energy bands 0.3-2.0 keV and 1.0-4.5 keV have the highest number of detections based on their maximum likelihood (ML) distributions compared to other bands at soft and mid-X-ray energies. We then analyzed a few pulsars with known X-ray detections using the archival data to test these values and also checked for other broader and narrower bands. We decided to add the following energy ranges for our analyses: 0.3-1.2 keV, 0.3-1.5 keV, and 0.3-4.5 keV. These ranges provided the highest detection significance defined as:

$$S = \frac{N_s}{\sqrt{\sigma(N_s)}} = \frac{N_T - \alpha N_{bgr}}{\sqrt{N_T + \alpha^2 N_{bgr}}}$$

where $N_s$ is the number of background-subtracted source counts, $N_T$ and $N_{bgr}$ are total counts within the source and background regions, and $\alpha$ is ratio of source to background region.\(^1\)

2.3. Data reduction and analyses

All data were reduced with XMM-Newton Science Analysis Software (SAS, V18.0.0.) applying standard tasks. We filtered with FLAG==0 to avoid CCD gaps and bad pixels. We performed a good time interval (GTI) screening to identify and remove flares caused by energetic protons. Since our short observations were impacted by many background flares, standard background flare screening would have often removed more than half of the exposure time. Therefore, we allowed a stronger background...\(^1\)

\(^1\) Although we list the conservative $S$ (Eq. 1), an alternate significance definition by Li & Ma (1983),

$$S = \sqrt{\frac{N_T}{\alpha N_{bgr}}} \left(\frac{N_s}{\sqrt{N_T + \alpha^2 N_{bgr}}} + N_{bgr} \ln \left(\frac{N_{bgr}}{N_T + \alpha^2 N_{bgr}}\right)^{1/2}\right)$$

would result in a significance higher by a factor of ~1.2-1.4.
Notes. Pulsar names and their XMM-Newton obsid’s are given in the first and second column. The pulsars in binary systems are marked with 8. The following six column displays EPIC-pn and EPIC-MOS total and GTI-filtered exposure times (given in parentheses) and the GTI filter for the background light curve and the corresponding filters for each EPIC detector. “TN” is thin filter and “M” is medium filter. Source properties are noted in the last five columns. P is the spin period in seconds, D the distance in kpc, Parthasarathy et al. 2019). We obtained the background-subtracted source significance, we used the cstat test statistics and obtained similar results, and therefore we only report the former. We provide the spectral fit results in §4.

2.4. Flux estimates

Since there are typically not enough counts to produce meaningful spectral fits for our sources, we had to assume a spectrum to convert the photon flux to energy flux. Ordinary and ms-pulsars can have both thermal and non-thermal emission components. Aiming to represent two extremes, we decided to convert count rates to fluxes assuming two different spectral models, namely a power law (PL) with a photon index of 1.7 (e.g., Becker 2009) and a blackbody (BB) with $kT = 300$ eV (e.g., Forestell et al. 2014). We used PIMMS v4.11 for this conversion. To account for absorption, we estimated the $N_H$ values using the formula

$$N_H (10^{20} \text{cm}^{-2}) = 3.0 \times 10^{18} (D_{kpc} [10^6])$$

For the BB (0.3-2.0 keV) and PL (1.0-4.5 keV) models we converted EPIC-pn count rates to absorbed and unabsorbed fluxes. For the PL model, we chose an output energy range of 1-10 keV for easier comparison with the literature. Since no good parallax or alternative distance estimates were available for our pulsars, we used the DM-based distances (Yao et al. 2017) to convert unabsorbed fluxes and upper limits to isotropic X-ray luminosities $L_{1-10 \text{keV}} = \pi D_{kpc}^2F_{\text{unabs}}$. PSR J1831–0952 was the only source in our list that satisfied this criterion. For this source we generated source and background spectra from the extraction region provided by erogianalyse. We produced redistribution matrices and effective area files using the usual SAS tasks rmfgen and arfgen. We then used the SAS task specgroup to group the source counts of each spectrum with $\geq 15$ per bin. We repeated the procedure with 5 cts binning and cstat test statistics and obtained

Table 1. Properties of the ordinary and millisecond pulsars investigated with XMM-Newton in this study.

