SEARCHES FOR MILLISECOND PULSAR CANDIDATES AMONG THE UNIDENTIFIED FERMI OBJECTS

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ABSTRACT

Here we report the results of searching millisecond pulsar (MSP) candidates from the Fermi LAT second source catalog (2FGL). Seven unassociated γ-ray sources in this catalog are identified as promising MSP candidates based on their γ-ray properties. Through the X-ray analysis, we have detected possible X-ray counterparts, localized to an arcsecond accuracy. We have systematically estimated their X-ray fluxes and compared them with the corresponding γ-ray fluxes. The X-ray to γ-ray flux ratios for 2FGL J1653.6-0159 and 2FGL J1946.4-5402 are comparable with the typical value for pulsars. For 2FGL J1625.2-0020, 2FGL J1653.6-0159, and 2FGL J1946.4-5402, their candidate X-ray counterparts are bright enough to perform a detailed spectral and temporal analysis to discriminate their thermal/non-thermal nature and search for the periodic signal. We have also searched for possible optical/IR counterparts at the X-ray positions. For the optical/IR source coincident with the brightest X-ray object associated with 2FGL J1120.0-2204, its spectral energy distribution is comparable with a late-type star. Evidence for the variability has also been found by examining its optical light curve. All the aforementioned 2FGL sources resemble a pulsar in one or more aspects, making them promising targets for follow-up investigations.

Key words: binaries; close – gamma rays: stars – pulsars: general – X-rays: binaries – X-rays: stars

1. INTRODUCTION

Before the launch of the Fermi Gamma-Ray Space Telescope, there were no millisecond pulsars (MSP) known as γ-ray emitters. Thanks to the sensitivity of the Large Area Telescope (LAT) on board Fermi, a group of eight γ-ray MSPs has been discovered shortly after its operation commenced (Abdo et al. 2009). Since then, the population of γ-ray emitting MSPs continues to rise. In the second Fermi LAT catalog of pulsars (Abdo et al. 2013), among 117 γ-ray pulsars detected at high significance, 40 of them are MSPs and therefore form a definite class of γ-ray sources.

In the second Fermi LAT source catalog (2FGL; Nolan et al. 2012), 31% of the γ-ray objects are not associated with any known object. These unidentified Fermi objects have formed the second largest class in 2FGL catalog. Of all these unidentified γ-ray objects, a number could possibly be MSPs. These γ-ray sources effectively provide a “treasure map” for pulsation searches with radio telescopes. Since the angular resolution of the LAT is much improved compared to its predecessors, most γ-ray sources can be localized to a region small enough to allow radio pulsar searches with a minimal number of telescope pointings. This strategy has been demonstrated to be fruitful, as a large number of MSPs have been discovered through this method (see Ray et al. 2012).

However, it should be noted that blind pulsation searches for MSPs are computationally demanding. Since most of the MSPs reside in binary systems, the dimension of the parameter space searched is increased with the orbital parameters. Furthermore, the fast rotation of MSPs requires an accurate knowledge of their positions for pulsation searches. However, even with the improved angular resolution of LAT, the positional uncertainties of the cataloged γ-ray objects (typically a few arcminutes) are still too large for constraining the MSP positions. Without additional information, blind pulsation searches require a fine scan of position over the error boxes of these MSP candidates. For a γ-ray pulsation search, since a very long integration time is required, the proper motion also needs to be taken into account.

Multiwavelength observations play an important role in alleviating the aforementioned problems in facilitating MSP searches. In particular, MSPs are known to be X-ray emitters. For isolated MSPs, the X-ray emission can come from the hot polar cap regions and/or the synchrotron radiation from the magnetospheric accelerator (e.g., Cheng & Zhang 1999). Of all the newly discovered MSPs, a considerable fraction have shown radio eclipses (Roberts 2013). These systems have very tight orbits with an orbital period less than a day (see Table 1 in Roberts 2013). Depending on the masses of their companions $M_*$, these systems are dubbed as “black widows” ($M_\ast \lesssim 0.1 M_\odot$) or “redbacks” ($M_\ast \gtrsim 0.1 M_\odot$) (for a recent view on these systems, please refer to Hui 2014). For such interacting binaries, X-ray emission can be produced through intrabinary shocks and can be orbitally modulated.

Therefore, one can constrain the position of the MSP candidates to an arcsecond accuracy by searching for possible X-ray counterpart within the γ-ray error box. If the identified X-ray sources show similar emission properties (e.g., spectral properties, γ-ray to X-ray flux ratio, variability) to those of known MSPs, they are considered to be promising candidates. Identifying possible optical counterparts with a spectrum/color similar to a late-type star/white dwarf can help us further narrow down the possible candidates. For the MSPs in binaries,
the optical emission is originated from their companions which are heated by the relativistic wind outflow from the pulsars. This leads to the optical orbital modulation as seen in black widows/redbacks. If such an orbital period can be found from a candidate, this will make the pulsation search easier by reducing one dimension in the parameter space. The accurate optical positions can further help in constraining the position of MSP candidates.

In summary, if a candidate counterpart lies in the γ-ray positional error box of a pre-selected unidentified Fermi object with X-ray/optical properties comparable to known black widow/redback systems and shows modulation with a period of less than a day, it is very likely to be a new black widow/redback MSP. Two remarkably successful examples of MSPs identified through this scheme are 2FGL J2339.6-0532 (Romani & Shaw 2011; Kong et al. 2012) and 2FGL 1311.7-3429 (Romani 2012). In this study, we present a systematic search for possible MSP candidates in the 2FGL catalog through a detailed X-ray/optical identification campaign.

2. DATA ANALYSIS AND RESULTS

In order to identify γ-ray sources as MSP candidates, we scanned over the 2FGL catalog and selected an object if it satisfied all of the following four criteria: (1) unassociated source located at a Galactic latitude $|b| > 10^\circ$; (2) its variability index (i.e., the parameter $\text{Variability\_Index}$ in 2FGL) is less than 41; (3) a curved spectrum (in contrast to a simple power law) is required in the fitting at a significance larger than 5σ (i.e., the parameter $\text{Curve\_Significance}$ in 2FGL); (4) the source detection significance (i.e., the parameter $\text{Detection\_Significance}$ in 2FGL) is larger than 10σ (see Ackermann et al. 2012; Kong et al. 2012; Nolan et al. 2012; Romani 2012).

