X-ray counterpart candidates for six new γ-ray pulsars

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ABSTRACT

Using archival X-ray data we have found point-like X-ray counterpart candidates positionally coincident with six γ-ray pulsars discovered recently in the Fermi Gamma-ray Space Telescope data by the Einstein@Home project. The candidates for PSRs J0002+6216, J0554+3107, J1844−0346 and J1105−6037 are detected with Swift, and those for PSRs J0359+5414 and J2017+3625 are detected with Chandra. Despite a low count statistics for some candidates, assuming plausible constraints on the absorbing column density towards the pulsars, we show that X-ray spectral properties for all of them are consistent with those observed for other pulsars. J0359+5414 is the most reliably identified object. We detect a nebula around it, whose spectrum and extent suggest that this is a pulsar wind nebula powered by the pulsar. Associations of J0002+6216 and J1844−0346 with supernova remnants CTB 1 and G28.6−0.1 are proposed.

Key words: compact objects: general — neutron stars: individual (PSR J0002+6216, PSR J0359+5414, PSR J0554+3107, PSR J1105−6037, PSR J1844−0346, PSR J2017+3625)

1 INTRODUCTION

The Large Area Telescope (LAT) aboard the Fermi Gamma-ray Space Telescope has discovered over 200 new young and millisecond γ-ray pulsars1. The inferred parameters for the young pulsars characterise most of them as relatively energetic rotation powered nearby neutron stars (NSs). With spin-down powers $E \gtrsim 10^{34}$ erg s$^{-1}$ and characteristic ages $\tau_c \lesssim 1$ Myr they are likely located in less than a few kpc from the Sun (Abdo et al. 2013). Young NSs, in particular nearby ones, are rare (e.g., Noutsos et al. 2013). As such, these discoveries contribute significantly to more complete understanding of the pulsar population, NS physics, and birthrates (Watters & Romani 2011). About a third of the LAT pulsars was detected during ‘blind’ searches for periodicity in sparse LAT γ-ray photons. Many of them remain undetected in the radio precluding independent distance estimates using the dispersion measure. In this case, follow-up observations at other wavelengths, especially in X-rays, were proven to be very productive (e.g., Marelli et al. 2013, 2015).

More distant and/or less energetic pulsars are weaker in γ-rays and long integration times are required for a detectable signal-to-noise ratio. The photon sparseness for them results in a large computational cost of the blind search. The problem is solved with the aid of the volunteer-based computing power of the Einstein@Home project2 (Allen et al. 2013). Within this project, 19 new γ-ray pulsars have been recently discovered in the blind search of pulsations in about hundred of unidentified point-like LAT sources whose γ-ray spectra are similar to those of pulsars (Pletsch et al. 2013; Clark et al. 2015, 2016, 2017). All of them are isolated pulsars with $\tau_c$ between 3 kyr and 2 Myr and $E$ between $10^{34}$ and $4 \times 10^{36}$ erg s$^{-1}$. No radio pulsations have been reported so far for any of these new pulsars. Therefore, X-ray identification of these objects is crucial for their further study.

Using archival Swift and Suzaku data we have found a plausible X-ray counterpart and a possible pulsar wind nebula (PWN) for PSR J1932+1916, which is one of the youngest ($\tau_c \approx 35.4$ kyr) pulsars from the Einstein@Home sample (Karpova et al. 2017). The X-ray data allowed us to constrain the distance to the pulsar and to suggest its possible association with the supernova remnant (SNR) G54.4−0.3.

Here we report the results of search for X-ray counterparts for the other eighteen Einstein@Home γ-ray pulsars using X-ray data archives and point source catalogues. We have found six counterpart candidates by position coincidence. We focus on their X-ray spectral properties and discuss if they are consistent with those of other Fermi pul-

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1 https://confluence.slac.stanford.edu/display/GLAMCOG/Public+List+of+LAT-Detected+Gamma-Ray+Pulsars
2 http://einstein.phys.uwm.edu

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Table 1. X-ray counterpart candidates for six Fermi pulsars from the Einstein@Home γ-ray coordinates are from Pletsch et al. (2013); Clark et al. (2017) and X-ray coordinates are from the 1st Swift X-ray Point Source Catalogue (1SXPS; Evans et al. 2014) and the Chandra Source Catalogue (Wang et al. 2016). Numbers in parentheses are 1σ uncertainties for the γ-ray coordinates and 90 per cent confidence position errors for the X-ray counterpart candidates related to the last significant digits quoted. The last column shows significances of the X-ray candidate detections as the signal to noise ratio S/N.