| Pulsar  | ObsID       | $l_{\text{sex}}$ (ks) | $b_{\text{sex}}$ (ks) | $l_{\text{sex}}$ (ks) | $b_{\text{sex}}$ (ks) | $l_{\text{sex}}$ (ks) | $b_{\text{sex}}$ (ks) | $P$ (ms) | $D_1$ (kpc) | $D_2$ (kpc) | $\log E$ (keV) | $N_{\text{H1}}$ |
|---------|-------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|----------|-------------|-------------|----------------|---------------|
| J0711–6830 | 0823030601 | 11.9 (6.1)             | 13.8 (9.8)             | 13.8 (9.2)             | 2.5 (TN)               | 0.35 (M)               | 0.35 (M)               | 5        | 0.11         | 0.86        | 33.6          | 0.6           |
| J0745–5535 | 0823031401 | 18.9 (13.5)            | 20.8 (18.4)            | 20.8 (16.1)            | 0.4 (TN)               | 0.2 (TN)               | 0.2 (TN)               | 215      | 0.57         | 0.25        | 34.0          | 3.8           |
| J0942–5552 | 0823031001 | 18.7 (13.5)            | 20.6 (20.2)            | 20.6 (20.2)            | 0.5 (TN)               | 0.35 (TN)              | 0.35 (TN)              | 664      | 0.30         | 3.8         | 33.5          | 5.6           |
| J0945–4833 | 0823031101 | 17.1 (11.2)            | 19.6 (17.5)            | 19.6 (17.2)            | 0.5 (TN)               | 0.2 (TN)               | 0.2 (TN)               | 331      | 0.31         | 1.51        | 33.7          | 3.0           |
| J0954–5430 | 0823030101 | 17.5 (5.6)             | 17.6 (7.2)             | 17.6 (7.3)             | 0.8 (M)                | 0.35 (M)               | 0.35 (M)               | 203      | 0.45         | 4.33        | 34.0          | 7.0           |
| J1000–5149 | 0823030301 | 7.0 (5.8)              | 8.9 (6.2)              | 8.9 (8.7)              | 0.4 (TN)               | 0.35 (M)               | 0.35 (M)               | 255      | 0.13         | 1.93        | 33.4          | 2.2           |
| J1003–4747 | 0823030201 | 14.7 (9.3)             | 15.7 (5.6)             | 15.7 (5.6)             | 0.8 (M)                | 0.35 (M)               | 0.35 (M)               | 307      | 0.37         | 2.94        | 34.5          | 3.0           |
| J1017–7156 | 0823030701 | 10.5 (3.3)             | 11.9 (10.7)            | 11.9 (10.0)            | 0.6 (TN)               | 0.2 (M)                | 0.2 (M)                | 5        | 0.26         | 2.98        | 33.8          | 2.9           |
| J1125–5825 | 0823031601 | 18.7 (5.7)             | 20.6 (16.9)            | 20.6 (16.9)            | 0.7 (TN)               | 0.35 (M)               | 0.35 (M)               | 3        | 1.74         | 2.62        | 34.9          | 3.9           |
| J1543–5149 | 0823030901 | 6.5 (3.3)              | 8.4 (8.3)              | 8.4 (8.2)              | 0.4 (TN)               | 0.35 (TN)              | 0.35 (TN)              | 2        | 1.15         | 2.42        | 34.9          | 1.6           |
| J1725–0732 | 0823031501 | 15.1 (12.3)            | 17.0 (16.7)            | 17.0 (16.7)            | 0.4 (TN)               | 0.35 (M)               | 0.35 (M)               | 240      | 0.20         | 1.90        | 33.1          | 1.8           |
| J1740–3015 | 0823030101 | 4.7 (1.7)              | 6.6 (6.0)              | 6.6 (5.7)              | 1.0 (TN)               | 0.35 (M)               | 0.35 (M)               | 607      | 0.40         | 2.94        | 34.9          | 4.7           |
| J1755–0903 | 0823030501 | 4.7 (3.9)              | 6.6 (6.5)              | 6.6 (6.5)              | 0.4 (TN)               | 0.35 (M)               | 0.35 (M)               | 191      | 0.23         | 1.79        | 33.6          | 2.0           |

2 For positions, proper motions, and parallaxes we used the values listed in the ATNF catalog V1.64

Contribution in some observations to maximize potential photon numbers from our target. The full list of GTI rates used for observations are presented in Table 1. We tested several GTI filters derived from 100 s binned light curves of events with energies above 10 keV. For each GTI-filtered event file, we generated images and exposure maps in five energy bands as specified above. For positions, proper motions, and parallaxes we used the values listed in the ATNF catalog V1.64.
Table 2. Properties of the selected ordinary and millisecond pulsars investigated in this study.