Condition (1) is imposed as MSPs are old objects and should be far away from the Galactic plane, which is presumably their birth place. For a 2FGL source with $\text{Variability\_Index} > 41.64$, the probability of it being a steady source is $< 1\%$ (Nolan et al. 2012). Therefore, we have imposed condition (2) so as to eliminate highly variable sources such as blazars. Since the γ-ray spectra of pulsars are typically described by a curved model with a form of an exponentially cut-off power law (see Abdo et al. 2013), condition (3) can further enhance the chance of the selected sources being a pulsar. The last condition ensures the selected sources are bright enough that their positions and other physical parameters (e.g., γ-ray flux) have been properly constrained. Seven candidates are selected in accordance with these criteria. The results are summarized in Table 1, which is arranged in order of increasing R.A.

| Source            | R.A. (2000) (h m s) | decl. (2000) (d m s) | $b^{\circ}$ (degree) | Vari. Index $^b$ | Curv. Sig.$^c$ | Detect. Sig.$^d$ | $F_\gamma$ $^e$ ($10^{-11}$ erg cm$^{-2}$ s$^{-1}$) |
|-------------------|---------------------|----------------------|---------------------|-----------------|----------------|-----------------|--------------------------------------------------|
| 2FGL J1120.0-2204 | 11 20 00.6          | −22 04 50            | 36.05               | 25.9            | 5.5            | 20.5            | 1.80 ± 0.15                                        |
| 2FGL J1539.2-3325 | 15 39 15.1          | −33 25 43            | 17.53               | 29.5            | 5.5            | 10.8            | 1.06 ± 0.15                                        |
| 2FGL J1625.2-0020 | 16 25 12.8          | −00 20 05            | 31.83               | 24.6            | 8.3            | 20.5            | 1.61 ± 0.13                                        |
| 2FGL J1653.6-0159 | 16 53 36.6          | −01 59 46            | 24.93               | 17.0            | 5.3            | 22.5            | 3.43 ± 0.25                                        |
| 2FGL J1729.5-0854 | 17 29 31.5          | −08 54 26            | 13.71               | 9.0             | 7.4            | 10.2            | 1.93 ± 0.20                                        |
| 2FGL J1744.1-7620 | 17 44 11.0          | −76 20 30            | 22.48               | 27.1            | 7.4            | 20.8            | 2.00 ± 0.19                                        |
| 2FGL J1946.4-5402 | 19 46 24.4          | −54 02 46            | 29.55               | 24.4            | 5.3            | 12.2            | 0.99 ± 0.13                                        |

Notes.

$^a$ Galactic latitude.

$^b$ $\text{Variability\_Index}$ in 2FGL catalog.

$^c$ $\text{Curve\_Significance}$ in 2FGL catalog (in units of $\sigma$).

$^d$ $\text{Detection\_Significance}$ in 2FGL catalog (in units of $\sigma$).

$^e$ γ-ray energy flux in 100 MeV–300 GeV.

2.1. Analysis of the X-Ray Point Sources in the γ-ray Error Ellipses

To search for the possible X-ray counterparts associated with our short-listed 2FGL sources, we utilized archival X-ray spectral imaging data and looked for all the X-ray sources that lie within their γ-ray positional uncertainties. Very recently, the third Fermi γ-ray point sources catalog (3FGL) has been released (Acero et al. 2015). With four years of LAT data, the 3FGL catalog can possibly provide an improved localization of the γ-ray sources. In searching for possible X-ray counterparts, we focused on X-ray point-like sources detected within the smallest possible 95% γ-ray confidence error ellipses provide by 2FGL/3FGL. The results are summarized in Table 2. All of these X-ray sources are detected at a significance larger than 4σ. Their observed and absorption-corrected fluxes are systematically computed with the aid of PIMMS (ver. 4.7) by assuming an absorbed power-law spectrum with a photon index $\Gamma = 2$ and a column absorption consistent with the Galactic HI column density in the corresponding direction.
that have been detected by the Swift XRT with multiple snapshots. With all the available Swift XRT data combined, we have an effective exposure of \( \sim 65 \text{ ks} \) in this field. Utilizing a wavelet source detection algorithm, we have searched for its possible X-ray counterparts. We binned the whole data into a \( 1024 \times 1024 \) image and we set the detection threshold such that no more than one false detection caused by background fluctuation is in the whole field. Two sources, J1120_X1 and J1120_X2, with a signal-to-noise ratio \( >4\sigma \) were found in its 3FGL 95% \( \gamma \)-ray error ellipse (see Figure 2). Their basic properties, including X-ray fluxes and the statistical position uncertainties, are summarized in Table 2. The X-ray fluxes were calculated by using the total Galactic HI column density, \( 3.9 \times 10^{20} \text{ cm}^{-2} \), in this direction (Kalberla et al. 2005) and assuming a power-law model with \( \Gamma = 2 \).

We have also computed the probability for one or more X-ray sources lying in the \( \gamma \)-ray error ellipse by chance. We counted the number of X-ray sources detected in the whole FoV and computed the source density. Based on this, we estimated the number of chance coincidences \( \lambda \) expected within the \( \gamma \)-ray error ellipse. Assuming a Poisson distribution, the probability of finding one or more chance coincidences is given by:

\[
P(n \geq 1) = \sum_{n=1}^{\infty} \frac{\lambda^n e^{-\lambda}}{n!} = 1 - e^{-\lambda}.
\]

For 2FGL J1120.0-2204, we found that \( P(n \geq 1) \approx 56\% \).

The limiting flux for a 4\( \sigma \) point source detection in this field is \( 3.7 \times 10^{-15} \text{ erg cm}^{-2} \text{s}^{-1} \) in an energy range of 0.3–10 keV. Apart from the basic source characterization presented in Table 2, we have also performed a detailed temporal and spectral analysis for those sources with more than 100 net counts detected throughout our investigation. Since the net counts of J1120_X1 and J1120_X2 are below 100, no further X-ray analyses will be conveyed.