| Fermi Pulsar | X-ray Counterpart Candidate | RAγ | Decγ | RAx | Decx | S/N |
|--------------|------------------------------|------|------|------|------|-----|
| J0002+6216   | 1SXPS J000257.6+621609       | 00:02:58:17(2) | +62:16:09.4(1) | 00:02:57.69(70) | +62:16:09.2(4.9) | 1.8 |
| J0359+5414   | CXOGSG J035926.0+541455      | 03:59:26.01(2) | +54:14:55.7(3) | 03:59:26.09(11) | +54:14:55.8(1.0) | 23.8 |
| J0554+3107   | 1SXPS J055404.8+310741       | 05:54:05.01(3) | +31:07:41(4) | 05:54:04.83(91) | +31:07:41.7(6.2) | 2.7 |
| J1105−0837   | 1SXPS J110500.3−083713       | 11:05:00.48(4) | −08:37:16.3(3) | 11:05:00.37(84) | −08:37:13.1(6.4) | 2.0 |
| J1844−6346   | 1SXPS J184432.9−634626       | 18:44:32.89(2) | −63:46:30.6(9) | 18:44:32.9(2) | −63:46:26.6(2.7) | 5.9 |
| J2017+3625   | CXOGSG J201755.8+362507      | 20:17:55.84(1) | +36:25:07.9(2) | 20:17:55.81(8) | +36:25:07.8(1) | 5.5 |

Table 2. Parameters of the pulsars listed in Table 1, which are derived from the Fermi-LAT timing solutions Pletsch et al. (2013); Clark et al. (2017): a period P, a period derivative ˙P, a characteristic age τc = P/2 ˙P, a spin-down luminosity L, a dipole magnetic field B. The Fermi-LAT flux density G100 in the 100 MeV–100 GeV range is taken from 3FGL catalogue (Acero et al. 2015). dγ is a pseudo-distance (see text for details).

| Fermi Pulsar | P (ms) | ˙P (10⁻¹⁵ s⁻¹) | τc (kyr) | ˚E (10³³ erg s⁻¹) | B (10¹² G) | G100 (10⁻¹¹ erg cm⁻² s⁻¹) | dγ (kpc) |
|--------------|--------|----------------|----------|-------------------|-----------|--------------------------|---------|
| J0002+6216   | 115.4  | 5.97           | 306      | 153               | 0.8       | 1.83                     | 2.3     |
| J0359+5414   | 79.4   | 16.7           | 75       | 1318              | 1.2       | 2.45                     | 3.45    |
| J0554+3107   | 465.0  | 142.6          | 52       | 56                | 8.2       | 1.73                     | 1.9     |
| J1105−0837   | 194.9  | 21.8           | 141      | 116               | 2.1       | 3.7                      | 1.53    |
| J1844−6346   | 112.85 | 154.7          | 12       | 4249              | 4.2       | 2.83                     | 4.3     |
| J2017+3625   | 166.75 | 1.36           | 1943     | 12                | 0.5       | 6.5                      | 0.656   |

sars which have been firmly identified in X-rays. Possible associations with nearby SNRs are proposed for two pulsars which allow for independent distance estimates. In Sect. 2 we present the search results and describe the general techniques and tools used for the X-ray analysis of the counterpart candidates. The X-ray properties of each candidate and the possible SNR associations are thoroughly considered in sub-sections of Sect. 3. Background optical objects within the position error ellipses of the candidates are considered in Sect. 4. In Sect. 5, we discuss the results.

2 X-RAY COUNTERPART SEARCH RESULTS

Using X-ray catalogues, we have found point-like X-ray counterpart candidates for six out of eighteen Einstein@Home γ-ray pulsars, which coincided by position with the Fermi pulsars at 90% confidence level. Four candidates have been detected with Swift X-Ray Telescope (XRT) and the other two have been detected with Chandra Advanced CCD Imaging Spectrometer (ACIS). The Fermi pulsar and X-ray counterpart candidate catalogue names and respective γ- and X-ray coordinates with their uncertainties are presented in Table 1. The parameters of the pulsars derived from the γ-ray data are shown in Table 2. For radio-quiet pulsars the distances are estimated using the empirical ‘pseudo’-distance relation for γ-ray pulsars (Saz Parkinson et al. 2010): dγ = 1.6×(˚E[10³³ erg s⁻¹])₀.₂₅ × (G₁₀₀[10⁻¹¹ erg cm⁻² s⁻¹])⁻⁰.⁵ kpc, where G₁₀₀ is the pulsar flux density in the 100 MeV–100 GeV range measured with the Fermi-LAT.

In most cases, the regions containing the pulsars were observed in X-rays several times. For Swift candidates, the number of observations varies from 2, for J0554+3107, to 64, for J1844–0346, and the total exposure times varies from 9.2, for J0002+6216, to 100 ks, for J1844–0346, respectively. For Chandra candidates, they varied from 1 to 9 and from 10 ks to 460 ks, for J2017+3625⁴ and J0359+5414⁵, respectively. In Table 1, the coordinates of the Swift candidates are taken from the 1st Swift X-ray Point Source Catalogue (Evans et al. 2014). They were measured on the stacked XRT images. For Chandra objects, the archival ACIS data were reprocessed using the CIAO v.4.9 tool CHANDRA_REPRO. For multiple observations, the data were merged using the MERGEBDS task. The candidate coordinates were measured on the resulting images using the WAVDETECT tool. They are consistent with those provided by the Chandra Source Catalogue (Wang et al. 2016).

