SEARCH FOR GAMMA-RAY EMISSION FROM FOUR ACCRETING MILLESECONDD PULSARS WITH FERMI/LAT

YI XING AND ZHONGXIANG WANG
Shanghai Astronomical Observatory, Chinese Academy of Sciences, 80 Nandan Road, Shanghai 200030, China
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ABSTRACT

We report our search for γ-ray emission in the energy range from 100 MeV to 300 GeV from four accreting millisecond pulsars (AMPs), SAX J1808.4−3658, IGR J00291+5934, XTE J1814−338, and XTE J0929−314. The data are from four-year observations carried out by the Large Area Telescope on board the Fermi Gamma-Ray Space Telescope. The AMPs were not detected, and the γ-ray luminosity upper limits we obtain are $5.1 \times 10^{33}$ erg s$^{-1}$ for SAX J1808.4−3658, $2.1 \times 10^{33}$ erg s$^{-1}$ for IGR J00291+5934, $1.2 \times 10^{34}$ erg s$^{-1}$ for XTE J1814−338, and $2.2 \times 10^{33}$ erg s$^{-1}$ for XTE J0929−314. We compare our results with γ-ray irradiation luminosities required for producing optical modulations seen from the companions in the AMPs, which has been suggested by Takata et al., and our upper limits have excluded γ-ray emission as the heating source in these systems except XTE J0929−314, the upper limit of which is not deep enough. Our results also do not support the model proposed by Takata et al. that relatively strong γ-ray emission could arise from the outer gap of a high-mass neutron star controlled by the photon–photon pair creation for the AMPs. Two AMPs, SAX J1808.4−3658 and IGR J00291+5934, have measurements of their spin-down rates, and we derive the upper limits of their γ-ray conversion efficiencies, which are 57% and 3%, respectively. We discuss the implications to the AMP systems by comparing the efficiency upper limit values with that of 20 γ-ray millisecond pulsars (MSP) detected by Fermi and the newly discovered transitional MSP binary J1023+0038.

Key words: binaries: close – gamma rays: stars – pulsars: general – stars: neutron

1. INTRODUCTION

Accreting millisecond pulsars (AMPs) are all in low-mass X-ray binary (LMXB) systems, spinning at frequencies more than 100 Hz and containing companion stars with masses less than $1 M_\odot$ (Patruno & Watts 2012). The periodical pulsed emission from AMPs is accretion-powered, which distinguishes them from normal radio millisecond pulsars (MSPs) that are powered by rotation. AMPs are believed to be the progenitors of MSPs spun up from old slowly rotating neutron stars (NSs) by the recycling scenario (Alpar et al. 1982; Bhattacharya & van den Heuvel 1991; Srinivasan 2010), which is when an NS in a binary system switches off the pulsed radio emission, and the mass and angular momentum of the companion star are transferred to the NS through accretion, producing a recycled pulsar that eventually spins on a period of milliseconds. The currently known AMPs are all transient systems with recurrent times of years. The evolution of their accretion disks leads to weeks-long outbursts, during which pulsed X-ray emission is detected.

The first known AMP SAX J1808.4−3658 was found by the BeppoSAX mission in 1996 (in ’t Zand et al. 1998) and was discovered to have pulsed X-ray emission with the Rossi X-Ray Timing Explorer during its 1998 outburst (Wijnands & van der Klis 1998; Chakrabarty & Morgan 1998). Since then, over a dozen AMP systems have been discovered (Patruno & Watts 2012). One interesting property of AMP binaries was first pointed out by Burderi et al. (2003): because the orbital optical modulation seen in SAX J1808.4−3658 has a larger than expected amplitude in the quiescent state (Homer et al. 2001), the AMP probably becomes rotation-powered and thus is able to provide the required energy output to heating the companion. Follow-up observations of SAX J1808.4−3658 at X-ray and optical energies have firmly verified the inconsistency between the large optical modulation and low X-ray luminosity in quiescence (Campana et al. 2004; Deloye et al. 2008; Wang et al. 2009b). X-ray emission from accreting compact stars is normally the heating source that causes orbital optical modulations seen in LMXBs (e.g., van Paradijs & McClintock 1995). In addition, inconsistency has also been seen in two other AMP systems, IGR J00291+5934 and XTE J1814−338 (D’Avanzo et al. 2007, 2009; Jonker et al. 2008), which suggests a common property of being able to become radio pulsars in quiescence for AMP systems, although no direct evidence has been found from radio observations of these systems (Burgay et al. 2003).