2.1.2. 2FGL J1539.2-3325

By merging all of the available data from the Swift XRT observations in the field of 2FGL J1539.2-3325, we have an effective exposure of \( \sim 84 \text{ ks} \). We attempted to search for possible X-ray counterparts within its 3FGL 95% \( \gamma \)-ray error ellipse. However, we cannot detect any source with a significance \( >4\sigma \) with the current data. We place a limiting flux of \( 6.1 \times 10^{-15} \text{ erg cm}^{-2} \text{s}^{-1} \) for the 4\( \sigma \) point source detection in this field.

2.1.3. 2FGL J1625.2-0020

2FGL J1625.2-0020 was observed by XMM-Newton on 2012 February 8 for a total exposure of \( \sim 26.6 \text{ ks} \) (Obs. ID: 0672990401) with both MOS cameras operated in full-frame mode and the planetary nebula (PN) camera operated in extended full-frame mode. Thin filters have been used to minimize the optical contamination for all cameras throughout the observation. With the most updated instrumental calibration, we generated the event lists from the raw data obtained from all EPIC instruments with the tasks emproc and epproc of the XMM-Newton Science Analysis Software (XMMMSAS version 12.0.1). The event files were subsequently filtered for the energy range from 0.3 to 10 keV and selected only those events for which the pattern was between 0–12 for MOS cameras and 0–4 for the PN camera. We further cleaned the data by accepting only the good times when the sky background was low in the whole CCD, and removed all events potentially contaminated by bad pixels. After filtering, the effective exposures were found to be 14.9, 14.0, and 10.7 ks for MOS1, MOS2, and PN, respectively. All of the subsequent analyses were performed in the energy range of 0.3–10 keV.
We performed a source detection by using maximum likelihood fitting on MOS1, MOS2, and PN data individually with the aid of the XMMSAS task `edetect_chain`. The detection threshold was chosen to be 4σ. Source lists resulted from three individual cameras are subsequently correlated and merged by the aid of the XMMSAS task `arfgen`. The spectrum was binned so as to have counts per spectral bin.

We first examined the spectrum with an absorbed power-law model. In view of the limited photon statistics, we fixed the column absorption at $N_H = 5.8 \times 10^{20}$ cm$^{-2}$ as inferred by the HI column density (Kalberla et al. 2005) and adopted C statistic for the modeling fitting (Cash 1979). Although the power-law model can provide a statistically acceptable fit ($C = 9.90$ for 14 degrees of freedom; dof), it results in an unphysically large photon index $\Gamma = 3.1^{+0.4}_{-0.3}$. Therefore, the non-thermal scenario is not favored. All of the quoted uncertainties of the spectral parameters are 1σ for 1 parameter of interest.

We have also examined its spectrum with an absorbed blackbody model. With $N_H$ fixed at $5.8 \times 10^{20}$ cm$^{-2}$ it yields a temperature of $kT = 0.16 \pm 0.02$ keV and an emission radius of $R = 162^{+63}_{-51} d_{\text{kpc}}$ m with $C = 12.50$ for 14 dof, where $d_{\text{kpc}}$ is source distance in unit of 1 kpc. Since this model provides a
more reasonable description of the data than the power law, we conclude that the X-ray emission from J1625_X1 has a thermal origin.

One important indication for a black widow/redback MSPs is the presence of X-ray orbital modulations, which result from intrabinary shocks (e.g., Tam et al. 2010; Huang et al. 2012; Hui et al. 2014). For the temporal analysis, we extracted the light curve of J1625_X1 and subtracted the background by adopting the regions used in the spectral analysis. All of its arrival times were first barycentric-corrected by using its X-ray position reported in Table 2. Updated planetary ephemeris JPL DE405 is used throughout this investigation. We have searched for periodic signals to $\sim 1.5$ hr, which corresponds to half of the effective exposure. We did not find any promising periodicity in this analysis.

For testing the robustness of the results, we repeated the analysis with various backgrounds sampled from the nearby source-free regions. We found the results obtained from these independent analyses are consistent with each other.

2.1.4. 2FGL J1653.6-0159

2FGL J1653.6-0159 has been observed by Chandra ACIS-I on 2010 January 24 with an exposure of $\sim 21$ ks (Obs. ID: 11787). A previous study has reported the X-ray analysis of this data (Cheung et al. 2012). However, as a number of investigations that are crucial for identifying the possible MSP nature were not reported in Cheung et al. (2012), such as a detailed spectral analysis and timing analysis, we decided to re-analyze this data set.

By using the script chandra_repro provided in the Chandra Interactive Analysis Observation software (CIAO 4.6), we reprocessed the data with CALDB (ver. 4.6.1.1). In order to utilize the superior angular resolution of Chandra to tightly constrain the X-ray positions, we applied sub-pixel event repositioning during the data reprocessing in order to improve the positional accuracy of each event (see Li et al. 2004). We restricted the analysis of this ACIS data in an energy range of 0.5–8 keV.

By means of the wavelet source detection algorithm (CIAO tool: wavdetect), we searched for possible X-ray counterparts of 2FGL J1653.6-0159. The exposure variation across the detector was accounted by the exposure map. Within the 3FGL 95% error ellipse of 2FGL J1653.6-0159, only two X-ray sources can be detected at a significance $> 4\sigma$ (see Table 2 and Figure 4). The limiting flux for a $4\sigma$ detection in this field is $1.4 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ (0.3–10 keV). The probability of one or more chance coincidences lying within the $\gamma$-ray error ellipse is $\sim 63\%$.

Since J1653_X1 has $\sim 360$ net counts collected with a circular aperture with a radius of 2 arcsec, we proceeded to examine its X-ray properties in further detail. Very recently, a possible orbital modulation with a period of $P = 4488$ s was independently reported by Romani et al. (2014) and Kong et al. (2014) using optical observations. This information can enable us to investigate the X-ray orbital modulation. Before we examined the temporal behavior of J1653_X1, its arrival times were first barycentric-corrected by using its X-ray position reported in Table 2. For the background subtraction, we have adopted an annular region with inner/outer radius of 5.5 arcsec/10 arcsec centered at its nominal X-ray position.

Figure 2. Potential X-ray counterparts (white circles) of 2FGL J1120.0-2204 as observed by the Swift XRT. This image is produced by using all available XRT data of this field. The dashed ellipse illustrates the 3FGL 95% confidence ellipse. The image is smoothed with a Gaussian kernal of $\sigma = 4''$. 