| Pulsar     | ObsID     | ΔX,ΔY (arcsec) | N \text{\textsubscript{UL}} (counts) | S (\text{cts/s}) | UL \text{\textsubscript{UL}} | N \text{\textsubscript{ML}} (counts) | S (\text{cts/s}) | UL \text{\textsubscript{ML}} | N \text{\textsubscript{EPIC}} (counts) | S (\text{cts/s}) | UL \text{\textsubscript{EPIC}} | N \text{\textsubscript{Combined}} (counts) | S (\text{cts/s}) | UL \text{\textsubscript{Combined}} |
|------------|-----------|---------------|--------------------------------------|----------------|-----------------|--------------------------------------|----------------|-----------------|--------------------------------------|----------------|-----------------|--------------------------------------|----------------|-----------------|
| J0711–6830 | 0823030001 | 1.7           | 23.5x13.0  1.8                       | 0.0080        | --              | 0.0005                  | 11.3e+7        | 2.4              | 0.0005                  | 54.8e+5        | 3.5              | 14.9                  |                |                 |
| J0745–5353 | 0823031401 | 1.5           | 27.2x7.6   3.6                       | --            | 6.2e+4         | 1.6                  | 0.0006                  | 8.1e+4         | 1.9              | 0.0007                  | 39.6e+5        | 4.3              | 16.2                  |                |                 |
| J0942–5552 | 0823031301 | 9.7           | 31.7x10.3  3.1                       | --            | --              | 0.0004                  | --                    | --              | --              | --                    |                | --              | --                    |                |                 |
| J0945–4833 | 0823031101 | 2.3           | 14.8x7.2   2.2                       | 0.0021        | 3.3x5.1        | 0.0008                  | --                    | --              | --              | --                    |                | --              | --                    |                |                 |
| J0945–5430 | 0823030401 | 1.2           | 4.4x4.2    1.1                       | 0.0021        | 1.7x3.2        | 0.0009                  | 2.5e+2         | 0.0002         | 0.0012                  |                | --              | --                    |                |                 |
| J0957–5432 | 0823030001 | 8.5           | 9.0x5.8    1.6                       | 0.0024        | 8.3x5.6         | 1.5                  | 0.0008                  | --              | --              | --                    |                | --              | --                    |                |                 |
| J1000–5149 | 0823030301 | 2.7           | --         --                          | 0.0007        | --              | 0.0005                  | --                    | --              | --              | --                    |                | --              | --                    |                |                 |
| J1003–4747 | 0823032001 | 2.1           | 10.5x8.4   1.3                       | 0.0019        | 3.4x3.8        | 0.0005                  | --                    | --              | --              | --                    |                | --              | --                    |                |                 |
| J1017–7156 | 0823030701 | 5.3           | 1.6x3.9    --                          | 0.0015        | --              | 0.0002                  | --                    | --              | --              | --                    |                | --              | --                    |                |                 |
| J1125–5825 | 0823031601 | 0.6           | 18.8x6.7   2.8                       | 0.0038        | 17.4x6.3       | 2.8                  | 0.0012                  | 10.3e+5        | 2.0              | 0.0009                  | 47.4e+10      | 4.7              | 20.9                  |                |                 |
| J1543–5149 | 0823030901 | 1.2           | 4.0x4.0    1.0                        | 0.0018        | 3.8x3.6        | 1.2                  | 0.0011                  | --              | --              | --                    |                | --              | --                    |                |                 |
| J1725–0732 | 0823031501 | 4.4           | 3.3x3.8    --                          | 0.0006        | 1.6x2.7        | 0.0004                  | --                    | --              | --              | --                    |                | --              | --                    |                |                 |
| J1740–3015 | 0823030101 | 7.8           | 6.4x3.5    1.8                        | 0.0064        | --              | 0.0008                  | --                    | --              | --              | --                    |                | --              | --                    |                |                 |
| J1755–0903 | 0823030501 | 0.3           | 6.2x4.1    1.5                        | 0.0031        | --              | 0.0006                  | --                    | --              | --              | --                    |                | --              | --                    |                |                 |

Notes. The ΔX,ΔY column displays angular separation in arcseconds between the pulsar’s radio timing position and the centroid of the nearest X-ray source. Background-subtracted counts \(N_{\text{UL}}\) at the optimized X-ray source position and their corresponding significance \(S\) according to Kraft et al. (1991). The ML values are given in 0.3-2.0 keV for PSRs J0745–5353 and J1017–7156, and in 0.3-4.5 keV for PSR J0711–6830.

2.5. Are there alternatives to explain the X-ray sources?

We used the 3\(σ\) position uncertainty radius to check for nearby optical or infrared sources that could be the origin of the observed X-ray emission or could contribute to it. We used the Gaia-EDR3 catalog (Riello et al. 2020), 2MASS (Skrutskie et al. 2006), WISE (Wright et al. 2010), NOMAD (Zacharias et al. 2004) and TESS Input Catalog (Stassun et al. 2018). To test the hypothesis of a different counterpart, we assumed that all the X-ray flux could come from an optical source, and investigated the resulting X-ray to optical flux ratios, and optical to NIR color-color and color-magnitude diagrams, and proper motions and distances if known. We used this information to classify each optical source based on the studies by Maccacaro et al. (1988), Covey et al. (2007), and Bailer-Jones et al. (2019).

We obtained visual magnitudes \(m_V\) by converting the Gaia-EDR3 passbands and colors using Landolt standard stars observed with Gaia (Riello et al. 2020). We interpret the obtained ratios of X-ray to optical flux by using the classification scheme by Maccacaro et al. (1988) to determine whether the optical source has a high likelihood of being an AGN or a main sequence star. Objects such as galaxies, and AGNs might not follow the Gaia photometry conversion relations (Riello et al. 2020). However, we also used astrometric properties such as distances and proper motions from Gaia-EDR3 to verify a stellar origin. In the absence of 2MASS counterparts, we converted Gaia colors to SDSS colors (Riello et al. 2020) for classifications shown in Table 3 of Covey et al. (2007). Bailer-Jones et al. (2019) did an empirical classification of Gaia-DR2 objects (with \(G \geq 14.5\) magnitudes) using only Gaia-DR2 data. They used a probabilistic classifier to catalogue sources as stars, quasars or galaxies based on their Gaia colors, magnitudes, and astrometric features such as parallax and proper motion. We took their results into account to classify the potential multiwavelength counterparts in our list.

Finally, we considered the classification into point sources (stars) and extended sources (e.g., galaxies) provided by the TESS Input Catalog. We found ten potential optical counter-
parts within the 3σ position uncertainty regions of six of our X-ray candidates (including five archival X-ray sources, see section §4). In order to determine whether these optical sources can be excluded as counterparts of the X-ray emission, we evaluated the respective results of the studies (Table 7).