The more recent discovery of the MSP binary PSR J1023+0038 (Archibald et al. 2009) has strengthened the likelihood of the radio-pulsar switching property of the AMP systems. The binary is considered to be the first system found at the end of its evolution from an LMXB to an MSP binary, as a short-term accretion disk was seen in it (Wang et al. 2009a, 2013a). γ-ray emission from PSR J1023+0038 was also found from observations carried out by the Fermi Gamma-Ray Space Telescope (Tam et al. 2010). Considering PSR J1023+0038 as an end product of LMXB evolution closely related to AMP systems, Takata et al. (2012) studied possible γ-ray emission mechanisms for the AMP systems known with large-amplitude optical modulations (see Table 1). In their work, they attributed the optical modulations of the AMP systems to γ-ray irradiation of the companions, which required γ-ray luminosity $L_\gamma > 10^{32}−10^{34}$ erg s$^{-1}$. The predicted γ-ray emission is possibly detectable by Fermi, and any detection would provide strong evidence for the existence of radio pulsars in these AMP systems in quiescence. We thus searched for γ-ray emission from the four AMPs in the data obtained by Fermi and report our results in this paper. The general properties of the four AMPs are summarized in Table 1.
In Section 2, we describe the data from the Fermi Large Area Telescope (LAT) observations and our analysis of the data for the four AMPs. We provide our results in Section 3 and discuss the implications of our results in Section 4.

## 2. OBSERVATION AND DATA ANALYSIS

LAT is an imaging instrument on board the Fermi Gamma-ray Space Telescope. Its main objective is to conduct continuous \( \gamma \)-ray monitoring of a large sample of sources in an energy range from 20 MeV to 300 GeV with much improved sensitivity compared with former \( \gamma \)-ray telescopes (Atwood et al. 2009). In our data analysis, we selected LAT events within 15° centered at the positions of the four AMPs during a time period from the start of the public release of Fermi data on 2008 August 4 15:43:36 (UTC) to 2012 July 8 18:59:57 (UTC) from the Fermi Pass 7 database. We included events in an energy range from 100 MeV to 300 GeV. Following the recommendations of the LAT team, we required the events zenith angle to be less than 100° to prevent the Earth’s limb contamination and excluded events in time intervals when spacecraft events affected the LAT data.

### 2.1. Maximum Likelihood Analysis

We rejected events below 200 MeV and included only events in the energy range from 200 MeV to 300 GeV for the likelihood analysis, because the instrument response function of LAT has relatively large uncertainties in the lower energy range. We included all sources within 20° centered at the four AMPs to make the source models based on the Fermi two-year catalog. Most are point sources, while a few of them are diffuse sources. The spectral function forms of these sources given in the catalog were used. We let the spectral normalization parameters of sources within 3° from the four AMPs free, and fixed all the other parameters of sources included in our source models to their catalog values. The four AMPs we are interested in were not included in the Fermi catalog. We modeled their \( \gamma \)-ray spectra with an exponentially cutoff power law, which is the typical spectral form of pulsars (Abdo et al. 2009, 2010c). The exponentially cutoff power law can be expressed by \( dN/dE = N_0E^{-\Gamma}\exp\left[-\left(E/E_{\text{cut}}\right)\right] \), where \( \Gamma \) is the spectral index and \( E_{\text{cut}} \) is the cutoff energy. In addition, we considered the Galactic and extragalactic diffuse emission using the model gal_2yearp7v6_v0.fits and the spectrum file iso_p7v6source.txt. The value of the Galactic diffuse emission model and the normalization of the extragalactic diffuse emission model were left free.