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The background-subtracted light curve folded at $P = 4488$ s is shown in Figure 5. $\chi^2$ test indicates that the distribution in Figure 5 differs from a uniform distribution at a confidence level of $99.2\%$.

In order to probe its emission nature in detail, we also re-examined the X-ray spectrum of J1653_X1. The source spectrum and the background spectrum were sampled from the same regions adopted for the aforementioned temporal analysis. The spectrum was grouped to have at least 15 counts per spectral bin. We found that the X-ray spectrum of J1653_X1 can be described by an absorbed power-law model ($C$ statistic = 15.50 for 19 dof). The best-fit model yields a column density of $N_H = 9.0^{+11.6}_{-9.0} \times 10^{20}$ cm$^{-2}$, a photon index of $\Gamma = 1.6^{+0.2}_{-0.1}$, and a normalization of $3.6^{+0.9}_{-0.7} \times 10^{-5}$ photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$ at 1 keV. We noted that the inferred $N_H$ is comparable with a total Galactic HI column density of $8.2 \times 10^{20}$ cm$^{-2}$ (Kalberla et al. 2005). On the other hand, we found that a blackbody is not able to provide any reasonable description of the data ($C$ statistic = 57.60 for 19 dof). Therefore, we concluded that the X-ray emission from J1653_X1 is mostly non-thermal dominant.

Although a simple power law can provide a reasonable overall description of the data, we have identified systematic deviations at the energies around 3.5 keV by examining the fitting residuals (see Figure 6). In examining Figure 5 in Cheung et al. (2012), there was also an indication for the residuals around this energy. We speculated that this might indicate the presence of an emission line feature. To test this hypothesis, we added an additional Gaussian component to the power-law model for the spectral fitting. This yielded a best-fit Gaussian line profile at energy $E = 3.4 \pm 0.1$ keV with a width of $\sigma = 0.17^{+0.12}_{-0.17}$ keV and the power law with $\Gamma = 1.7 \pm 0.2$ with a normalization of $3.6^{+1.0}_{-0.7} \times 10^{-5}$ photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$ at 1 keV. The best-fit column absorption $N_H = 9.0^{+11.9}_{-9.0} \times 10^{20}$ cm$^{-2}$ is consistent with the simple power-law fit model and the HI column density within the tolerance of statistical uncertainties. The corresponding goodness-of-fit is $C = 10.18$ for 16 dof.

To further examine the evidence for the line feature, we have simulated the null distribution of likelihood ratio between the alternative model (i.e., absorbed power law plus Gaussian) and the null model (i.e., absorbed power-law model) following the method suggested by Protassov et al. (2002). With the aid of Sherpa, we simulated 10,000 data sets with Poisson noise according to the best-fit parameters of the null model. The simulation was performed with the same instrumental responses and the exposure of the observed data. Each of the simulated data was fitted with the null and alternative model. The resultant distribution of the likelihood ratio implies a $p$-value of $\sim 11\%$. Therefore, based on this test, there is no solid evidence for the emission line. A deeper observation is encouraged for investigating this feature.

2.1.5. 2FGL J1729.5-0854

For 2FGL J1729.5-0854, we note that its 95% $\gamma$-ray error ellipse in 3FGL ($0:58 \times 0:45$) is larger than that in 2FGL ($0:20 \times 0:18$). To investigate this, we performed a brief $\gamma$-ray analysis of this source by using the $\sim 6$ years of LAT data. We subtracted the background contribution by including the Galactic diffuse model (gll_iem_v05_rev1.fits) and the isotropic background (iso_source_v05.txt), as well as all sources in the 3FGL catalog within the circular region of 25$^\circ$ radius around 2FGL J1729.5-0854. In Figure 7, we show the background-subtracted count map at energies $>100$ MeV. 2FGL J1729.5-0854 is apparently extended. If the extended
feature is genuine and it is indeed associated with a pulsar, the feature might have originated from a pulsar wind nebula. However, given the current source significance, it is difficult to discern whether 2FGL J1729.5-0854 is truly extended or if it consists of more than one unresolved point source. Furthermore, the inadequacy of the adopted diffuse model in a possibly complex region can also lead to a poor localization accuracy of the source. A further dedicated γ-ray analysis of this source is encouraged to identify its nature.

With the above caveats in mind, we considered the error ellipse given by 2FGL in searching for possible X-ray counterparts. By merging all of the available data from the Swift XRT observations in the field of 2FGL J1729.5-0854, we have an effective exposure of ∼57 ks. We detected 13 X-ray sources within its 2FGL 95% γ-ray error ellipse (see Figure 8). Their X-ray properties are summarized in Table 2. The probability of one or more chance coincidences lying within the γ-ray error ellipse is ∼99.9%. This indicates a large fraction of the detected sources might lie in the γ-ray error ellipse by chance, which mainly due to the relatively large γ-ray positional error. The limiting flux for a 4σ point source detection in this field is 9.3 × 10^{-15} erg cm^{-2} s^{-1} in an energy range of 0.3–10 keV.

2.1.6. 2FGL J1744.1-7620

2FGL J1744.1-7620 has been observed by XMM-Newton on 2012 August 21 for a total exposure of ∼25.9 ks (Obs. ID: 0692830101). While both MOS1 and MOS2 cameras were operated in full-frame mode with a medium filter, PN camera was operated in extended full-frame mode with a thin filter. For the calibration and data reduction, we adopted the procedures as described in Section 2.1.3. After applying the good-time-interval filtering by accepting the times when the sky background was low in the CCD and removing all events potentially contaminated by bad pixels, the effective exposures are found to be 25.3, 25.3, and 17.0 ks for MOS1, MOS2, and PN, respectively.

Only one source, J1744_X1, is detected within the 3FGL 95% γ-ray error ellipse of 2FGL J1744.1-7620 at a signal-to-noise ratio >4σ by using the XMMSAS task edetect_chain and srcreg (see Figure 9). Its basic X-ray properties are summarized in Table 2. The probability of one or more chance coincidences lying within the γ-ray error ellipse is ∼48%. The limiting flux for a 4σ detection in this field is 8.3 × 10^{-15} erg cm^{-2} s^{-1} (0.3–10 keV).