3. Results
Among the five energy bands mentioned in §2.2, 0.3–2.0 keV provided the highest overall detection significance in the EPIC instruments for our survey sources. We therefore present the results for this band. We note that the sensitivity loss due to background flaring events (up to 65% exposure time loss) was higher than anticipated for our sources.

In the framework of our program we detected three X-ray point sources with at least 3.5σ sufficiently close to the radio positions of pulsars J0711–6830, J0745–5353, and J1125–5825 to investigate a possible association. The exposure times, used distances, and source properties are listed in Table 1. The angular separation between radio and X-ray position of these pulsars and their EPIC-pn and EPIC-MOS significance are given in Table 2. The corresponding EPIC images of the X-ray counterpart candidates to the three pulsars are displayed in Figure 1. Their estimated flux and luminosity values are given in Table 5.

**PSR J0711–6830**

The X-ray counterpart candidate is detected 1.7″ away from the radio position of the pulsar. The source may be an example of strong non-thermal emission as the inclusion of higher energies resulted in a detection in contrast to the narrower soft energy band that did not have enough counts. However, detailed inspection of the data revealed an irregular shape of the count distribution in EPIC-MOS2, a noise-like appearance in EPIC-pn, and the absence of the source in EPIC-MOS1, raising doubts about the reality of the detection of this source.

**PSR J0942–5552**

For this X-ray source, the location with the highest significance according to *regionanalyse*, is 9.7″ away from the radio pulsar position. However, the lack of detection in EPIC-MOS1/MOS2 and the high angular separation between the X-ray and radio position prevents us from claiming a match. We also noticed a nearby (unknown) extended X-ray source, but the angular separation of ≈ 25″ between its emission peak and the radio pulsar position indicates that an association with the pulsar is unlikely. Thus, we conclude that in the sample of 14 pulsars only 2 pulsars, J0745–5353 and J1125–5825, are likely detected.

4. Additional archival X-ray counterpart candidates of pulsars
While using archival X-ray source catalogs to optimize our detection energy range, we noticed some potential pulsar counterparts, which to our best knowledge, have not been reported. To identify them, we first matched the radio position of pulsars in the latest ATNF catalog (Manchester et al. 2005, V1.64) with the *XMM-Newton* (4XMM DR10, Webb et al. 2020) and *Chandra* (CSC v2, Evans et al. 2010) catalogs, and selected all the pulsars that fall within the search radius of 10″ (4XMM DR10) and 5″ (CSC v2), respectively. We selected 340 X-ray sources. Assuming an upper limit of 2 kpc on pulsar distance, the number of candidates is reduced to 101. Finally, we excluded all pulsars with known X-ray counterparts using archives such as SIMBAD and ADS. As a result, we identified new potential X-ray counterparts for three nearby pulsars in the 4XMM-DR10 catalog not reported in the literature.

Furthermore, we used the same catalogs to also look for new significant detections of pulsars for which upper limits were reported in X-ray surveys such as carried out by Prinz & Becker (2015) and Lee et al. (2018). Typically, new detections are due to additional data or improved SAS/CIAO processing routines. We found five additional *XMM-Newton* catalog sources within a 10″ search radius of the radio pulsar positions. We did not find any unpublished X-ray emitting pulsar candidates in the *4XMM-DR10* catalog. For consistency, for all the archival sources, we performed the same analyses as we did for our survey pulsars. This allowed a direct comparison in terms of energy bands and fluxes. The source properties and analysis results are provided in Table 3 and Table 4. The fluxes are given in 0.3–2.0 keV for the BB model and 1-10 keV for the PL model in Table 5. The total positional uncertainty of archival sources are obtained from the 4XMM-DR10 catalog. We use the P05ERR at the 3σ confidence level. We note that two of our archival sources have a distance > 2 kpc based on the *YMW+17* model, but we decided to include them due to their interesting X-ray characteristics.

**PSR J1622–0315**

The redback millisecond pulsar was observed in 2017 in a 22 ks exposure with EPIC and reported to be fitted well with a PL (Γ = 2.0±0.3) in the PhD thesis by Gentile (2018). The X-ray counterpart candidate is located 0.8″ away from the radio pulsar position.

Considering a total position uncertainty of 3.3″ (3σ), we found one *Gaia* source 0.9″ away from the X-ray source which can be excluded as the sole counterpart to the X-ray source (Table 7). The Gaia source is reported as the companion counterpart of the pulsar (Strader et al. 2019), but the X-ray emission is expected to come from the pulsar and possibly from an intra-binary shock (e.g., Romani & Sanchez 2016). We can also exclude this source as the main X-ray counterpart of the pulsar based on the contradiction between the expected temperature of an M star (~3200 K; Rajpurohit et al. 2013) and the reported temperature $T_{eff} = 6108K$ according to Stassun et al. 2019. There is also one WISE source (ID: J162259.63–031536.9) with an angular separation of 1.2″, and due to the lack of WISE colors we are not able to classify the nature of this source.

**PSR J1831–0952**

Since the X-ray counterpart candidate has 155±40 combined net counts in the energy range 0.3–10 keV, we performed a spectral fit. *XMM-Newton* only covered the source with EPIC-MOS. For the fit we combined EPIC-MOS1 and EPIC-MOS2 spectra in the 0.3–10 keV energy range. We fitted the spectra with a single PL model, but we decided to include them due to their interesting X-ray characteristics.
The solitary (τ = 2 Myr) pulsar J1926–1314 was discovered by Rosen et al. (2013) with a relatively high inferred magnetic dipole field of $B_{\text{surf}} = 1.4 \times 10^{13}$ G. A faint soft X-ray source is detected 5.4″ from the pulsar.