We performed standard binned likelihood analysis with the LAT science tools software package \texttt{v9r27p1}. The binned likelihood used events in a square region instead of a circle, so we selected events inside a 20° × 20° region centered at each interested source, which is nearly the inscribed square of the circular region we selected above. We obtained the test statistic (TS) of the four AMPs, and the TS maps of 3° × 3° regions centered at each of the four AMPs are shown in Figure 1. Each of the maps was extracted by assuming a putative source and performing binned likelihood analysis to obtain the TS value at each grid point of the regions. The sources in the source models outside of the regions and the Galactic and extragalactic diffuse emission were considered. We found that IGR J00291+5934, XTE J1814−338, and XTE J0929−314 had TS values of \( \sim 0 \), and SAX J1808.4−3658 had a TS value of \( \sim 3 \). A TS value is approximately the square of the detection significance of a source and it can be used to assess whether or not a source exists. Actually, in the Fermi source catalog only sources with TS values greater than 25 were included, which corresponds to the detection significance of 4.6\( \sigma \) (Abdo et al. 2010b). The TS values of the four AMPs thus indicate that they were not detected by Fermi/LAT in 200 MeV–300 GeV band.

### 2.2. Flux Upper Limit Calculation

The \( \gamma \)-ray flux upper limits of these four AMPs were estimated by the binned likelihood analysis with the source models we described above. We fixed the \( \Gamma \) and \( E_{\text{cut}} \) parameters of the spectral models of the four AMPs to 1.4 and 1.6 GeV, respectively, which are the averaged spectral parameters of the eight MSPs Fermi detected during the first six months monitoring

### Table 1

| Source Name | \( d \) (kpc) | \( \nu \) (Hz) | \( \nu / \Gamma \) (10^{-15} Hz s^{-1}) | \( E_{\text{cut}} \) (10^{33} erg s^{-1}) | \( \tau \) (10^{9} yr) | Quiescence (MJD) | \( L_{\gamma} \) (10^{33} erg s^{-1}) | \( \eta_{\gamma} \) |
|-------------|---------------|---------------|---------------------------------|---------------------------------|----------------|----------------|-------------------------------|----------------|
| SAX J1808.4−3658 | 3.5^a | 400.97521024^d | −0.55^e | 9 | 11.56 | 54682–54720 | 54780–55855 | 55915–56116 | <5.1 | <0.57 |
| IGR J00291+5934 | 5^b | 598.89213061^f | −3.0^g | 70 | 3.17 | 54777–56116 | <2.1 | <0.03 |
| XTE J1814−338 | 8^c | 314.35610879^h | ... | ... | ... | ... | <12 | ... |
| XTE J0929−314 | 6^d,e | 185.105259^i | ... | ... | ... | ... | <2.2 | ... |

Notes: Column 5 lists the spin-down luminosities of the sources with spin-down rate measurements. Column 6 lists the characteristic ages derived by \( \nu / 2 \Gamma \). Column 7 lists the epoch of quiescent state defined in this paper. Column 8 lists the 100 MeV to 300 GeV \( \gamma \)-ray luminosity upper limits resulting from binned likelihood analysis of the LAT data with \( \Gamma \) and \( E_{\text{cut}} \) of the spectral models of these sources fixed to 1.4 and 1.6 GeV. Column 9 lists the 100 MeV to 300 GeV \( \gamma \)-ray conversion efficiency upper limits for the sources with measurements of spin-down rates.

^a Gallaway (2006).
^b Falanga et al. (2005).
^c Strohmayer et al. (2003).
^d Gallaway et al. (2002).
^e Iacolina et al. (2009).
^f The epoch time is MJD 52499.9602472 (Hartman et al. 2009).
^g The epoch time is MJD 54692.0 (Patruno 2010).
^h The epoch time is MJD 52797.2738758968 (Papitto et al. 2007).
^i The epoch time is MJD 52405.48676 (Iacolina et al. 2009).
Figure 1. 200 MeV–300 GeV TS maps of $3^\circ \times 3^\circ$ regions centered at the four AMPs. The image scales of the maps are $0.1\,\text{pixel}^{-1}$ and the crosses in the center of each maps mark the positions of the AMPs. The circles in two of these maps mark the $\gamma$-ray sources reported in the Fermi two-year catalog.

(Ando et al. 2009, 2010c) and derived from the Fermi two-year catalog (see Table 2). The spectral normalization factors were let free. We extracted the upper limits of normalization factors by increasing these factors until the maximum likelihood values decreased by $e/2$ in logarithm, following the procedure introduced by the LAT team. Then, using the upper limits of normalization factors, we derived the 95% flux upper limits in energy range from 100 MeV to 300 GeV by integrating the spectral
The frequency derivatives were considered for sources with them into 20 phase bins using X-ray ephemerides (Table 1).