Besides this XMM-Newton observation, there was a ∼42 ks Suzaku observation of 2FGL J1744.1-7620 performed on 2010 April 14 (Obs. ID 705013010). However, we found that J1744_X1 cannot be detected in this data. Adopting the total Galactic HI column density of 8.5 × 10^{20} cm^{-2} (Kalberla et al. 2005) and a power-law model with Γ = 2, we place a 3σ limiting of 6.3 × 10^{-14} erg cm^{-2} s^{-1} in 0.3–10 keV, which is above the observed flux of J1744_X1 in the same energy range (see Table 2). Therefore, the null-detection of this Suzaku observation can be ascribed to the poor instrumental sensitivity for point sources.

Figure 4. Potential X-ray counterparts (white circles) of 2FGL J1653.6-0159 as observed by Chandra. The dashed ellipse illustrates the 95% 3FGL confidence ellipse. The image is smoothed with a Gaussian kernel of σ = 5′.
2.1.7. 2FGL J1946.4-5402

2FGL J1946.4-5402 was observed by Suzaku on 2011 October 31 with an exposure of \( \sim 42 \) ks (Obs. ID 706026010). Figure 10 shows the image extracted from the merged observations obtained with the two front-illuminated detectors (XIS0 and XIS3) and one back-illuminated detector (XIS1). Within the 3FGL 95\% error ellipse of 2FGL J1946.4-5402, only one source, J1946_X1, can be detected with a signal-to-noise ratio \( \sim 17\sigma \). The probability of one or more chance coincidences lying within the \( \gamma \)-ray error ellipse is \( \sim 24\% \). The limiting flux of 4\( \sigma \) source detection is \( 3 \times 10^{-14} \) erg cm\(^{-2}\) s\(^{-1}\) (0.3–10 keV).

Its nominal position is R.A. (J2000) = 19\(^{h}\)46\(^{m}\)34\(^{s}\)241 and decl. (J2000) = \(-54^\circ 02^\prime 32^\prime\prime\)96. Nevertheless, due to its inferior spatial resolution, the positional uncertainty resulted from Suzaku observation is typically at an order of \( \sim 1^\prime \) (Uchiyama et al. 2008). Therefore, it is not possible to constrain the position of J1946_X1 to an arcsecond accuracy with the Suzaku data.

In order to better constrain the X-ray position, we observed 2FGL J1946.4-5402 with Swift XRT on 2014 November 14.

**Figure 5.** Background-subtracted light curve of J1653_X1 as observed by Chandra in 0.5–8 keV, which is folded at the periodicity of 4448 s. The epoch of phase zero is set at the start of the good time interval of this observation. Two cycles of orbital modulation are shown for clarity.

**Figure 6.** X-ray spectrum of J1653_X1 as observed by Chandra and fitted with an absorbed power-law model (upper panel) and the ratio between the observed data and the best-fit model (lower panel). We note the excess at energies around 3.5 keV.
With a 6.4 ks exposure, ∼20 photons from J1946_X1 were detected in 0.3–10 keV. With an improved positional determination by Swift XRT, its X-ray position is constrained to be R.A. (J2000) = 19°46′33.69" and decl. (J2000) = −54°02′34.91" with a positional uncertainty of 3″.9 (see Table 2).

For both spectral and temporal analyses, we used the Suzaku data which provides a desirable photon statistic. The source events within a circular region with a radius of 1.5 arcmin around J1946_X1 were selected, which corresponds to a ∼75% encircled energy fraction. The background events were sampled from a nearby source-free region. After background subtraction, there are ∼153, ∼215, and ∼161 cts available from XIS0, XIS1, and XIS3, respectively. For the spectral analysis, the response files were generated with the latest Suzaku/XIS calibration files (20140701). The spectra were grouped so as to have at least 20 counts per spectral bin. All the spectral fits were performed in the energy range of 0.2–10 keV.

In examining the observed spectra with an absorbed blackbody model, we found that it cannot yield any statistically reasonable fit (with χ² = 45.63 for 18 dof). On the other hand, an absorbed power-law model can describe the data fairly well (χ² = 20.70 for 18 dof), which clearly indicates the X-ray emission from J1946_X1 is dominated by non-thermal emission. However, in estimating the uncertainty of the column absorption, we found that this parameter cannot be properly constrained. Therefore, in all subsequent analysis, we fixed NH at 4.3 × 10²⁰ cm⁻² as inferred from the total Galactic HI column density (Kalberla et al. 2005). The power-law fit with NH fixed at this value yields Γ = 1.5 ± 0.2 and a normalization of (1.4 ± 0.4) × 10⁻⁵ photons keV⁻¹ cm⁻² s⁻¹ at 1 keV. The corresponding goodness-of-fit is χ² = 22.35 for 19 dof, which provides an acceptable description of the observed data.

We have performed a periodicity search for J1946_X1. After barycentric correcting all of the events, we first applied the epoch-folding method to look for possible signals. However, no significant signal was detected except for the one related to the orbital period of Suzaku (96 minutes). To avoid the possible contamination caused by the background, we also worked on background-subtracted light curves and searched for periodicity by using the Lomb–Scargle periodogram and the analysis of variance. No significant periodic signal was detected.

2.2. Searches for Optical/IR Counterparts

With the aforementioned X-ray analysis, we constrained the positions of the potential X-ray counterparts possibly associated with the γ-ray MSP candidates to an arcsecond accuracy. Such well-determined positions enable us to further look for their possible optical/IR counterparts. For an MSP in a binary, the optical/IR emission is presumably originated from its companion. Therefore, this search can provide insight on the nature of their companions. Utilizing the USNO-B1.0 catalog (Monet et al. 2003), we first searched for possible optical counterparts. In order to minimize the chance of misidentification, we selected the optical sources with their proper-motion corrected positions lie within the X-ray positional error of each source by combining their statistical uncertainties in Table 2.
Figure 8. Potential X-ray counterparts (white circles) of 2FGL J1729.5-0854 as observed by Swift XRT. This image is produced by using all the available XRT data of this field. The dashed ellipse illustrates the 2FGL 95% confidence ellipse. The image is smoothed with a Gaussian kernel of $\sigma = 4^\circ$.

Figure 9. Potential X-ray counterpart (white circle) of 2FGL J1744.1-7620 as observed by XMM-Newton. This image is produced by merging all three CCD data. The dashed ellipse illustrates the 3FGL 95% confidence ellipse. The image is smoothed with a Gaussian kernel of $\sigma = 4^\circ$. 