The sections of the stacked/merged X-ray images containing the pulsars are presented in Fig. 1 where dashed yellow and solid white ellipses show 1σ position uncertainties of the γ-ray pulsars and centroids of their X-ray counterpart candidates, respectively. The former account for the Fermi 1σ timing position uncertainties from Table 1 and

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3 https://heasarc.gsfc.nasa.gov/w3browse/all/xray.html; http://www.swift.ac.uk/1SXPS/
4 Observation ID 14699
5 Observation IDs 4657, 14688, 14689, 14690, 15548, 15549, 15550, 15585, 15586

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Figure 1. *Swift/XRT* and *Chandra/ACIS* images of the point-like X-ray counterpart candidates for the γ-ray pulsars listed in Table 1. 1σ positional uncertainties of the point-like candidate centroids and the γ-ray pulsars in the images are shown by solid white and dashed yellow ellipses, respectively. The green annulus in the bottom-left panel was used to extract the spectrum of the extended emission around the point-like counterpart candidate. The insert in this panel shows the zoomed-in 8 arcsec × 8 arcsec region with the candidate near the centre of the extended emission. A different count scale is used in the insert to reveal the point-like counterpart candidate.
the X-ray telescope 1σ astrometric accuracy. This quantity, in turn, is estimated from 90% confidence aspect solution accuracy of 3.5′ and 0′′.8 for Swift (Evans et al. 2014) and Chandra6, respectively. The solid white ellipses include only statistical point source position measurement errors on the stacked/merged images. It is seen that positions of the counterpart candidates are consistent with those of the pulsars in all cases.

Due to shallow total exposures, mainly of about 10 ks, the formal X-ray signal-to-noise ratio $S/N$ for the counterpart candidates on the XRT images is low. It varies from 1.8, for J0002+6216, to 5.9, for J1844−0346 (see the last column in Table 1). Such a low $S/N$ is the main reason for relatively large absolute position errors as compared to the Fermi position errors (cf. Table 1). Nevertheless, all the objects are classified as ‘Good’ point sources in the Swift catalogue based on an iterative point spread function and likelihood analysis (Evans et al. 2014). $S/N$ for the ACIS counterpart candidates of J2017+3625 and J0359+5414 is ≈5.5 and ≈23.8, respectively.

As one can see in Fig. 1, there is a diffuse emission around the point-like candidate of J0359+5414 extended roughly along SE–NW direction by about 30 arcsec. This can be the PWN, which is not a surprise for the pulsar with a relatively high spin-down power of ≈1036 erg s−1. The visible size of the presumed PWN (≈30 arcsec × 20 arcsec) is roughly compatible with that of the Vela PWN (≈6 arcmin × 5.5 arcmin) assuming that the latter is moved to about 12 times larger distance corresponding to J0359+5414 (from 0.3 to 3.5 kpc).

For further spectral analysis of the proposed counterpart candidates detected with Swift, we have obtained their spectra using the Swift/XRT data product generator (Evans et al. 2009). For two Chandra candidates, the spectra were extracted from the archival data using the CIAO SPECEXTRACT tool. For the J0359+5414 candidate, we have used the extraction aperture with a 2 arcsec radius for the point-like source, whereas for the extended source, we have used the annulus centred at the point-like candidate with the inner and outer radii of 2 and 15 arcsec, respectively. The annulus is shown in Fig. 1. For the J2017+3625 candidate, a 1.5 arcsec aperture radius was used. In all the cases, the background was taken from regions free of any sources.

The spectra were fitted in the 0.3–10 keV range using the XSPEC v.12.9.0 tool by plausible absorbed spectral models. We applied a power law (PL) model, describing nonthermal radiation from the NS magnetosphere, a blackbody (BB) model and a magnetised NS atmosphere models NSMAXG (Ho et al. 2008), describing the thermal emission from the NS surface. Depending on the count statistics, we used either a single model or a composite model. The latter is the sum of the thermal and nonthermal spectral components, e.g. BB+PL or NSMAXG+PL. For the diffusive source, we applied the PL model assuming the synchrotron nature of the PWN emission. For the photoelectric absorption, the TBABS model with the XILLER interstellar abundances was used. Due to low count numbers C-statistics (CASH 1979) was used to estimate fit qualities. Unless stated otherwise, all the spectra were binned by at least 1 count per energy bin.

Independent information on the absorbing column density $N_H$ towards a pulsar was employed, when this was required to facilitate the fit.