γ-ray pulsations (Abdo et al. 2010c), thereby indicating that no significant γ-ray pulsations from these four AMPS were detected. In addition, since our targets are all located in the Galactic plane, contamination from diffuse emission and nearby sources may prevent the detections of γ-ray pulsations. We thus tested to decrease the radii of the target regions from 5 to 0.5 to search for γ-ray pulsations. However, no significant γ-ray pulsations were detected either with χ² values of 7–32 (19 dof) and H values of 0.1–9.3.

For SAX J1808.4–3658 and IGR J00291+5934, which had X-ray outbursts after 2008 August under the Fermi coverage, we also searched their γ-ray pulsations during the outbursts. SAX J1808.4–3658 had the X-ray outbursts in 2008 starting at MJD 54730 with ν of 400.97521009 Hz and ∼0.6 × 10⁻¹³ Hz s⁻¹ (Hartman et al. 2009), and in 2011 starting at MJD 55865 with ν of 400.97520981 Hz and non-significant ν of < 4 × 10⁻¹⁴ Hz s⁻¹ (Patruno et al. 2012). IGR J00291+5934 had two X-ray outbursts in 2008 starting at MJD 54691 and MJD 54727 (Lewis et al. 2010). X-ray observations in MJD 54691.94–54696.77 revealed ν of 598213046 Hz and non-significant ν of 0.1–5 Hz s⁻¹, and in MJD 54730.51–54760 (19 dof) and H values of 0.1–9.3.

We performed timing analysis of the Fermi/LAT observations of the four AMPS to search for any γ-ray pulsations. We included events in an energy range from 100 MeV to 300 GeV within 1° centered at the positions of these four sources and folded them into 20 phase bins using X-ray ephemerides (Table 1).

The frequency derivatives were considered for sources with them into 20 phase bins using X-ray ephemerides (Table 1).

| Source Name | d (kpc) | ν (Hz) | ν (10⁻¹⁵ Hz s⁻¹) | Eₚd (10⁻⁵ erg s⁻¹) | τ (10⁹ yr) | Lν (10⁻⁵ erg s⁻¹) | ην |
|-------------|--------|--------|------------------|-------------------|-----------|------------------|-----|
| J0030+0451* | 0.3°   | 205.3° | −0.4°            | 3                 | 7.72      | 0.67 ± 0.02      | 0.197 ± 0.007 |
| J0034−0534  | 0.5°   | 531.9° | −1.4°            | 12                | 7.84      | 0.39 ± 0.04      | 0.032 ± 0.004 |
| J1010−6422  | 0.6°   | 389.4° | −0.8°            | 12                | 7.84      | 0.39 ± 0.04      | 0.032 ± 0.004 |
| J0218+4232  | 2.7°   | 431.0° | −1.3°            | 243               | 0.48      | 41 ± 2           | 0.17 ± 0.01  |
| J0437−4715* | 0.2°   | 173.6° | −0.4°            | 3                 | 6.52      | 0.054 ± 0.004    | 0.018 ± 0.001 |
| J0610−2100  | 3.5°   | 262.3° | −0.9°            | 9                 | 4.88      | 12 ± 2           | 1.3 ± 0.3    |
| J0613−0200* | 0.5°   | 326.8° | −1.0°            | 12                | 5.39      | 0.85 ± 0.06      | 0.068 ± 0.005 |
| J0616−3329  | 1.9°   | 317.5° | −1.8°            | 22                | 2.85      | 48 ± 1           | 2.2 ± 0.1    |
| J0751+1807* | 0.6°   | 287.4° | −0.5°            | 6                 | 9.20      | 0.67 ± 0.07      | 0.12 ± 0.01  |
| J1231−1411  | 0.4°   | 271.7° | −1.7°            | 18                | 2.56      | 2.02 ± 0.06      | 0.112 ± 0.003 |
| J1614−2230* | 1.3°   | 317.5° | −0.4°            | 5                 | 12.49     | 4.6 ± 0.4        | 0.91 ± 0.08  |
| J1744−1134* | 0.5°   | 245.7° | −0.4°            | 4                 | 9.22      | 0.94 ± 0.07      | 0.23 ± 0.02  |
| J1823−3021A | 8.4°   | 183.8° | −114.2°          | 829               | 0.03      | 133 ± 23         | 0.16 ± 0.03  |
| J1959+2048  | 2.5°   | 625.0° | −6.6°            | 163               | 1.50      | 12 ± 1           | 0.077 ± 0.009 |
| J2017+0903  | 1.6°   | 344.8° | −1.0°            | 13                | 5.54      | 11.0 ± 0.7       | 0.82 ± 0.05  |
| J2043+1710  | 1.8°   | 420.2° | −0.9°            | 15                | 7.20      | 11.4 ± 0.8       | 0.74 ± 0.05  |
| J2124−3338* | 0.3°   | 202.8° | −0.5°            | 4                 | 6.51      | 0.28 ± 0.01      | 0.070 ± 0.004 |
| J2214+3000  | 1.5°   | 320.5° | −1.4°            | 18                | 3.53      | 8.9 ± 0.5        | 0.49 ± 0.03  |
| J2231−5236  | 0.5°   | 457.3° | −1.4°            | 25                | 5.19      | 1.02 ± 0.06      | 0.042 ± 0.002 |
| J2302+4442  | 1.2°   | 192.7° | −0.5°            | 4                 | 6.19      | 6.7 ± 0.4        | 1.8 ± 0.1    |