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and the corresponding systematics affecting absolute astrometry in quadrature. Six potential counterparts have been identified with this selection criterion. We noted that the position of the possible optical counterpart of J1653_X1 differs from its X-ray position by 1.14 arcsec, which fails to meet our predefined criterion. However, through a dedicated optical temporal investigation, Kong et al. (2014) revealed the optical emission modulated at the same periodicity as X-ray and therefore optical identification is secured. For completeness, we have included this source and the results are summarized in Table 3. Apart from the optical bands, we also looked for the infrared identification of these X-ray sources by searching the 2MASS catalog (Skrutskie et al. 2006) and the ALLWISE catalog (Wright et al. 2010). The results are summarized in Tables 4 and 5. For computing the probability of chance coincidences, we estimated the stellar densities in a field and find the expected chance coincidences $\lambda$ in the X-ray error circles. Except for J1653_X1, the probabilities of one or more optical/IR sources lying in the X-ray error circles by chance are computed using Equation (1) and are summarized in Tables 3–5.

For those candidate counterparts having photometric measurements in both optical and infrared regimes, we construct their spectral energy distributions (SEDs) and probe their nature in further details. This includes the potential counterparts of J1120_X1, J1653_X1, J1729_X2, J1729_X4, J1729_X9, and J1946_X1. Since 2FGL J1653.6-0159 has its optical and X-ray counterpart (i.e., J1653_X1) securely established and its optical spectral and temporal properties

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**Table 3**

| Source | R.A. (J2000) (d m s) | decl. (J2000) (h m s) | $B_1$ (mag) | $R_1$ (mag) | $B_2$ (mag) | $R_2$ (mag) | $I$ (mag) | Offset (arcsec) | $P(\geq 1)\%$ |
|--------|---------------------|----------------------|-------------|-------------|-------------|-------------|----------|----------------|----------------|
| J1120_X1 | 11 19 58.252 | −22 04 56.29 | 15.62 | 15.15 | 15.59 | 15.29 | 14.69 | 1.77 | 3.25 |
| J1653_X1 | 16 53 37.970 | −01 58 36.57 | 19.72 | 19.31 | 20.40 | 19.41 | 20.00 | 1.14 | ... |
| J1729_X2 | 17 29 17.280 | −08 55 03.41 | 21.68 | 18.48 | 20.21 | 18.87 | 18.05 | 1.07 | 8.61 |
| J1729_X4 | 17 29 22.923 | −08 48 31.60 | ... | 19.15 | 21.29 | 19.70 | ... | 2.66 | 9.06 |
| J1729_X9 | 17 29 35.803 | −08 56 53.74 | 18.72 | 16.11 | 17.92 | 16.08 | 14.17 | 2.36 | 8.79 |
| J1946_X1 | 19 46 33.639 | −54 02 36.40 | ... | 17.78 | 18.83 | 19.42 | 18.72 | 1.57 | 11.57 |

**Notes.** The photometric accuracy is $\sim 0.3$ mag.

$^a$ Angular distance between the X-ray positions and the proper-motion corrected optical positions.

$^b$ Probability of one or more optical sources lying in the X-ray error circles by chance.

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**Figure 10.** Potential X-ray counterpart (white circle) of 2FGL J1946.4-5402 as observed by Suzaku. This image is produced by merging the data from the cameras XIS0, XIS1, and XIS3. The dashed ellipse illustrates the 3FGL 95% confidence ellipse. The image is smoothed with a Gaussian kernel of $\sigma = 12''$. 

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Swift: [http://heasarc.nasa.gov/docs/heasarc/caldb/swift/docs/xrt/SWIFT-XRT-CALDB-07_v4.pdf](http://heasarc.nasa.gov/docs/heasarc/caldb/swift/docs/xrt/SWIFT-XRT-CALDB-07_v4.pdf)

XMM-Newton: [http://xmm2.esac.esa.int/docs/documents/CAL-TN-0018.pdf](http://xmm2.esac.esa.int/docs/documents/CAL-TN-0018.pdf)

Chandra: [http://cxc.harvard.edu/cal/ASPECT/celmon/](http://cxc.harvard.edu/cal/ASPECT/celmon/)
have already been explored in details by Kong et al. (2014) and Romani et al. (2014), we will not discuss the optical/IR properties of J1653_X1 any further in this work. For the other five sources under our consideration, we first performed the extinction-correction by adopting the column densities used in computing their absorption-corrected X-ray fluxes (see Cardelli et al. 1989; Predehl & Schmitt 1995). Their de-reddened SEDs were plotted in Figure 11.

For J1120_X1, we compared its SED with various stellar spectral models obtained from Pickles (1998). We found that it is consistent with that of a K4V star (see Figure 11). The SED of J1729_X9 also suggests a thermal origin and is peaked in the IR regime. Since the spectral flux library (i.e., Pickles 1998) that we used in this study only covers the spectral classes down to M stars, there is no model in this library available for comparing with the SED of J1729_X9. For constraining its property, we used a simple blackbody model instead. Since the photometric measurement at 22 μm of J1729_X9 has no error estimate, which is due to the low signal-to-noise measurement in this band, we discarded it in the analysis. Under this assumption, the surface temperature of J1729_X9 is found to be on the order of T \sim 3000 K (see Figure 11), which suggests a possible red dwarf nature.

On the other hand, the SEDs of J1946_X1, J1729_X2, and J1729_X4 do not resemble the thermal emission from a star/ blackbody. Instead, we compare their distributions with a power law F_ν \propto \nu^{\alpha}$. For J1729_X2, the emission from mid-IR to $B$ band can be modeled by a power law with $\alpha = -1.24$. Similar behavior has also been found in J1729_X4. As the data point of J1729_X4 at 22 μm has no error estimate due to its low significance, it was ignored in the analysis. With this measurement excluded, the SED of J1729_X4 can be described by a power law with $\alpha = -0.35$. Therefore, these two sources are likely to be AGNs and can be ruled out as MSP candidates. For J1946_X1, there appears to be an excess from the best-fit power law ($\alpha = -1.54$) in the optical regime. Limited by the sparse data, we are not able to make any firm conclusion about its nature. A dedicated spectroscopic observation is encouraged for J1946_X1.