3 PROPERTIES OF THE PULSAR X-RAY COUNTERPART CANDIDATES

3.1 PSR J0002+6216

The counterpart candidate for this pulsar accounts for only 9 XRT source counts detected during the ≈9.2 ks total exposure. This precludes any quantitative spectral analysis. $N_H$ can be estimated if the pulsar is associated with the well studied SNR CTB 1 (G116.1+0.2). The ROSAT X-ray image of CTB 1 is presented in Fig. 2. This is an oxygen-rich mixed morphology core-collapsar remnant where a black-hole or an NS are expected to be born at the supernova event but none have been found so far (Pannuti et al. 2010a,b). As seen from Fig. 2, PSR J0002+6216 is located near the edge of the remnant at the angular distance of only about 17 arcmin from its centre. Another nearby pulsar B2351+61 shown in the image cannot be associated with CTB 1 because its trail calculated using known proper motion and characteristic age (Harrison et al. 1993) does not point to the remnant. The PSR J0002+6216 pseudo-distance (Table 2) is consistent with the SNR distance range of 1.5–4 kpc (e.g., Feen et al. 1997) favouring the association.

The age of CTB 1 is estimated to be in the range of 7.5–44 kyr (Koo & Heiles 1991; Hailey & Craig 1994). This is smaller than the pulsar characteristic age of 306 kyr. However, such a large discrepancy is frequently observed for pulsars associated with SNRs (e.g., PSR J0538+2817 in the SNR S147 (Kramer et al. 2003); PSR J1101–6101 in the

Figure 2. ROSAT X-ray image of the field containing the SNR CTB 1, PSR J0002+6216, and unrelated PSR B2351+61 whose positions are marked by a cross and an ‘X’, respectively. Contours show the CTB 1 radio shell structure obtained from the Westerbork Northern Sky Survey (WENSS: Rengelink et al. 1997).
SNR MSH 11–61A (Halpern et al. 2014). If the real pulsar age is consistent with that of the SNR, then the initial pulsar period $P_0$ according to the standard real age $t \cdot P_0$ relation,

\[
t = \frac{P}{(n-1)P} \left[ 1 - \left( \frac{P_0}{P} \right)^{n-1} \right].
\]

was in the range of 107–114 ms for the magnetic dipole spin-down model with $n = 3$. This is a typical value for birth periods (see, e.g., Popov & Turolla 2012; Noutsos et al. 2013) which is also in good agreement with recent core-collapse models (e.g., Wongwathanarat et al. 2013; Fuller et al. 2015).

Based on the 17 arcmin pulsar offset from the CTB 1 centre, its expected proper motion and transverse velocity are $\mu = 50 \pm 3$ mas yr$^{-1}$ and $v_\perp = 550 \pm 27$ km s$^{-1}$, where $d_{2.3}$ is the pulsar distance scaled to its pseudo-distance of 2.3 kpc (Table 2) and $P_0$ is the real age divided by 20 kyr. Given the age uncertainty of 7.5–44 kyr, the $v_\perp$ uncertainty of $(250-1500) d_{2.3}$ km s$^{-1}$ is large, but it is compatible with the mean 2D pulsar speed of $\approx 250$ km s$^{-1}$ (Hobbs et al. 2005) and the largest NS velocity of $\approx 1100$ km s$^{-1}$ precisely measured so far (Chatterjee et al. 2005).

Therefore, the association of PSR J0002+6216 and CTB 1 appears to be plausible. Assuming that it is real, we fixed $N_\text{H}$ for the pulsar at $6 \times 10^{21}$ cm$^{-2}$, the value accepted for the remnant (Pannuti et al. 2010a). Then, to estimate the pulsar counterpart candidate flux, we fitted its spectrum with the absorbed PL with the photon index $\Gamma = 2$, which is typical for pulsars (e.g., Kargaltsev & Pavlov 2008). The resulting $C$-value was 12 per 6 degrees of freedom (d.o.f.). The fit result in the observed and unabsorbed X-ray fluxes of $4.4_{-2.0}^{+3.8} \times 10^{-14}$ and $7.4_{-3.9}^{+4.6} \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$, respectively, in the 0.3–10 keV band. For the distance of 2.3 kpc this translates into the X-ray luminosity of $4.7_{-2.2}^{+3.2} \times 10^{31} d_{2.3}^2$ erg s$^{-1}$. It is consistent with non-thermal X-ray luminosities of 10–100 kyr old pulsars (e.g., Kargaltsev & Pavlov 2008). The X-ray efficiency in the 0.3–10 keV range is $\log(L_X/E) = -3.5$. The ratio between the $\gamma$-ray and unabsorbed X-ray fluxes is $\log(G_{100}/F_X) \approx 2.4$. According to Abdo et al. (2013, see their Fig. 18), this is consistent with a typical for radio-loud $\gamma$-ray pulsars ratio of 2.4±1.1, encouraging further search for the pulsar radio counterpart.