**5. Discussion**

The X-ray analyses of our radio pulsars revealed a few important aspects that explain the low detection rate in the sample. First, more observation time than anticipated was lost due to bad weather and technical issues. The X-ray analyses of our radio pulsars revealed a few important aspects that explain the low detection rate in the sample. First, more observation time than anticipated was lost due to bad weather and technical issues.

**Table 3.** Properties of the ordinary and millisecond pulsars that are investigated in this study.

| Pulsar | ObsID    | $b_{\text{ps}}$ (ks) | $\Delta b_{\text{ps}}$ (ks) | $b_{\text{ns}}$ (c/s) | $\Delta b_{\text{ns}}$ (c/s) | $b_{\text{m1}}$ (c/s) | $\Delta b_{\text{m1}}$ (c/s) | $P$ (ms) | $D_1$ (kpc) | $D_2$ (kpc) | $\log E$ (erg s$^{-1}$) | $N_{\text{at21}}$ |
|--------|----------|----------------------|-----------------------------|-----------------------|-----------------------------|-----------------------|-----------------------------|---------|-------------|-------------|-------------------------|---------------|
| J0340+4130 | 0005470101 | 19.5 (6.3) | 20.7 (14.8) | 20.6 (15.0) | 0.4 (TN) | 0.35 (TN) | 0.35 (M) | 3 | 1.60 | 1.73 | 33.9 | 1.5 |
| J1345–5954 | 0092050101 | 130.1 (90.0) | -- | -- | 0.4 (M) | -- | -- | 473 | 1.06 | 1.18 | 32.7 | 1.3 |
| J1355–4114 | 0652610201 | 101.4 (63.2) | 102.4 (84.6) | 102.4 (93.9) | 0.4 (TK) | 0.35 (TK) | 0.35 (TK) | 432 | 2.77 | 1.95 | 33.3 | 1.99 |
| J1622–0315 | 0784770401 | 19.0 (6.8) | 20.6 (16.5) | 20.6 (16.1) | 0.4 (M) | 0.30 (M) | 0.35 (M) | 4 | 1.14 | 1.11 | 33.9 | 0.6 |
| J1643–1224 | 0742520101 | 21.8 (9.3) | 23.4 (13.8) | 23.4 (11.1) | 0.4 (M) | 0.35 (M) | 0.35 (M) | 5 | 0.74 | 2.40 | 33.8 | 1.87 |
| J1831–0952 | 0822330101 | -- | 66.6 (6.2) | 66.6 (8.7) | -- | 0.35 (M) | 0.35 (M) | 67 | 3.68 | 4.05 | 36.0 | 7.41 |
| J1857+0493 | 0742520201 | 10.5 (5.3) | 11.6 (6.3) | 11.6 (8.8) | 0.4 (M) | 0.25 (M) | 0.25 (M) | 5 | 1.20 | 1.17 | 33.6 | 0.40 |
| J1926–1314 | 0742620101 | 75.0 (56.6) | 76.6 (54.4) | 76.6 (74.7) | 0.4 (TN) | 0.35 (TN) | 0.35 (TN) | 4864 | 1.53 | 1.48 | 31.1 | 1.22 |

**Notes.** Pulsar names and their XMM-Newton obsid’s are given in the first and second column. The pulsars in binary systems are marked with R. The following six column displays EPIC-pn and EPIC-MOS total and GTI-filtered exposure times (given in parentheses) and the GTI filter for the background light curve and the corresponding filters for each EPIC detector. “TN” is thin filter, “TK” is thick filter and “M” is medium filter. Source properties are noted in the last five columns. $P$ is the spin period in seconds, $D_1$ is the best estimate of the pulsar distance in kpc according to the ATNF pulsar catalog which uses the $YMW+17$ DM-based distance as default, $\log E$ is the common logarithm of the spin-down energy loss rate in erg s$^{-1}$ and $N_{\text{at21}}$ is the hydrogen column density in unit of 10$^{21}$ cm$^{-2}$ estimated from the DM as outlined in §2.4. Sources with parallactic distance are marked with *.

**Table 4.** Properties of ordinary and ms-pulsars with possible counterparts in the 4XMM-DR10 catalog for which we could not find a respective note in the literature or that were previously marked as upper limits.