Notes. Observational properties of the 20 confirmed γ-ray MSPs in Fermi two-year catalog. The sources marked with “*” are the first eight γ-ray MSPs detected by Fermi/LAT. Column 2 lists the distance of each source. Columns 3 and 4 list the frequency and spin-down rate of each source. Column 5 lists the spin-down luminosities of sources. Column 6 lists the characteristic ages derived by ν/2π. Column 7 lists the 100 MeV–100 GeV γ-ray luminosities derived from catalog. Column 8 lists the 100 MeV–100 GeV γ-ray conversion efficiencies. The uncertainties of luminosities and efficiencies are derived from flux uncertainties, the distance uncertainties are not considered here.

Table 2
Observational Properties of the 20 Confirmed γ-Ray MSPs in the Fermi Two-year Catalog

2.3. Timing Analysis

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Figure 2. 100 MeV–300 GeV folded light curves of the four AMPs included in our work. The phase resolution of each light curve is 0.05. The spin parameters we used in epoch folding are those listed in Table 1. For each light curve, we performed the $\chi^2$ and $H$ tests to identify possible presence of pulsations. The obtained $\chi^2$/dof and $H$ values are given in the upper right corner of each panel.

2.4. Analysis of the Data in the Quiescent State

The data used in our analyses in Sections 2.1 and 2.2 were nearly four years from 2008 to 2012. As given in Section 2.3, during the time period SAX J1808.4−3658 had two X-ray outbursts and IGR J00291+5934 had two close X-ray outbursts. According to the current models for the $\gamma$-ray emission mechanism for pulsars (see discussion in Section 4), accretion of the MSPs in these two binaries in the outbursts should have quenched $\gamma$-ray emission from their magnetospheres. Although the durations of the outbursts were short compared to the four-year length of the total data, we checked whether our nondetections of the two sources and upper limit calculations would be significantly affected. The outburst state of the two sources lasted about 20–50 days (Hartman et al. 2009; Patruno et al. 2012; Lewis et al. 2010), and optical observations showed that the brightening of the accretion disks started several tens of days before the outbursts (Wang et al. 2013b; Lewis et al. 2010). We excluded Fermi/LAT data from 10 days prior to and 50 days after the beginning of each outburst and performed likelihood analysis using the data only in the quiescent state given in Table 1. With the same event selections and source models, the TS values we obtained in quiescent state are $\sim 3$ for SAX J1808.4−3658 and $\sim 0$ for IGR J00291+5934, and the $\gamma$-ray luminosity upper limits are $5.0 \times 10^{33}$ erg s$^{-1}$ for SAX J1808.4−3658 and $2.3 \times 10^{33}$ erg s$^{-1}$ for IGR J00291+5934, which are nearly the same as that we obtained using the total data sets.