Alternatively, the single BB fit results in the temperature $T = 147_{-43}^{+84}$ eV, the emitting area radius $R = 1.3_{-1.3}^{+3.3} d_{2.3}$ km, and the observed and unabsorbed X-ray fluxes of $1.5_{-0.6}^{+0.8} \times 10^{-14}$ and $1.2_{-0.8}^{+2.4} \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$, respectively. The fit quality was only marginally better than that for the PL model, $C$(d.o.f.) = 9.6(5). In principle, this result could be consistent with the thermal emission from pulsar hot polar caps. However, uncertainties are too large for definite conclusions.

To summarise, we can state that the detected X-ray source is a plausible counterpart of PSR J0002+6216.

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7 Hereafter, 1σ flux and fitting parameter errors are presented.

8 After this paper has been submitted, the detection of J0002+6216 in the radio was reported (Wu et al. 2017).

Figure 3. Top panel: X-ray spectrum of the PSR J0359+5414 X-ray counterpart candidate best fitted by the sum (solid line) of the NSMAXG and the PL models which are dominated in the 0.5–2 and 2–8 keV ranges, respectively (dotted lines). Middle and bottom panels: fit residuals.

3.2 PSR J0359+5414

To reveal the nature of the serendipitously detected Chandra pulsar and PWN counterpart candidates, we have used the COMBINE SPECTRA tool to co-add the source and background spectra from all the observation IDs. This resulted in 150 and 293 ACIS source counts for the point and the diffuse objects, respectively, detected during the ≈600 ks total exposure in the 0.3–10 keV range. The spectra were grouped to ensure 5 and 10 counts per the energy bin for the presumed pulsar and PWN, respectively. We fitted the spectra simultaneously with the shared $N_\text{H}$ parameter using all spectral models listed in Sect. 2.

For the pulsar counterpart candidate only the composite models BB+PL and NSMAXG+PL were statistically acceptable. Both of them provided equal fit qualities. $C_{BB+PL}$(d.o.f.) = 89.8(85) and $C_{NSMAXG+PL}$(d.o.f.) = 89.95(86). For the PL+NSMAXG model (with NS mass $M_{\text{NS}} = 1.4 M_\odot$, radius $R_{\text{NS}} = 13$ km and magnetic field $B = 10^{12}$ G), fixing the distance at the pseudo-distance value of 3.45 kpc, we have obtained the column density $N_H = (0.9 \pm 0.2) \times 10^{22}$ cm$^{-2}$, the photon index $\Gamma = 0.5 \pm 0.6$ and the NS temperature (gravitationally redshifted) $T^\infty = (6.1 \pm 0.2) \times 10^3$ K ($\approx 53$ eV). For the BB+PL model, the column density $N_H = (0.9 \pm 0.3) \times 10^{22}$ cm$^{-2}$, the photon index $\Gamma = 0.8 \pm 0.6$, the temperature $T = 162_{-25}^{+29}$ eV and the emitting area radius $R = 0.8_{-0.5}^{+1.4} d_{2.3}$ km, where $d_{2.3}$ is the pulsar distance normalised to the pseudo-distance. In this case, the thermal emission comes from a compact hot region on the NS surface whose radius is consistent with the polar cap radius of 0.76 km estimated for this pulsar in the standard way (e.g., Sturrock 1971). For the presumed PWN, in both cases we got $\Gamma = 1.6 \pm 0.3$, which is typical for PWNe (Kargaltsev & Pavlov 2008). For the NSMAXG+PL case, the point-like and the extended object spectra and the respective best fit models are presented in Figs. 3 and 4.

Our spectral analysis strongly supports the pulsar na-
nature of the counterpart candidate. Its X-ray spectrum is consistent with the spectrum expected from this middle-aged pulsar with the soft thermal component from the entire surface of the cooling NS, or from its hot regions, and a hard nonthermal spectral tail of the pulsar magnetosphere origin.

The absorbing column density value for PSR J0359+5414 derived from the spectral fit is consistent with \( N_H \approx 1.1 \times 10^{22} \) cm\(^{-2}\) estimated towards the pulsar for the pseudo-distance of 3.45 kpc using the relation \( N_H = (8.9 \pm 0.4) \times E(B - V) \times 10^{21} \) cm\(^{-2}\) (Foight et al. 2016) and the interstellar extinction \( E(B - V)\)-distance relation which is based on the Pan-STARRS and 2MASS photometry\(^9\) (Green et al. 2015). This means that 3.45 kpc is a quite realistic distance estimate.