| Pulsar | ObsID | $\Delta_{X-R}$ (arcsec) | $\theta$ (arcmin) | IAU name | ML | $\sigma$ | MOS1 in 2 keV | MOS2 in 2 keV |
|--------|-------|--------------------------|-------------------|----------|-----|--------|-------------|-------------|
| J0340+4130 | 0005470101 | 4.74 | 7.8 | 4XMM J034023.3+413040 | 12.0 | 11.4±5.4 | 2.1 | 13.9±5.6 |
| J1345–5954 | 0092050101 | 2.59 | 16.9 | 4XMM J134530.1-595452 | 11.3 | 66.8±17.9 | 3.7 | -- |
| J1622–0315 | 0784770401 | 0.84 | 1.7 | 4XMM J162259.6-031538 | 63.5 | 33.9±7.8 | 4.3 | 24±6.8 |
| J1535–4114 | 0652610201 | 5.6 | 4.3 | 4XMM J153516.5-411402 | 12.7 | 72.5±16.5 | 4.4 | 21±6.8 |
| J1643–1224 | 0742520101 | 1.5 | 1.1 | 4XMM J164338.0-122458 | 112.7 | 66.8±11.3 | 5.9 | 24±6.4 |
| J1831–0952 | 0822330101 | 2.2 | 2.3 | 4XMM J183134.1-095201 | 96.9 | -- | -- | 28±9.6 |
| J1857+0493 | 0742520201 | 1.3 | 1.2 | 4XMM J185736.4+049317 | 38.3 | 27.9±6.8 | 4.1 | 7±4.5 |
| J1926–1314 | 0742620101 | 5.5 | 1.1 | 4XMM J192653.7-131358 | 6.9 | 59.6±16.7 | 3.5 | 13.5±8.2 |

**Notes.** $\Delta_{X-R}$ column displays angular separation in " between the pulsar’s radio timing position and the centroid of the nearest X-ray source. $\theta$ is the EPIC-pn off-axis angle. ML is the reported 4XMM-DR10 maximum likelihood in the energy band 0.2-12.0 keV. Background-corrected counts $N_s$ at the optimized X-ray source position and their corresponding significance are displayed for EPIC-pn and EPIC-MOS1/MOS2. PSR J1831–0952 has a ~6σ significance in 0.3–4.5 keV with EPIC-MOS cameras. The off-axis angle is given for EPIC-MOS1.

mand. Abichandani et al. (2019) briefly reported the Chandra detection of a possibly extended source which is coincident with the XMM-Newton source (XGPS-I J183134–095155). We also investigated the corresponding Chandra observation. The source was observed in VFAINT mode with ACIS-I for 29 ks. We obtained 30.6 net counts in 0.3-8.0 keV. The Chandra image of the source is shown in Figure 3. The image indicates that the source is more extended than a typical point source with the extension of ~ 10″. Most of these counts (~60%) of this extended emission are detected in the energy range 2.4-8.0 keV. Considering this is likely an extended emission, the PWN could be the main contributor of the non-thermal emission.
A. Vahdat et al.: Toward an X-ray inventory of nearby neutron stars

Fig. 2. X-ray counterpart candidates in 0.3-2.0 keV as seen with the EPIC-pn (except for J1831 and J1535, which are displayed in EPIC-MOS1). The green circles are centered at the radio timing position of the pulsars, whereas the blue circles are centered at the X-ray source with the highest significance. The magenta circles show the 4XMM-DR10 positions close to these pulsars. The images have pixel scales of 0.4" and are smoothed with Gaussian length scales $\sigma = 2.2"$ (except for PSRs J1535–4115 and J1926–1314, with $\sigma = 1.4"$). The angular separations between X-ray and radio positions are given in Table 4.

Fig. 3. Chandra image of PSR J1831–0952 and X2, a point source in the field of view. The green circle is centered at the radio timing position of the pulsar, whereas the yellow circles are centered at the positions of Chandra X-ray sources (with off-axis angle of 12.2" for the extended source, X, and 1.1" for X2) with the highest significance in Chandra observations. The image has a pixel scale of 0.49" and was smoothed with a Gaussian length scale of $\sigma = 1.25"$. The red square shows the position of the Chandra optical axis. Although the X-ray counterpart of the pulsar is much closer to the optical axis, only X2 has a point-like shape, not showing a tail as the pulsar.

5.1. Distance

Since none of our survey sources had a reliable parallax measurement, we used distances that are based on the DM and the YMW+17 electron density model. YMW+17 noted that for high-latitude pulsars, the model benefited considerably from recent parallax measurements of VLBI and pulsar timing array projects, resulting in smaller distance errors compared to NE2001-based distance.

In our sample, for ~ 70% of the sources, the distances differ by more than a factor of ~ 2 between the two models with the NE2001 model mostly resulting in the larger distance estimates. Interestingly, 57% of our target list would not have satisfied the 2 kpc criterion if we had used the NE2001 model for the distances. Among our detected sources, for J0745–5353 and J1125–5825, the distances provided by the two models differ by a factor of ~ 2 whereas for J0711–6830 the NE2001-based distance is ~ 8 times higher.

Based on our detection rates, we conclude that we may have underestimated distances in our initial assessments. An improved approach would be to compare different estimates and only observe targets that have parallax measurements, have small distance deviations (less than a factor of 2) for different DM models, or are detectable for the largest listed distance.

5.2. X-ray efficiency

Assuming temporarily that the X-ray fluxes of our candidates are solely attributed to pulsars and that the distance estimates are close to reality, we show in Figure 4 the $L_X$ versus $E$ plot for the survey and archival sources for both thermal and non-thermal emission. Many sources in our sample cluster around an efficiency $\eta \sim 10^{-4}$. Only three pulsars from our list of archival X-ray observations have parallactic distances (in yellow in Figure 4), which are reasonably firm flux estimates. Except for J0711–6830, the two DM distance estimates agree within a factor of 2 for the rest of the pulsars.