3. RESULTS

We found that the four AMPs included in our work were not detected by Fermi/LAT at $\gamma$-ray energies. We obtained upper limits of their $\gamma$-ray luminosities: $5.1 d_{15}^2 \times 10^{33}$ erg s$^{-1}$ for SAX J1808.4−3658, $2.1 d_{15}^2 \times 10^{33}$ erg s$^{-1}$ for IGR J00291+5934, $1.2 d_{15}^2 \times 10^{34}$ erg s$^{-1}$ for XTE J1814−338, and $2.2 d_{15}^2 \times$
10^{33} \text{ erg s}^{-1} \text{ for XTE J0929}−314, \text{ where } d \text{ is the source distance with its subscript indicating the value (in units of kpc; Table 1) used. These results are summarized in Table 1. Two AMPs—SAX J1808.4−3658 and IGR J00291+5934—have measurements of their spin-down rates (Table 1), through which we estimated the spin-down luminosities by \(\dot{E} = 4\pi^2 I \Omega^2\), \text{ where } I \text{ is the NS moment of inertia and assumed to have a canonical value of } I = 10^{45} \text{ g cm}^2. \text{ We calculated the upper limit of } \gamma\text{-ray conversion efficiency } \eta_\gamma = L_\gamma / \dot{E} \text{ for these two sources with the upper limits of } \gamma\text{-ray luminosities we obtained above. SAX J1808.4−3658 has } \eta_\gamma \text{ of } \leq 0.057 d_5^{-0.5}, \text{ and IGR J00291+5934 has } \eta_\gamma \text{ of } \leq 0.03 d_5^{-0.3}. \text{ The latter provides a strong constraint on the } \gamma\text{-ray emission from this source.}

4. DISCUSSION

We searched \(\gamma\text{-ray} \text{ emission from four AMPs, SAX J1808.4−3658, IGR J00291+5934, XTE J1814−338, and XTE J0929−314 with Fermi/LAT observations. The four sources were not detected by Fermi/LAT in the 200 MeV to 300 GeV energy range. We obtained the 100 MeV to 300 GeV } \gamma\text{-ray luminosity upper limits of these four sources. In addition, for SAX J1808.4−3658 and IGR J00291+5934, with the measurements of their spin-down rates, we estimated the 100 MeV to 300 GeV } \gamma\text{-ray conversion efficiency upper limits. The obtained values of these sources can be used to compare with model predictions of AMPs and conversion efficiencies of } \gamma\text{-ray MSPs, which provides constraints on their properties including } \gamma\text{-ray emission mechanisms.}

Depending on different assumptions, a wide range of } L_\gamma \text{ values for the four AMPs have been predicted by Takata et al. (2012). Furthermore, they have suggested that optical modulations seen in the AMP binaries could be caused by } \gamma\text{-ray irradiation of the companion stars. The irradiation } \gamma\text{-ray luminosities of these sources required for optical modulations were used to constrain the theoretical emission models. For SAX J1808.4−3658, IGR J00291+5934, and XTE J1814−338, the inferred } \gamma\text{-ray irradiation luminosities of } > 10^{33} \text{ erg s}^{-1} \text{ favored the outer gap model with a high-mass NS controlled by the photon–photon pair creation between } \gamma\text{-rays and X-rays from full surface cooling emission, or the outer gap model controlled by the magnetic pair-creation process (Takata et al. 2012). Such a high luminosity cannot be produced by the outer gap model controlled by the photon–photon pair creation between } \gamma\text{-rays and X-rays from the heated polar cap because an unreasonably high NS magnetic field is required. For XTE J0929−314 with a lower inferred } \gamma\text{-ray irradiation luminosity of } \sim 10^{32} \text{ erg s}^{-1}, \text{ the outer gap model with a low-mass NS controlled by the photon–photon pair creation between } \gamma\text{-rays and X-rays from full surface cooling emission might be preferred (Takata et al. 2012).}