For the pulsar and PWN spectra, the unabsorbed nonthermal fluxes in the 0.3–10 keV range are \( (9 \pm 3) \times 10^{-15} \) and \( (2 \pm 0.3) \times 10^{-14} \) erg cm\(^{-2}\) s\(^{-1}\), respectively. These translate into nonthermal luminosities \( L_{X}^{psr} \approx 1.3 \times 10^{31} d^2_{1.45} \) and \( L_{X}^{pwn} \approx 2.8 \times 10^{31} d^2_{1.45} \) erg s\(^{-1}\) which are compatible with known PSR/PWN luminosities of pulsars with \( E \sim 10^{36} \) erg s\(^{-1}\) (Kargaltsev & Pavlov 2008). Finally, the ratio between the \( \gamma\)-ray and the nonthermal X-ray fluxes of the pulsar is \( \log(G_{10}/F_X) \approx 3.4\). This is consistent with the value of 3.5 \pm 0.5 derived for the radio-quiet population of \( \gamma\)-ray pulsars (Abdo et al. 2013).

To summarise, the \( \gamma\)-ray properties of the \textit{Chandra} point and extended sources leave little doubts that they represent the real \( \gamma\)-ray counterparts of PSR J0359+5414 and its PWN.

### 3.3 PSR J0554+3107

There are 17 source counts from the XRT counterpart candidate detected during the \( \approx 10 \) ks total exposure in the 0.3–10 keV range. This precludes any quantitative spectral analysis using the XRT data alone. Nevertheless, since 13 out of 17 counts are detected in the 0.3–1 keV band, a preliminary conclusion can be drawn that the source spectrum is soft. This suggests that the detected emission may be dominated by the thermal component from the NS surface, as is typically observed for middle-aged pulsars, a class to which PSR J0554+3107 likely belongs in view of its characteristic age (Table 2).

This is further supported by the pulsar association with an evolved SNR G179.0+2.6 proposed by Pietsch et al. (2013). The pulsar characteristic age of 52 kyr is compatible with the remnant age range of 10–100 kyr (Fuerst & Reich 1986). Detection of G179.0+2.6 in the optical OIII narrow band\(^10\) implies that this is an oxygen rich core-collapse SNR where a NS could have been born. Based on an empirical surface luminosity–SNR angular size relation (Milne 1979) and \( d_g \) for the pulsar (Table 2), the likely distance to the presumed pulsar+SNR system lies in the range of 1.9–3.5 kpc.

This distance range, the \( E(B - V)\)-distance (Green et al. 2015) and \( E(B - V) - N_H \) (Foight et al. 2016) relations allow us to constrain \( N_H \) for the pulsar to the range of \( (1.9 - 2.5) \times 10^{21} \) cm\(^{-2}\) and perform a rough spectral analysis of the counterpart candidate. Fixing \( N_H \) in the obtained range we have fitted the XRT source spectrum in the 0.3–10 keV range by the PL, BB, and NSMAX models. For the latter model, we have selected \( B = 10^3 \) G and the gravitational redshift parameter \( \Gamma + 2 \approx 1.21\), corresponding to \( M_{NS} = 1.4M_\odot \) and \( R_{NS} = 13 \) km.

The PL fit results in an unreasonably steep spectral slope with \( \Gamma > 4\). This is not typical for pulsars and thus can be rejected. Both thermal fits are equally acceptable with \( C(\text{dof.f.}) = 15(12)\). The BB fit results in the temperature of 100–110 eV and the emitting area radius of \( (2 - 3) d_{1.9} \) km depending on the \( N_H \) value from the allowed range. Here \( d_{1.9} \) is the pulsar distance in units of 1.9 kpc. The NSMAX fit yields the NS surface temperature and emitting area radius (gravitationally redshifted) of 47–54 eV and (11–19)\( d_{1.9} \) km, respectively. For both thermal models the absorbed flux is about \( (3.1 - 3.2) \times 10^{14} \) erg cm\(^{-2}\) s\(^{-1}\) in the 0.3–10 keV band.

The temperature and the emitting area derived from the fits using the thermal emission models are consistent with those expected for a middle-aged cooling NS. This supports the pulsar nature of the XRT counterpart candidate.

### 3.4 PSR J1105–6037

There are 16 source counts from the XRT counterpart candidate detected during the \( \approx 16 \) ks total exposure in the 0.3–10 keV range. 10 out of 16 counts are in the 0.3–1 keV range implying, as in the case of PSR J0554+3107, that the spectrum may contain a soft thermal component corresponding to the surface emission from a middle-aged NS.

Unfortunately, no advanced interstellar extinction–distance relation is provided for the pulsar direction by Green et al. (2015) to constrain \( N_H \) to the pulsar and to facilitate spectral fits. Therefore we have utilised the extinction map which is based on a model fit to the COBE DIRBE

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\(^9\) http://argonaut.skymaps.info/

\(^10\) http://astro.neutral.org/imagehtml/20161128-snr-G179.0+2.6.html
Applying the $E(B-V)-N_H$ relation \cite{Drimmel2003} we obtained $N_{\text{HI}} \approx 3.2 \times 10^{21} \text{ cm}^{-2}$ for the pulsar pseudo-distance of 1.53 kpc (Table 2).