To search for the temporal variation of these candidate optical/IR counterparts, we looked into the data of Catalina Real-time Transient Survey (CRTS) for multi-epoch photometric measurements. Ignoring those possible counterparts for 2FGL J1653.6-0159 (see Kong et al. 2014 for the optical temporal properties of this source), five sources in Table 2 have been observed by CRTS for more than one time. Their light curves are shown in Figure 12. Using $\chi^2$ test, we determined the statistical significance for the temporal variability of their optical emission. The results are summarized in Table 6. For J1946_X1, J1729_X2, J1729_X4, and J1729_X12, we do not find any evidence for optical variability. On the other hand, the optical emission of J1120_X1 is found to be variable at a confidence level of \sim 96%.

As the optical emission of an MSP binary is originated from continuous heating by the radiation and relativistic wind outflow from the pulsar, this can possibly result in orbital modulation. As there are more than 200 measurements for J1120_X1, we attempted to search for the periodicity with CRTS data. J1120_X1 was observed by the Sidings Springs Survey (SSS) 0.5 m Schmidt telescope for 217 exposures and the Catalina Sky Survey (CSS) 0.7 m Schmidt telescope for 76 exposures. Utilizing the online tool of CRTS on the SSS light curve, several periodicity candidates have been revealed. The most significant one is found at $P \sim 25.31$ days with a false alarm probability of $1.6 \times 10^{-5}$. The second strong candidate is $P \sim 0.96$ days with a false alarm probability of $1.8 \times 10^{-4}$.

### Table 4

The Potential Infrared Counterparts for the X-Ray Sources Listed in Table 2 as Identified in 2MASS Catalog

| Source    | R.A. (J2000) (h m s) | decl. (J2000) (d m s) | $J$ (mag) | $H$ (mag) | $K_s$ (mag) | Offset (arcsec) | $P(\geq 1)^b$ |
|-----------|----------------------|-----------------------|-----------|-----------|------------|----------------|---------------|
| J1120_X1  | 11 19 58.356         | -22 04 56.65          | 15.19 ± 0.04 | 15.06 ± 0.08 | 14.90 ± 0.14 | 0.86 ± 0.08 | 0.90 |
| J1729_X2  | 17 29 17.316         | -08 55 03.57          | 16.33 ± 0.11 | 15.68 ± 0.11 | 15.27 ± 0.15 | 0.75 ± 0.07 | 6.11 |
| J1729_X9  | 17 29 35.801         | -08 56 53.17          | 12.05 ± 0.02 | 11.27 ± 0.02 | 10.95 ± 0.02 | 2.65 ± 0.07 | 6.29 |

Notes.

\( ^a \) Angular distance between the X-ray positions and the IR positions.

\( ^b \) Probability of one or more infrared sources lying in the X-ray error circles by chance.

### Table 5

The Potential Infrared Counterparts for the X-Ray Sources Listed in Table 2 as Identified in WISE Catalog

| Source    | R.A. (J2000) (h m s) | decl. (J2000) (d m s) | W1 (3.4 μm) (mag) | W2 (4.6 μm) (mag) | W3 (12 μm) (mag) | W4 (22 μm) (mag) | Offset (arcsec) | $P(\geq 1)^b$ |
|-----------|----------------------|-----------------------|------------------|------------------|-----------------|-----------------|----------------|---------------|
| J1120_X2  | 11 20 01.787         | -22 04 57.04          | 15.64 ± 0.04     | 15.10 ± 0.08     | 11.68 ± 0.25    | 8.70 ± 0.14     | 3.14 ± 0.07     | 4.78 |
| J1729_X2  | 17 29 17.316         | -08 55 03.66          | 13.79 ± 0.03     | 12.52 ± 0.02     | 9.80 ± 0.06     | 7.13 ± 0.11     | 0.53 ± 0.07     | 7.32 |
| J1729_X4  | 17 29 22.933         | -08 48 32.80          | 15.50 ± 0.050    | 15.14 ± 0.09     | 12.28 ± 0.43    | 8.59 ± 0.47     | 1.47 ± 0.47     | 7.69 |
| J1729_X9  | 17 29 35.796         | -08 56 53.42          | 10.78 ± 0.02     | 10.60 ± 0.02     | 10.47 ± 0.08    | 8.64 ± 0.08     | 2.56 ± 0.08     | 7.50 |
| J1729_X10 | 17 29 38.532         | -09 00 25.54          | 16.66 ± 0.11     | 16.44 ± 0.11     | 12.38 ± 0.11    | 8.99 ± 0.11     | 3.32 ± 0.11     | 8.42 |
| J1729_X12 | 17 29 43.975         | -08 57 24.14          | 11.21 ± 0.02     | 11.02 ± 0.02     | 10.93 ± 0.15    | 8.94 ± 0.15     | 3.50 ± 0.15     | 7.60 |
| J1729_X13 | 17 30 01.947         | -08 56 57.14          | 15.93 ± 0.06     | 15.00 ± 0.08     | 12.27 ± 0.47    | 8.14 ± 0.47     | 2.58 ± 0.47     | 7.60 |
| J1946_X1  | 19 46 33.630         | -54 02 36.43          | 15.20 ± 0.04     | 14.56 ± 0.05     | 11.83 ± 0.26    | 8.16 ± 0.23     | 1.62 ± 0.23     | 12.28 |

Notes.

\( ^a \) Angular distance between the X-ray positions and the IR positions.

\( ^b \) Probability of one or more infrared sources lying in the X-ray error circles by chance.
Figure 11. Spectral energy distributions (SEDs) for the possible optical/infrared counterparts associated with J1120_X1, J1729_X2, J1729_X4, J1729_X9, and J1946_X1. All of the data points have been de-reddened. Their distributions are compared with a stellar spectral model (Pickles 1998), a blackbody, or a power law.
Figure 12. Optical light curves of the potential counterparts of several X-ray sources as obtained from CRTS.
To cross-check the robustness of these results, we also performed a more detailed analysis by computing the Lomb–Scargle periodogram on the combined SSS+CSS light curve. We detected a series of peaks that were denoted as the harmonics of one-year observational gap. Besides them, two signals are also significantly detected as \( P \sim 25.36 \) and \( P \sim 27.35 \) days. To further investigate the effect of observational gaps, we examined the power spectrum of the window function. The \( \sim 1 \) year and 1 day signals remain the strongest peaks in the power spectrum of the window function. Except for these two signals, another strong peak located at \( P \sim 29.53 \) days, which corresponds to a synodic month, was also significantly obtained. In addition, several aliases that represent the beat periods of yearly and monthly signals, including \( P \sim 27.32 \) days (a sidereal month) and \( P \sim 25.39 \) days, are also clearly observed. Considering the possible differences between SSS and CSS data, we also applied the same analysis on the SSS light curve solely. The result is similar to that obtained with the combined light curve although the yearly signal and corresponding harmonics are much weaker. Therefore, the putative \( \sim 25.36 \) days periodicity identified by the online CRTS tool is very likely caused by the non-uniform distribution of data points.