In our work, we found that the } \gamma\text{-ray luminosities of SAX J1808.4−3658 and IGR J00291+5934 observed by Fermi/LAT had the upper limits of } 5.1 d_5^{-0.5} \times 10^{33} \text{ erg s}^{-1} \text{ and } 2.1 d_5^{-0.5} \times 10^{33} \text{ erg s}^{-1}, \text{ respectively, which are significantly lower than the required } \gamma\text{-ray irradiation luminosities of these two sources. For XTE J1814−338 and XTE J0929−314, the } \gamma\text{-ray luminosity upper limits of } 1.2 d_5^{-0.5} \times 10^{34} \text{ erg s}^{-1} \text{ and } 2.2 d_5^{-0.5} \times 10^{33} \text{ erg s}^{-1} \text{ are consistent with the required } \gamma\text{-ray irradiation luminosities. However, for XTE J1814−338, the } \gamma\text{-ray irradiation luminosity lower limit given by Takata et al. (2012) is nearly equal to the luminosity upper limit we obtained. Considering that the actual luminosities of these AMPs might be significantly smaller than the upper limits, the Fermi observations of these sources indicate that the } \gamma\text{-ray emission of three AMPs, SAX J1808.4−3658, IGR J00291+5934, and XTE J1814−338, are lower than the values needed to interpret the optical modulations. Thus, } \gamma\text{-ray irradiation from the AMPs should not be the main heating source of their companions. The irradiation from release of the rotational energy of the pulsars should be preferred, which indeed provide the required energy output of } 10^{32}−10^{33} \text{ erg s}^{-1} \text{ to heat the companions (Burderi et al. 2003; our Table 1), although there are a few unresolved theoretical uncertainties in this model (Burderi et al. 2003; Takata et al. 2012).}

\(\gamma\text{-ray} \text{ emission from pulsars is generally agreed to originate from accelerations of charged particles, while it is still uncertain where the accelerations occur. At present there are polar cap, outer gap, and slot gap models to be advanced to interpret the high energy emission of pulsars. The polar cap model (Ruderman & Sutherland 1975) has acceleration regions near the surface of an NS, which predicts pulsed emission aligned with the magnetic poles. The model fails to interpret the } \gamma\text{-ray pulsed profiles of pulsars because most pulsars have two sharp peaks that are not aligned with radio peaks (Abdo et al. 2009, 2010c). The outer gap (Muslimov & Harding 2004) and slot gap models (Cheng et al. 1986) have acceleration regions along the last open field lines to near the light cylinder, starting from the null surface and the polar cap, respectively. The two models are both predicted to have wide-fan beams that are not aligned with magnetic poles so that they are more preferred for interpreting } \gamma\text{-ray emission from pulsars. Comparing with that on the basis of the outer gap model predicted by Takata et al. (2012), our results basically rule out their model of a high-mass NS controlled by the photon–photon pair creation between } \gamma\text{-rays and X-rays from full surface cooling emission for SAX J1808.4−3658, IGR J00291+5934, and XTE J1814−338. For XTE J0929−314, the outer gap emission with a low-mass NS is predicted and our results is still consistent with their model prediction.}

The newly born MSP PSR J1023+0038 from an LMXB system has been detected by Fermi/LAT with a detection significance of \(\sim 7.9\) in the 200 MeV to 20 GeV band (Tam et al. 2010), which greatly motivated our search for } \gamma\text{-ray} \text{ emission from the AMPs to verify the possible existence of rotation-powered pulsars in the quiescent state. However, although many } \gamma\text{-ray} \text{ MSPs have been detected by Fermi/LAT (Abdo et al. 2009, 2010c), no } \gamma\text{-ray} \text{ AMPs have been found. In our work, we gave the upper limits of 100 MeV to 300 GeV } \eta_\gamma \text{ for two AMPs that are } 57\% \text{ for SAX J1808.4−3658 and } 3\% \text{ for IGR J00291+5934. We compared them with MSPs detected by Fermi/LAT. In the Fermi 2-year catalog, there are 38 possible } \gamma\text{-ray MSPs, among which } 20 \text{ are confirmed MSPs that have typical spectral form of pulsars (exponentially cutoff power law) and pulsations detected in } \gamma\text{-ray band. A summary of these } 20 \text{ MSPs is given in Table 2. We calculated the 100 MeV to 100 GeV } \eta_\gamma \text{ of these MSPs with flux values given in the catalog and timing parameters listed in Table 2. These sources’ } \eta_\gamma \text{ are plotted in Figure 3, with uncertainties derived from flux uncertainties given in the catalog. In addition, the uncertainties related to distance measurements are approximately } 60\% \text{, presuming } 30\% \text{ distance uncertainties. As can be seen, the } \gamma\text{-ray conversion efficiency of } < 3\% \text{ of IGR J00291+5934 lies in the very lower range of that of } \gamma\text{-ray MSPs. This upper limit is a strict constraint on the } \gamma\text{-ray emission of IGR J00291+5934, which likely suggests that this source may not emit in the } \gamma\text{-ray band, or that its } \gamma\text{-ray beam, at least the bright portion of its } \gamma\text{-ray beam, may not cross the Earth. For SAX J1808.4−3658, its } \gamma\text{-ray conversion efficiency is } < 57\%.}
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which is not sufficiently low suggesting this source as a candidate $\gamma$-ray source for further monitoring with longer observation time.