Fixing $N_{\text{HI}}$ at this value, we have fitted the source spectrum trying the PL, BB and NSMAXG models. The PL fit resulted in a too steep photon index $\Gamma \approx 4$ which is not typical for pulsars. The nonthermal model can thus be rejected. Both thermal models resulted in acceptable fits with $C_{\text{BB}}(\text{d.o.f.}) = 5.7(9)$ and $C_{\text{NSMAXG}}(\text{d.o.f.}) = 6.3(10)$. Using the BB model, we obtain the temperature of $165_{-38}^{+38} \text{ eV}$ and the radius of the emitting area of $0.5 \pm 0.3 d_{43}$ km, where $d_{43}$ is the pulsar distance in units of the pseudo-distance. The latter value is consistent with the polar cap radius of 0.49 km estimated for this pulsar in the standard way \citep[e.g.,][]{Sturrock1971}. For the NSMAXG model \citep[the NS mass $M_{\text{NS}} = 1.4M_\odot$, radius $R_{\text{NS}} = 13$ km and magnetic field $B = 10^{12} \text{ G}$,][]{Ho1995}, fixing the distance at the pseudo-distance value, we obtain the gravitationally redshifted temperature of $(5.1 \pm 0.3) \times 10^5 \text{ K}$ ($\approx 44 \text{ eV}$). The observed flux in the 0.3–10 keV band is $\approx 2 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$ for both thermal models.

The thermal fit parameters are reasonable for a middle-aged cooling NS supporting the pulsar nature of the XRT counterpart candidate.

### 3.5 PSR J1844–0346

This is the youngest and most energetic pulsar in our sample but it is likely to be the most distant object as well (Table 2). About 100 source counts during the $\approx 100$ ks total exposure were detected from the XRT candidate allowing one to perform an initial spectral analysis without additional assumptions. The spectrum is well fitted by the PL model with $N_{\text{HI}} = 5.3_{-1}^{+4} \times 10^{22} \text{ cm}^{-2}$ and $\Gamma = 0.9_{-0.8}^{+0.9}$. $C_{\text{PL}}(\text{d.o.f.}) = 44.2(61)$. This suggests that the candidate can be indeed a distant young pulsar whose spectrum is dominated by the nonthermal emission of the NS magnetosphere origin, as is observed, e.g., for the Crab pulsar. The BB fit is also acceptable but results in an unrealistically high for NSs temperature $\lesssim 1.5 \text{ keV}$. Due to this reason, the thermal model can be rejected. The spectrum with the PL fit is shown in Fig. 5. The observed and unabsorbed fluxes are $1.6^{+0.3}_{-0.4} \times 10^{-13}$ and $2.2^{+1.3}_{-0.4} \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$, respectively, in the 0.3–10 keV band. This yields the X-ray luminosity of $4.9_{-0.9}^{+2.0} \times 10^{32} \rho_{43}^2 \text{ erg s}^{-1}$, where $d_{43}$ is the pulsar distance in units of the pseudo-distance. $\log(G_{10}/F_{2}) = 2.1$ is compatible with the value obtained for the radio-loud $\gamma$-ray pulsar population \citep{Abdo2013}.

PSR J1844–0346 is located about 10 arcmin off the G28.6–0.1 SNR centre (Fig. 6). This is a young SNR thoroughly explored by \cite{Ueno2016} with Chandra. They obtained the column density of $(3.2 \pm 4.5) \times 10^{22} \text{ cm}^{-2}$ to the remnant, which is compatible with what we obtained for the pulsar counterpart candidate. The SNR X-ray radiation is dominated by synchrotron emission from an expanding shell. It exhibits a clumpy morphology with an overall elliptical shape with the NE major axis orientation. The radio and X-ray emission regions are not correlated \citep{Bamba2001}, which is typical for mixed morphology SNRs. The distance to the remnant and its age were recently estimated to be $9.6 \pm 0.3$ kpc and 19 kyr, respectively \citep{Ranasinghe2017}.

No pulsar detection has been reported within the remnant, while PSR J1844–0346 is located near its NE boundary which has not been observed by Chandra. The association with the SNR implies the pulsar proper motion $\mu = 50_{-12}^{+12} \text{ mas yr}^{-1}$ and the transverse velocity $v_{\perp} \approx 1020d_{43} t_{12}^{-1} \text{ km s}^{-1}$, where $t_{12}$ is the pulsar age scaled by its characteristic age of 12 kyr (Table 2). This velocity is close to the highest firmly established NS velocity of $\approx 1100 \text{ km s}^{-1}$ \citep{Chatterjee2005}. If the real age and distance of the presumed PSR+SNR system are equal to those estimated...
for the remnant, the transverse velocity becomes higher, 1440 ± 50 km s⁻¹, but it is still not outstanding.