The solitary ms-pulsar J0711–6830 has an X-ray efficiency that is 1-1.5 orders of magnitude lower than the typical value. However, if the distance uncertainty is taken into account, this
Table 5. X-ray fluxes and luminosities of the investigated sources.

| Pulsar      | Blackbody ($kT = 0.3$ keV) | Power-law ($\Gamma = 1.7$) |
|-------------|----------------------------|----------------------------|
|             | $F_{\text{unabs}}^{0.3-2\text{keV}}$ | $L_{\text{BB}}^{0.3-2\text{keV}}$ | $F_{\text{unabs}}^{1-10\text{keV}}$ | $L_{\text{PL}}^{1-10\text{keV}}$ |
|             | ($10^{-14}$ erg s$^{-1}$ cm$^{-2}$) | ($10^{29}$ erg s$^{-1}$) | ($10^{-14}$ erg s$^{-1}$ cm$^{-2}$) | ($10^{29}$ erg s$^{-1}$) |
| J0340+4130  | 0.46±0.23 | 14.1±7.1 | 1.07±0.58 | 33.4±18.1 |
| J0711–6830  | 0.58±0.32 | 0.10±0.06 | 2.75±1.22 | 0.44±0.21 |
| J0745–5353  | 0.80±0.23 | 3.15±0.90 | 0.92±0.33 | 3.58±1.21 |
| J0942–5552  | 1.38±0.43 | 1.48±0.52 | 0.25±0.30 | 0.23±0.40 |
| J1125–5825  | 1.36±0.48 | 49.3±17.5 | 2.45±1.44 | 88.9±51.2 |
| J1435–5954  | 0.45±0.14 | 6.05±1.3 | 0.59±0.23 | 7.93±3.12 |
| J1535–4114  | 0.31±0.10 | 28.5±6.4 | 0.34±0.10 | 31.2±10.1 |
| J1622–0315  | 0.85±0.24 | 13.2±2.9 | 1.30±0.42 | 20.2±6.5 |
| J1643–1224  | 1.58±0.27 | 10.4±1.8 | 2.23±0.51 | 14.6±3.2 |
| J1831–0952  | 0.41±0.14 | 66.4±22.7 | 2.36±0.40 | 371±60 |
| J1857+0943  | 0.84±0.23 | 13.8±3.4 | 0.54±0.22 | 9.4±4.9 |
| J1926–1314  | 0.20±0.05 | 5.8±1.4 | 0.15±0.11 | 4.3±3.1 |
| J0942–5552  | <1.21 | <1.30 | <2.69 | <2.90 |
| J0945–4833  | <0.79 | <1.16 | <1.74 | <2.55 |
| J0954–5430  | <1.22 | <2.70 | <2.65 | <5.86 |
| J0957–5432  | <1.57 | <3.80 | <3.38 | <8.19 |
| J1000–5149  | <0.19 | <0.03 | <0.42 | <0.08 |
| J1003–4747  | <0.63 | <1.03 | <1.39 | <2.28 |
| J1017–7156  | <0.49 | <0.40 | <1.07 | <0.87 |
| J1543–5149  | <0.42 | <6.65 | <0.90 | <14.2 |
| J1725–0732  | <0.15 | <0.07 | <0.32 | <0.15 |
| J1740–3015  | <2.96 | <5.67 | <6.50 | <12.4 |
| J1755–0903  | <0.81 | <0.51 | <1.75 | <1.11 |

Notes. The flux values are based on the EPIC-pn count rates (or limits) and two spectral model assumptions. $F_{\text{unabs}}^{\text{BB}}$ represents the unabsorbed X-ray flux whereas $L_{\text{BB}}^{0.3-2\text{keV}}$ and $L_{\text{PL}}^{1-10\text{keV}}$ columns represent the X-ray BB and PL luminosities respectively. For the luminosity calculation, distances based on the Yao et al. (2017) electron density model are used. The distance uncertainty is not taken into account for error estimation. For PSR J1831–0952, spectral parameters have been obtained (see Table 6) but here we list the flux derived from typical model parameters for consistency.

Table 6. Spectral fit parameters for PSR J1831–0952 obtained from combined MOS data.

| Model | $\Gamma / kT$ (keV) | $N_{\text{H,21}}$ | $F_{\text{unabs}}^{0.3-2\text{keV}}$ | $F_{\text{unabs}}^{1-10\text{keV}}$ | $\chi^2$/d.o.f |
|-------|-------------------|------------------|-----------------|-----------------|----------------|
| PL    | 0.9±0.3           | 7.4              | 4.3±0.4         | 4.0±0.7         | 17.8/15        |
| BB    | 1.2±0.2           | 7.4              | 0.4±0.1         | 0.2±0.04        | 12.3/15        |

Notes. Absorbed and unabsorbed fluxed are calculated in 1-10 keV for PL model and in 0.3-2 keV for BB model. Errors are estimated with a 90% confidence interval.

X-ray efficiency is very uncertain. The source does not have a parallax measurement and there is factor of 8 difference between the two DM-based distances ($(D_2/D_1)^2 = 61.1$). If we assume the pulsar is located at 0.86 kpc based on the NE2001 model, we obtain a luminosity of $L_{\text{BB}}^{0.3-2\text{keV}} = 5.2 \times 10^{29}$ erg s$^{-1}$ for the BB model and $L_{\text{PL}}^{1-10\text{keV}} = 2.5 \times 10^{30}$ ergs s$^{-1}$ for the PL model which places the source at the typical $10^{-4}$ range in the X-ray efficiency diagram.