It can be noted that PSR J1023+0038 has been detected with the lowest conversion efficiency of $\sim 0.5\%$ in $>100$ MeV band (Figure 3; derived from spectral parameters given in Tam et al. 2010). This may suggest that $\gamma$-ray emission of MSPs is related to their evolutionary stage. The fast rotating AMPS may have almost no $\gamma$-ray emission, but at the end of the accreting phase, the newly born MSPs begin to emit in the $\gamma$-ray band with low $\gamma$-ray conversion efficiencies. We have also searched for pulsed emission from J1023+0038 in the $\gamma$-ray Fermi data from 2008 to the present (to 2010 July in the data of Tam et al. 2010), but have not found any detection. Comparisons of the properties of its $\gamma$-ray pulsed emission with that of its radio emission may have implications as to what are expected from AMPS. In addition, we note that no $\gamma$-ray MSPs are located in the lower right corner of Figure 3. We may approximately define a “death line,” $\eta_{\gamma} = 10^{0.325\eta_{0}}^{-4.3}$ where $\eta_{0}$ is the characteristic age in units of $10^{6}$ yr, by making all $\gamma$-ray MSPs above the line. Comparing to a theoretical death line, for example, $\log{\dot{P}} = -14.1 + 2.83 \log{\dot{P}}$, which was recently derived by Wang & Hirotani (2011) for $\gamma$-ray MSPs on the basis of the outer gap model, the line is nearly straight in Figure 3 if a constant $L_{\gamma}$ is considered (dotted line; $L_{\gamma} \approx 2 \times 10^{30}$ erg s$^{-1}$ is used to draw the line). Takata et al. (2012) found that $L_{\gamma} \approx 10^{34} \eta_{0}^{-5/4}$ erg s$^{-1}$ fits luminosities of $\gamma$-ray MSPs relatively well (derived from the outer gap model controlled by magnetic pair creation; cf. Equation (32)), which implies that $\eta_{\gamma}$ is generally inversely proportional to $\tau$ (note $E \sim \dot{P} / \dot{P}^{5} \sim 1 / (\tau \dot{P}^{5})$ or $E \sim \dot{P}^{-5/4}$ when the death line of $\log{\dot{P}} = -14.1 + 2.83 \log{\dot{P}}$ is used). The line we define instead suggests that older detectable MSPs tend to have higher $\eta_{\gamma}$. If this is a true feature, SAX J1808.4−3658 would have no $\gamma$-ray emission detectable because its conversion efficiency upper limit is very close to the line. We hope that as more MSPs are detected by Fermi in the near future, whether or not this line exists can be verified.

Finally, the complex regions near the Galactic plane, in which the four AMPS are located, certainly affects the $\gamma$-ray detections and the upper limit evaluations of them. As can be seen from the TS maps (Figure 1), while the Galactic diffuse emission was removed from the source regions at a satisfactory level, there is excess in these regions in addition to those corresponding to the nearby $\gamma$-ray sources in the catalog, particularly for SAX J1808.4−3658. The TS excess near the location of SAX J1808.4−3658 is not sufficiently strong for the $\gamma$-ray detection of this source due to the low TS value. On the other hand, if we consider TS excess as an indication of other possible weak sources, the luminosity upper limit of the source should be slightly lower than that we have obtained. It is also worth noting that our likelihood analysis of $\gamma$-ray emission from the four AMPS has uncertainties including that from the LAT instrument response function, Galactic diffuse emission, and nearby sources’ emission. Data that has been monitored for a longer period of time by Fermi/LAT will help reduce the uncertainties and thus provide tighter constraints on the emission properties of the AMPS.