3.6 PSR J2017+3625

This is the oldest and least energetic but likely closest pulsar in our sample (Table 2). Gotthelf et al. (2016) failed to identify it in X-rays in the same Chandra data-set using the 3FGL catalogue, which are different from more accurate coordinates obtained from the timing analysis by Clark et al. (2017). There are 10 ACIS source counts from the counterpart candidate detected during the ≃10 ks exposure in the 0.3–10 keV range.

We have estimated N_H to the pulsar using the interstellar extinction–distance relation (Green et al. 2015) and the pulsar pseudo-distance of 0.656 kpc (Table 2). The resulting N_H is about 5.3×10²⁰ cm⁻² which was then frozen in spectral fits. The spectrum was fitted by the PL and BB models.

For the BB model we have obtained the temperature T = 1.2×10³ K and the bolometric luminosity L_B = 1.2×10³⁰ erg s⁻¹. The corresponding X-ray efficiency ξ_{X} = 9.1×10⁻³ erg cm⁻² s⁻¹. The latter translates in the X-ray luminosity L_X = 1.2×10³⁰ erg cm⁻² s⁻¹, respectively. This favours the correct X-ray identification of the pulsar using the interstellar origin or a thermal spectra from the NS surface, which can hardly produce such a hard X-ray spectrum as is observed for the candidate. We have also not found any known active galactic nuclei at our candidate position which could be responsible for the nonthermal X-ray spectrum.

We have found a relatively bright background star VPHAS J110500.49+603713.41 with m' = 17.96, g' = 16.97, r' = 16.33, i' = 16.1 within the position error ellipse of the J1105+6037 Swift X-ray counterpart candidate. Its spectral energy distribution is typical for main-sequence stars.

There are two faint red point objects PSO J055404.767+310739.519 with i = 21.655 and PSO J055405.198+310742.124 with i = 21.918 within the position ellipse of the Swift counterpart candidate for J0554+3107. They are not detected in other optical bands. In the absence of any information on the object colours, their nature remains unknown.

Finally, within the position error ellipse of the Swift counterpart candidate for J0002+6216 there are two relatively bright background point optical sources PSO J000257.781+621607.150 with g = 18.9, r = 17.9, i = 17.42, z = 17.17 and y = 17, and PSO J000025.830+621613.565 with g = 17.76, r = 16.9, i = 16.49, z = 16.29 and y = 16.1. Both sources are likely main sequence stars.

Therefore, the X-ray identification of the latter three pulsars has to be viewed with caution. More sensitive, high spatial and temporal resolution X-ray observations can help to distinguish possible false identifications from the real ones.

Within the position error ellipse of the Swift counterpart candidate for J1844–0346 with purely nonthermal X-ray spectrum (Sect. 3.5), we have found a relatively bright optical source PSO J184433.074–034628.369 with magnitudes g = 19.729, r = 18.169, i = 17.243, z = 16.715. By its colour, it appears to be an M-class main sequence star which can hardly produce such a hard X-ray spectrum as is observed for the candidate. We have also not found any known active galactic nuclei at our candidate position which could be responsible for the nonthermal X-ray spectrum.

There are two faint red point objects Swift Galactic Plane sources from VPHAS J110500.49+603713.41 with m' = 17.96, g' = 16.97, r' = 16.33, i' = 16.1 within the position error ellipse of the J1105+6037 Swift X-ray counterpart candidate. Its spectral energy distribution is typical for main-sequence stars.

There are two faint red point objects PSO J055404.767+310739.519 with i = 21.655 and PSO J055405.198+310742.124 with i = 21.918 within the position ellipse of the Swift counterpart candidate for J0554+3107. They are not detected in other optical bands. In the absence of any information on the object colours, their nature remains unknown.

5 DISCUSSION AND CONCLUSIONS

We have found possible X-ray counterparts for six recently discovered γ-ray pulsars and have proposed SNR associations for two of them. All the counterpart candidates coincide by position well with the pulsars. They are located in the Galactic plane and their X-ray fluxes are ≥2×10⁻¹⁴ erg cm⁻² s⁻¹. According to the LogN–LogS distribution for the Chandra Galactic Plane sources from Ebisawa et al. (2005), the probability of chance detection of an unrelated X-ray source with F_X > 2×10⁻¹⁴ erg cm⁻² s⁻¹ at the γ-ray pulsar position is ≤10⁻⁴. This small value supports the correct X-ray identifications.

Despite a low count statistics for most candidates, qualitative conclusions on X-ray spectral properties can be estimated for all of them. These properties are consistent with those observed for other rotation powered pulsars, which demonstrate either a non-thermal PL spectra of the NS magnetosphere origin or a thermal spectra from the NS surface, or a combination of the two. The estimated spectral indices and temperatures are in a good agreement with those observed for other pulsars with similar parameters. Moreover, the ratios of the γ-ray fluxes to the nonthermal X-ray fluxes, in cases where it is possible to estimate the latter, are also compatible with the respective ratios for other γ-ray pulsars.
X-ray counterpart candidates for six new γ-ray pulsars

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