Another outlier in Figure 4 is the middle-aged pulsar J1926–1314 with an X-ray efficiency of $\eta_X \sim 10^{-1.5}$. We note that the X-ray efficiency only marginally changes if the NE2001-based distance is used. As mentioned in §4, this source is thought to have a dipole magnetic field that is stronger by a factor 10 than that of a typical middle-aged pulsar. If the X-ray source is indeed the pulsar counterpart and the DM distances are correct, this could indicate a case of magnetothermal heating (see §4).
As can be seen from Figure 4, our X-ray efficiency values do not vary much for different spectra and energy bands. One reason is that we converted a fixed number of counts in the same energy band to fluxes for both spectral models. Therefore, a large flux variation is not expected. More reliable X-ray efficiencies can be obtained in future works if pulsars have better distance estimates and their thermal versus non-thermal components are resolved with follow-up observations, as illustrated by PSR J1831–0952.

6. Summary and conclusion

In this study, we reported the first result of our XMM-Newton survey aimed at a better sampling of the nearby NS population. We also checked archival catalogues for new X-ray counterpart candidates of pulsars. Our work can be summarized as follows:

1. We searched for X-ray counterparts for 14 nearby pulsars as part of our XMM-Newton survey. We analyzed data in all EPIC cameras and obtained background-subtracted source counts and 3σ upper limits for non-detections.

2. We detected two X-ray counterpart candidates at the pulsar positions with over ~ 4.3σ significance and one candidate with ~ 3.5σ significance.

3. We report on eight X-ray counterpart candidates in the 4XMM-DR10 catalogue for which we could not find a respective note on the X-ray detection of the pulsar in the literature.

4. We suspect that some of our initially chosen distance values may have been underestimated. For the optimized continuation of our survey, a more promising approach is to compare different distance models and choose only pulsars with good parallactic distances or small differences of DM-based distances.

5. Assuming that the X-ray sources are indeed the pulsar counterparts, we calculated the X-ray fluxes, X-ray luminosities, and X-ray efficiencies of these pulsars with two stand-in spectra and energy bands. One reason efficiencies do not vary much for different spectra and energy bands. One reason is that we converted a fixed number of counts in the same energy band to fluxes for both spectral models. Therefore, a large flux variation is not expected. More reliable X-ray efficiencies can be obtained in future works if pulsars have better distance estimates and their thermal versus non-thermal components are resolved with follow-up observations, as illustrated by PSR J1831–0952.

6. We assessed the possibility of an alternative MW counterpart of the reported X-ray sources using their 3σ position uncertainties in combination with the Gaia-EDR3, 2MASS, and TESS source catalogs.

7. We argued the possibility of extended emission in PSR J1831–0952 by examining both XMM-Newton and Chandra data.

8. We speculated that the high X-ray efficiency of PSR J1926–1314 could be attributed to the magneto-thermal heating if the distance is correct and the three stellar sources are excluded as counterparts of or contributors to the X-ray source in the pulsar vicinity.

We obtained X-ray constraints for 22 pulsars, increasing in particular the sample of X-ray investigated pulsars with $E < 10^{34}$ erg s$^{-1}$. Nearby stars might contribute to the X-ray fluxes of some of our pulsar counterpart candidates. For clarification, the candidates could be probed with follow-up X-ray observations aiming for higher position accuracy or pulsation detections.

Acknowledgements. We thank the anonymous referee for constructive comments that helped to improve the manuscript. This work was supported by the Bundesministerium für Wirtschaft und Energie through Deutsches Zentrum für Luft- und Raumfahrt (DLR) under the grant number 50 OR 1917. BP acknowledges funding from the UK Science and Technology Facilities Council (STFC) Grant Code ST/R50506/1. GGP acknowledges support from the ACIS Instrument Team contract SV4-74018 issued by the Chandra X-ray Observatory Center, which is operated by the Smithsonian Astrophysical Observatory for and on behalf of NASA under contract NAS8-03060. This research has made use of the VizieR catalogue access tool, CDS, Strasbourg, France (DOI: 10.26093/cds/vizier). The original description of the VizieR service was published in 2000, A&AS 143, 23.

Software: Astropy (Astropy Collaboration et al. 2018), NumPy (Harris et al. 2020), Matplotlib (Hunter 2007), Seaborn (Waskom 2021)

References
Abichandani, R., Mathur, M. B., Drake, J. J., et al. 2019, The Astronomer’s Telegram, 12463, 1
Fig. 4. X-ray luminosity of ordinary and millisecond pulsars investigated in this study versus their spindown powers $\dot{E}$ calculated with YMW+17-based distances (left) and NE2001-based distances (right). Sources with parallax measurements are displayed with yellow. The up-pointing triangles show the 1–10 keV non-thermal luminosities obtained via the PL assumption (with $\Gamma = 1.7$) for the underlying spectra, and the down-pointing triangles show the 0.3–2.0 keV thermal luminosities obtained via the BB assumption (with $kT = 300$ eV) (see discussion in §2.4). The spectrum-derived PL flux for J1831–0952 is shown as a green triangle. $\dot{E}$ values are corrected for the Shklovskii effect where relevant (Shklovskii 1970).