2.3. Searches for Potential Radio Counterparts

Since all the known MSPs are radio emitters, we have also searched for possible radio counterparts for all the X-ray sources in Table 2. Using the point source catalogs of Sydney University Molonglo Sky Survey (Bock et al. 1999) and NRAO VLA Sky Survey (Condon et al. 1998), we did not find any radio source within \( 5\sigma \) X-ray positional uncertainties of all the tabulated X-ray sources. Barr et al. (2013) have performed a target pulse survey of 2FGLs J1120.0-2204 and J1625.2-0020 with Effelsberg 100 m radio telescope. This survey does not result in any pulsar detection associated with these two \( \gamma \)-ray sources. A limiting flux density of \(<70 \mu\text{Jy} \) at 1.36 GHz has been placed.

3. SUMMARY AND DISCUSSION

We have systematically searched for MSP candidates from the unidentified 2FGL objects. Seven unassociated \( \gamma \)-ray sources are suggested to be promising candidates. We have also searched for the X-ray and optical/IR sources within their \( \gamma \)-ray error ellipses. This enables us to constrain the positions of these \( \gamma \)-ray selected MSP candidates to a much higher accuracy, which facilitates the pulsation search and multi-wavelength follow-up investigations in the future.

Apart from characterizing their X-ray positions and X-ray fluxes through a systematic analysis, we have also performed a detailed X-ray spectral analysis for those sources that have sufficient photon statistics. In particular, we confirm the non-thermal X-ray nature of J1653_X1 and J1946_X1. For an MSP in a tight binary system, the non-thermal X-rays can be resulted from the intrabinary shock. The Doppler boosting of the post-shocked pulsar wind can result in the X-ray orbital modulation as observed in the case of J1653_X1 (Figure 5). For J1653_X1, besides the power-law spectrum, we have also identified a putative emission feature at \( \sim 3.5 \text{ keV} \) (see Figure 6). However, the current data do not allow us to confirm its existence unambiguously. Observations with improved photon statistic are needed for further investigation of this feature. Another possible X-ray MSP candidate is J1946_X1. It is the only X-ray source found within the \( \gamma \)-ray error ellipse. The spectral analysis shows that its X-ray emission is also clearly non-thermal dominant. Also, the X-ray to \( \gamma \)-ray flux ratios of J1653_X1 and J1946_X1, \( f_x/f_{\gamma} \sim 10^{-2} \), are comparable to the typical values of MSPs or radio-loud pulsars \( f_x/f_{\gamma} \sim 5 \times 10^{-3} \) (Marelli et al. 2011; Abdo et al. 2013). This further suggests J1653_X1 and J1946_X1 to be promising pulsar candidates.

2FGL J1120.0-2204 is another candidate that deserves a follow-up investigation. Through identifying the potential optical/IR counterparts of the brightest X-ray source J1120_X1 within the \( \gamma \)-ray error ellipse, we have constructed its SED and found that it is comparable with a late-type star. This suggests it to be a possible candidate of a low-mass X-ray binary/redback MSP. Also, its optical light curve as obtained from CRTS shows evidence of variability. Therefore, the optical behaviors make J1120_X1 another interesting target for the follow-up studies with dedicated X-ray and optical/IR observations.

On the other hand, for 2FGL J1744.1-7620 and 2FGL J1625.2-0020, we do not identify any possible optical/IR association in this study. This might indicate they are candidates for isolated MSPs or non-recycled pulsars. Taking a limiting magnitude of \( V \sim 21 \) (Monet et al. 2003), the X-ray to optical flux ratios of J1744_X1 and J1625_X1 are found to be \( f_x/f_{opt} \gtrsim 10^{-3} \). However, this is not constraining in determining their emission nature (e.g., Maccacaro et al. 1988; Stocke et al. 1991). Dedicated optical/IR observations at their X-ray positions are required to place tighter constraint. We also compare their X-ray to \( \gamma \)-ray flux ratios with that of non-recycled radio-loud pulsars \( (f_x/f_{\gamma} \sim (0.34-53) \times 10^{-3}) \), radio-quiet pulsars \( (f_x/f_{\gamma} \sim (0.1-1.0) \times 10^{-3}) \), and MSPs \( (f_x/f_{\gamma} \sim (1.6-15) \times 10^{-3}) \); Abdo et al. 2013). Within a 1\( \sigma \) uncertainty, the low flux ratio of 2FGL J1744.1-7620, \( f_x/f_{\gamma} \sim (0.5-0.8) \times 10^{-3} \), is consistent with that of non-recycled radio-loud/radio-quiet pulsars. On the other hand, the flux ratio of 2FGL J1625.2-0020, \( f_x/f_{\gamma} \sim (1.0-1.6) \times 10^{-3} \), is consistent with all three classes mentioned above.

The non-detection of any possible radio counterpart for these pulsar candidates can be ascribed to the relatively low sensitivities of the existing surveys. Targeted observations are encouraged to search for the radio emission from the X-ray/optical positions constrained in this study. While radio pulsation search can unambiguously confirm the pulsar nature, radio imaging observation is also useful. Since some of these MSP candidates can be redbacks, they are subjected to possible state-switch (Li et al. 2014; Takata et al. 2014). When they are flipped to an accretion-powered state, the increased mass-transfer rate can result in a complicated local ionized environment that can smear the pulsed radio emission. In this case, even though the radio pulsar emission mechanism is still
active, it will be very difficult to detect it. On the other hand, as a direct imaging is free from the problem of correcting complicated dispersion, it can be a robust method to investigate if there is any radio emission from the X-ray/optical position.

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